ART. III.—*The Iron Ores of the Penokee-Gogebic Series of Michigan and Wisconsin*; by C. R. VAN HISE. With Plate II.

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THE Penokee-Gogebic Series runs nearly continuously from the vicinity of Numakagon Lake, T. 44 N., R. 6 W., Wis., to Gogebic Lake, T. 47 N., R. 42 W., Mich., a distance of more than 80 miles. The west part of this belt was first fully described by Professor R. D. Irving, and Mr. Charles E. Wright.* A general account of the Range has been given by President Chamberlin.† Other papers have also been published in this Journal, which have from various standpoints treated particular questions in reference to this region.‡ It will, however, be necessary here to give very briefly its struc-

* Geology of Wisconsin, vol. iii, 1880, Part IEL, pp. 100-167, The Huronian System, by R. D. Irving; Part IV, pp. 239-301, The Huronian Series west of Penokee Gap, by C. E. Wright.

† Geology of Wisconsin, vol. i, 1883, pp. 80-94, The Huronian Age, by T. C. Chamberlin.

‡ This Journal, III, vol. xxix, pp. 237-245, Divisibility of the Archæan in the Northwest, by R. D. Irving. Vol xxxi, pp. 453-459, Upon the Origin of the mica-schists and black mica-slates of the Penokee-Gogebic iron-bearing series; by C. R. Van Hise. Vol. xxxii, pp. 263-265, Origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving; Vol. xxxiv, pp. 257-259, Is there a Huronian Group? by R. D. Irving.

ure as a whole before considering the subject of this paper. The series of rocks runs across the country in an approximately east and west direction, the general trend being somewhat north of east. It is a simple series, which has been tilted to the north at an angle of from 60° to 80°. It contains no subordinate folds, and thus the succession of belts is easily made out; one following above the other in perfect conformity. The series rests upon a complex of granite, gneiss, and various green schists. It is overlain by the eruptives of the Keweenaw Series. In our new mapping it will be divided into four belts (see fig. 1), the principle of division being a fragmental or non-fragmental character. At the base of the series is a cherty limestone-member which, in one place, is as much as 300 feet thick, and which varies from this to disappearance. The second member is a feldspathic quartz-slate. On the average it is from 300 to 400 feet thick, and is composed of green, red and brown fragmental slates which contain a good deal of clayey matter. The upper part of this fragmental member is a pure vitreous quartzite, the induration of which has been due to the enlargement of the quartz-grains originally deposited as a sandstone.* The third member of the series is a belt of non-fragmental sediments, about 800 feet thick, which is known as the iron-bearing member from the fact that all the known ore-bodies and heavily ferruginous rocks occur within it. The uppermost member of the series is a thick layer of greywackes, greywacke-slates, and mica-schists and slates. This member is several times as thick as the three lower combined, but in its essential fragmental character it is to be considered as a unit in the series.

The origin of the ferruginous rocks and ores of the iron-bearing member has been considered in a general way in a paper by Professor Irving already referred to. The fundamental conclusion of that paper has been borne out by our later investigations, i. e. that the original rock of the iron-bearing formation is a cherty iron carbonate,† from which the various phases of rock and the ore found in it have been produced by a complex series of alterations.

The principal phases of rock in that part of the formation in which the ore-deposits occur, aside from the cherty carbonate, are heavily ferruginous regularly banded slates, brecciated and concretinary ferruginous cherts, and the ore-

* Bull. U. S. Geol. Survey, No. 8. Upon the Secondary Enlargement of Mineral Fragments in Certain Rocks; by R. D. Irving and C. R. Van Hise.

† The origin of this cherty iron carbonate is a question of great interest, but one which it would take an article of some length to discuss, so this rock is taken as a starting point.

bodies. The carbonate has proved to be far more abundant than was supposed when the paper alluded to was written, and is found at all horizons, but most plentifully in the upper ones. The regularly bedded ferruginous slates are prevalent in the middle, and the ore bodies and ferruginous cherts at the lower horizons. In this paper I have not space to add anything further to what Professor Irving has said as to the particular processes by which the different phases of rock, aside from the ores, have been produced.

Position of the ore in the iron-bearing member.—The iron-ores are all located, as far as known at present, in that part of the iron-bearing formation between Sec. 33, T. 45 N., R. 1 W., Wis., and the east line of T. 47 N., R. 45 W., Mich., a distance of about 30 miles. The greater number of the larger deposits are found in the central half of this area. Also most of the known deposits lie at the base, or very near the base of the iron-bearing member; that is, they rest upon or close to the coarse-grained fragmental quartzite which constitutes the uppermost horizon of the quartz-slates. The number of important mines is about 23, and of these all have deposits upon the fragmental quartzite except five, and three of these, situated east of Sunday Lake, at the eastern extremity of the belt of mines, have exceptional characteristics which exclude them from the present discussion. It is true that three other mines have also deposits which are north of the fragmental quartzite; but in one case, that of the Colby Mine (fig. 4), the two ore-bodies have been shown by developments to have such connections as to show that they are essentially a single deposit. It is not meant to imply that the numerous deposits resting upon the foot-wall quartzite have clean ore always in contact with it. Quite often there is a layer of what the miners denominate "paint rock," or a layer of sand rock between the quartzite and the ore. This latter material is sometimes as much as 20 feet in thickness, although it is usually not more than a few inches, or at most a few feet. Sometimes also there is, between the ore and the quartzite, a mass of greater or less thickness of the ferruginous chert or mixed ore of the miners; rarely a thin layer of nearly pure white chert is found between the ore and quartzite. Notwithstanding these exceptions, the south side of the ore never penetrates the quartzite and in a general way follows it, so that it may be spoken of as resting upon it. This quartzite, although subject to local variations, has an average dip to the north of 60° to 70° , and thus furnishes an approximately regular wall, north of which the ore lies, and is consequently called the foot-wall by the miners. The few deposits north of the foot-wall quartzite are described by Mr. J. Parke Channing as also having regular south walls

which dip with the formation and are known as foot-walls. Whether the ore-deposits rest upon the fragmental quartzite or are north of it, they have then as their southern boundaries a plane dipping to the north at an angle of 60° to 70° .

Dykes in the iron-bearing member.—Mining developments have shown that the iron-bearing member is cut by numerous greenstones, the presence of which would not have been suspected from natural exposures. These greenstones are much altered; many of them are so decomposed as to be soft friable matter which can be picked to pieces with the fingers, and which now contain none of the original minerals which compose ordinary basic eruptives. They retain, however, distinctly their diabasic structure, and occasionally can be traced into comparatively unaltered phases which are true diorites. These altered greenstones are known to the miners, either as soapstones, or as diorite dykes. That they are dykes is manifest from their shape, and the way in which they cut across the layers of the iron-bearing member being traced at times into the foot-wall quartzite. This dyke-like character is well shown by figs. 2 to 7. The association of the ores and these soapstones was found to be so constant, that Mr. J. Parke Channing, Inspector, of Mines for Gogebic County, Mich., was secured to work out the relation of the ore-bodies and dyke-rocks. What follows as to the position of the dykes themselves, and as to the position of the ore-bodies with reference to them, is wholly the result of data furnished by his investigations.

The position of the dykes is given with reference to the iron formation in which they occur. This formation has a northern dip and a general east and west strike. As used in reference to the dykes, an east and west direction means parallel with the iron formation, a north and south direction transverse to it. The important thing for the present purpose, is not the absolute direction in which the dykes run, but their relations to the containing formations. The dykes vary a good deal in their dip and strike in different mines, and the same dyke at times in the same mine also varies in dip and strike. However, certain of their elements are quite constant. The dykes always dip to the south, and generally the southern dip, or its component transverse to the formation, is from 20° to 30° . The northern dip of the iron formation has been said to be from 60° to 70° . *It follows from this, that if the stratified rocks were placed again in a horizontal position, the dykes would be vertical.* The true dip of the dykes is usually, however, not exactly transverse to the formation, but east of it; so that a component along the dykes, parallel to the strike of the rocks, has usually an eastern pitch (figs. 2 and 5). This pitch

may be as high as 35° . From this amount it varies to horizontality, or even to a western pitch of 10° . The position of these dykes with reference to the foot-wall quartzite will be better understood by figs. 2 to 8.

The thickness of the dykes varies greatly, running from those of but a few inches in thickness, to those nearly 90 feet thick, fig. 4. In most of the mines in which the ore-deposits are of any magnitude the dykes are six feet or more in thickness; while it is noticeable that the three largest mines have dykes of considerable thickness. At least one dyke has been found in connection with every deposit west of Sunday Lake, with the single exception of the Ironton-Puritan ore-body, and it is possible that when the workings of these mines penetrate deeper they will come in contact with a dyke—one is known to come to the surface three or four hundred feet west. As to the three mines east of Sunday Lake, it has already been noted that their character is quite exceptional. From the eastern pitch of the dykes, it is evident that they must, if they continue in their observed directions, reach the surface to the west of the present workings of each of the mines. As these workings are but a few hundred feet deep, it follows that when these dips are high the dykes would reach the surface but a short distance from the ore-deposits. It thus becomes probable that there are as many dykes in the lower horizon of the iron-bearing member as are seen in all of the different mines, while doubtless there are many more. In some mines there are as many as three or four parallel dykes. In those cases in which there are several dykes in a single mine, one is generally known as the main dyke. The smaller ones are in some cases clearly offshoots from the larger, the actual connections between them being traced.

Position of the ore in reference to the dykes.—The ore has been spoken of as resting upon the fragmental quartzite as a foot-wall, and in exceptional cases as resting upon a non-fragmental quartz-rock, which belongs in the iron-bearing member, but which nevertheless forms a foot-wall for the ore deposits, dipping north with the formation. From the description of the position of the dykes and the quartzites, it is evident that the two rocks form V-shaped troughs, which have at the apices right angles, and the south arms of which are nearer vertical than the north arms; the first being upon an average 20° to 30° from a vertical, while the second is from 20° to 30° from a horizontal position. The relation is that of a right angled trough tilted toward the north until it lacks 20° to 30° from having its arms in horizontal and vertical positions. In one or two mines, for a short distance, these troughs do not incline either east or west, but at most of them, from what has gone before,

it is evident they incline to the east. *The ore-bodies lie in the apices of these roughly shaped troughs*, figs. 3, 4, 7. Each deposit of ore in following a trough will evidently be at different depths at different places east and west, depending upon the nearness of the dykes to the surface. All ore-deposits in the position described would reach the surface if the underlying dykes dip to the east or to the west. As a matter of fact, many of them were found at the rock-surface, but others were found after cutting an overlying rock. However, at present (October, 1888), mining developments have traced all deposits which are large enough to warrant working, with two exceptions, to the surface, and these exceptions are newly discovered deposits, which in all probability will be traced to the surface in the future. As would be expected, it is also true that the development of the deposits which were originally found at the surface have carried them, in every case in which they are of any magnitude, below the surface of the country rock. Both of these facts, the tracing of the ore-deposits discovered at depth to the surface, and those discovered at surface beneath rock, are inevitable deductions from what has preceded.

Rock above the ore.—The rocks which are found above the ore-deposits are the ferruginous cherts—the rocks which have been spoken of as the characteristic ones near the base of the iron-bearing member throughout the area in which the ores occur. The upper boundary of the deposits differs from the quartzite and dyke-boundaries, in that the change from ore to the cherty rock is a transition instead of an abrupt one. In passing upward through an ore-deposit, as its border is reached, the ore becomes mixed with chert until so poor in iron as to become unsalable. In passing still farther upward, the amount of chert becomes greater, until a fractured chert and iron ore, known to the miners as “mixed ore,” is found. In passing up still farther this mixed ore grades into the ordinary ferruginous chert of the lower horizons.

To summarize then, the boundaries of the ore-deposits are to the south, either fragmental quartzite or ferruginous quartz-rock in the ore-formation—generally the former; under the ore, the dyke rocks; and above the ore, the typical ferruginous cherts of the region.*

The horizon above the ferruginous cherts, is in most cases a regularly banded red ferruginous slate. This slate is composed of chert and iron peroxide and is as regularly bedded as the unaltered carbonates. Above this slate, constituting the upper horizon of the ore formation, are often found cherty iron carbonates. While this section is known to occur at several of

* Evident practical deductions for carrying on prospecting and mining follow from the foregoing, but in this paper my space is too limited to give them.

the more important mines, it cannot certainly be said to be common to all of them. Also the respective thicknesses of the ill-defined belts are very different at different mines. A general statement may be made, that at most of the mines a cross section of the iron formation shows the proportion of unaltered iron carbonate to increase in passing from lower to higher horizons. It is true that almost solid carbonate occurs at three places at relatively low horizons, although none of them are known to be at the base of the member, while one is certainly underlain by a ferruginous chert. Also at several localities a typical chert is found at very high horizons. Figs. 2 to 8 illustrate as wide variations of the relations of the ore-bodies to the surrounding rocks as is anywhere found; yet all are alike in essential points.

Character of the ore.—The iron ore is a soft, red, somewhat hydrated hematite. By chemical analyses it is shown to be more or less manganiferous, the manganese occasionally running to a high percentage. Much of it is so friable that it can be broken down with a pick, although as taken from the mines it is compact enough to hold together in tolerably large lumps. These lumps are porous, often more or less nodular, and also often roughly stratiform. The strata conform in a general way to the strike and dip of the formation. Mingled with this soft hematite, in a few mines, is a small quantity of aphanitic steel-blue hematite. The south deposits carry upon an average more manganese than the north deposits, the average in the South Iron King being above 10 per cent, while from the South Colby, ore has been taken which contained as much as 30 per cent metallic manganese.

THE ORIGIN OF THE ORES.

We have before us the character of the iron ores, the shape of the deposits, their relations to the rocks surrounding them, the nature of the rocks of the iron formation above the ore horizon, and the character of the formations above and below that bearing iron. An attempt will now be made to suggest an explanation of the character and location of the ore-bodies.

The shape of the deposits and their relations to the strata of the iron formation are such as to exclude the idea of original sedimentation in place; neither can they be considered as the result of oxidation of iron carbonate in place alone. All of the unaltered iron carbonate now found contains a much larger quantity of silica than the ores, so much as to make them entirely valueless. Also the red banded slates found at the middle horizons give every evidence of being a material which has resulted from the oxidation of the bedded carbonate in place.

Further, the large amount of manganese which the ores, especially the south deposits, contain is greater than that found in any carbonate from which analyses have been made; and the average content of manganese in the ore is much greater than the average of the carbonates. While it is thus true that the ores are not carbonates of iron which have altered in place, it is almost as certainly true that the iron carbonates of the belt have been the source whence the iron oxides for these ores have been derived. The nature of the evidence upon which this statement is based has been suggested; but the conclusion would be much clearer if there were place to give a detailed description of the rocks of the iron formation as a whole.

Since, then, the iron ores cannot be explained by oxidation of carbonate alone in place, and since the carbonate was the source whence they were derived, they are necessarily concentrations of iron oxide, combined perhaps with iron oxide furnished by oxidation of carbonate in place. If this explanation is adopted, however, it is not only necessary to explain the presence of the iron oxide in its peculiar position, but the nature of the whole lower part of the formation. The explanation must account for the great increase in the amount of silica in the lower horizon of the ore formation as compared with the original cherty carbonate; for its almost total absence in the ore; for the concentration of the iron oxide; for the almost complete absence of carbonate of iron at the lower horizons; for the red banded slates and carbonates in the middle horizons; and for the relatively much more abundant unaltered carbonate in the upper horizons.

A particular occurrence of iron ore.—Before attempting to give a general explanation of these facts, it will first be well to refer to one of several occurrences of narrow belts of iron ore in natural exposure. At Sunday Lake outlet, in Sec. 13, T. 47 N., R. 46 W., Mich., the actual transformation from cherty iron carbonate to iron ore is seen in all its phases. In clefts, joints and partings along the bedding of the exposure are narrow seams of hematite. In passing from the seams, the hematite becomes mingled with some chert; going still farther, the chert increases in quantity until a groundmass of silica contains many rhombohedra of iron oxide. The iron oxide then gradually passes into siderite. This siderite is in perfect rhombohedra, and it is evident, in thin section, that the iron oxide adjacent is pseudomorphous after it. The rock has now passed from an ore into a sideritic chert, which is of a light-gray color, aphanitic texture, and breaks with conchoidal fracture. The latter rock is manifestly in its original condition. The processes by which the seams of iron oxide occupied the space once taken by sideritic chert are plain. The iron carbonate has de-

composed in place to iron oxide, the rock becoming a hematitic chert. Along the seams, waters bearing iron in solution have passed. These waters have particle by particle dissolved out the chert and replaced it with iron oxide, and where once was lean sideritic chert is rich ore. A part of the iron oxide is due to the oxidation in place of iron carbonate, but the larger part has come from a greater or less distance there to be deposited. The seams of iron oxide at this point are but a few inches in thickness, but it is probable that the series of changes which have here taken place upon a small scale, will upon a large scale explain the concentration of workable ore-deposits.

Time at which concentration of the main ore-bodies occurred.
—It has been stated that the iron belt rocks are much less altered as a whole in the upper horizons, being there composed largely of unaltered cherty carbonate, while the lower horizons contain very little carbonate and are mostly composed of ferruginous chert and iron ore. It follows as a deduction from this succession, that the series of changes which have so completely altered the lower horizons of the formation have occurred subsequently to the uplifting of the series. The alterations can only be explained by the action of percolating waters bearing oxygen, and which therefore came from above. If the layers were horizontal when the changes occurred, the waters passing downward would have altered most that part of the formation nearest the surface. The reverse would be the case if the alteration was subsequent to the tilting, for the upper layers of the member would partially escape the action of percolating waters, as will readily be seen by glancing at figs. 1 and 9, and taking into consideration the nature of the belt of rock above the ore formation. It is a member composed of black and gray clay-slates, greywacke and greywacke-slates, all of which contain a large amount of clay, rocks particularly impervious to water. A rock underlying any great thickness of such a formation in a horizontal position could not be greatly affected by waters from above. However, when the series had been uplifted and eroded, this upper impervious member would have been removed, and the waters would come directly in contact with the lower horizons of the ore formation, while the upper horizons of the belt would still be somewhat protected.

Before going farther, it is necessary to consider the porosity of the rocks which underlie the ore formation. They have been said to be composed of quartzites and feldspathic quartz-slates. Included in the latter are clay-slates; consequently the rocks of this member are also almost impenetrable to percolating waters. The uppermost layer of the member, the quartzite, is not itself a perfect barrier to the passage of water, on account of the joints which are always found in such a brit-

tle rock. These joints do not affect the underlying slates, for these thinly laminated clayey rocks are so flexible that under the slight bowing which they have received, they are scarcely fractured at all.

Process of Concentration.—An attempt will now be made to trace the passage of percolating waters through the inclined layers of the iron formation. Fig. 9 is a section showing the condition of this member at the present time at the surface, and illustrating how this state of affairs was reached. The strata of the formation are now exposed by their dipping at a high angle, 65° , to the north. The whole Penokee-Gogebic series, more than 13,000 feet thick in some places, of which the iron formation is a part, is exposed in the same fashion. Therefore thousands of feet of the iron member have certainly been carried away by erosion. The figure assumes that about 2000 feet have been eroded from this member since it was upturned. It would, however, make no difference with the argument if this erosion occurred during the time of the upturning. The upper part of the figure represents the surface of the iron formation, and a part of the underlying and overlying rocks at some past time. Near the bottom of the figure is the present land surface, showing the succession of rocks from north to south which are now actually found. A transition from unaltered cherty carbonate to completely decomposed carbonate is noted. At the time when the upper supposed land surface was an actual one, the present surface would be but little exposed to the action of percolating water. It could not pass through the slates which overlie the iron formation; neither could it get in through the underlying feldspathic quartz-slates. Therefore, most of the water which at that time was able to reach the present land surface, must have done so by passing down, along and through the layers of the iron formation itself. The dotted broken line represents a perpendicular course which the water would follow were its passage not deflected by the laminated character of the rocks; but there would be a tendency for this water to follow the bedding, so that, entering the iron formation at its uppermost horizon, it would follow an irregular course marked by a broken line and would reach the foot-wall quartzite at the line of the present surface of the country. It is immaterial to the argument whether this line ought to vary farther from the perpendicular than marked or not; for, in any case, nearly the whole of the present surface of the iron formation would escape the percolating waters, or if not this surface, some other yet lower down. It is, however, probable that the lowest horizon would not thus escape until a great depth was reached; for the waters entering the formation, would

steadily work their way to a greater and greater depth along the foot-wall, until such depths were reached as to prevent its farther penetration.

Now, suppose erosion to gradually sweep away the rocks which are between the old surface of the country and the present surface. Beginning at the base of the formation the rocks at the present surface would be more and more exposed to the action of percolating waters, which would in turn affect the middle, and finally the higher layers until its whole width was subject to the agencies of alteration. There is, then, a gradual increase in the time that percolating waters have acted upon the various layers of the formation in passing from south to north. The difference in time to which the highest and lowest layers have been subjected to such action, is at least the length of time that it has taken erosion to remove the thickness of rock between the old surface of the country and the present surface; therefore the slower the erosion is taken to have been, the greater the difference in time.

Next suppose that erosion had continued until the surface of the land is at some intermediate point. In tracing the percolating waters, it is necessary to take into account the deflection to which they would be subjected by its layers, and the impenetrable character of the underlying slates and intersecting dykes. The relative position of the ore-bodies, quartzites and dykes has already been given. The water which fell upon the layers of the iron formation near its base, would readily pass through the rock, it being here already much altered and broken by the long action of water. Passing through these ferruginous cherts, the water would quickly reach a dyke or the fragmental quartzite, and would follow along this barrier, deflected to the north if upon the quartzite, and to the south if upon a dyke, until it reached a trough made by the dyke and quartzite, along which it would follow, traveling toward the east as it penetrated deeper. Such water would be likely to contain oxygen in solution, and would be capable, if it contained alkalis, which might be readily obtained from the alteration of the basic dykes, of taking up a small amount of silica. Other water falling upon higher layers would make its way slowly and with difficulty through these less altered parts, and would oxidize iron carbonate until all oxygen had been extracted from it. This oxidation of a part of the iron carbonate would liberate carbon dioxide, which would be taken into solution and added to the carbon dioxide which the water already contained.* Such

* In this discussion carbonated water is taken as the agent of solution. It is likely enough that organic acids have helped to take the iron carbonate in solution and bear it to the points of precipitation.

water would take into solution unaltered iron carbonate. It would also in its upper course take up what silica it was able to carry. As it penetrated farther and took more carbon dioxide in solution, and consequently also more iron carbonate, it would be less able to carry silica, and would deposit that material as chert in the lower horizons. The water thus traveling on with an increasing amount of iron carbonate, would finally reach a dyke and be deflected toward the foot-wall quartzite. It would follow this dyke until the apex of the trough was reached; here it would mingle with a larger amount of water more directly from the surface bearing oxygen, and therefore capable of oxidizing the iron carbonate. The iron would then be precipitated in the apex of the trough as more or less hydrated sesquioxide of iron.

Upon the other hand, the silica would here be dissolved; for the carbon dioxide solution containing iron carbonate would be greatly diluted by the large amount of water which bore the precipitating agent for the iron, and the resultant abundant dilute solution of carbon dioxide bearing perhaps alkalies with it, would be capable of taking up silica which was either originally present or had been subsequently deposited in the apex of the trough. Such solutions may have furnished the silica which has enlarged the particles of quartz in the foot-wall and thus indurated it. The result of this leaching would be to steadily add iron oxide to and remove the silica from the apices of the trough formed by the quartzite and dyke, and thus to form ore-bodies. At the same time the other parts of the formation would be steadily impoverished in iron content. Much of that which remained disseminated through the formation would have been changed from carbonate to oxide. In its lower part, the silica which was taken into solution in the upper part of the water's course would be precipitated.*

The processes thus outlined would penetrate to deeper parts of the formation as erosion steadily advanced until the present surface of the country is reached, and the ore-bodies thus formed at depth are now found at surface. It follows that a large amount of iron found in the ore-bodies was originally in rock which has been removed by erosion. So far as the deposits are at the surface, all of the iron oxide, except that

* The chemistry of the processes thus outlined assumes the following: that the oxygen of percolating waters is sufficient to oxidize iron carbonate not in solution and set carbon dioxide free; that the resultant carbonated waters are sufficient to take iron carbonate in solution; that if such waters bearing dissolved carbonates are mingled with other waters bearing oxygen, the iron carbonate or a portion of it will be precipitated; that silica may be carried in percolating waters; that carbon dioxide is sufficient to precipitate silica from such solutions; and that a carbon dioxide solution strong enough to precipitate silica, by dilution, may be made so weak in carbon dioxide that it would be capable of taking silica into solution. All of these facts and principles of chemistry are so well known that no discussion of them or reference to authorities is needed.

which came from the oxidation of carbonate in place, must have come from such a source, while it is probable that a large part of the deposits located at considerable depths have been stored from rock which has been broken down and scattered far and wide. These are not so much concentrations of iron oxide which were originally deposited as a carbonate above them, as from the layers which stretched to the southward, but which were subsequently by upturning placed over the ore-bodies. Also the large proportion of silica now found near the surface, and particularly in the southern half of the belt, is probably much greater than was here originally present. The silica of these highly cherty rocks associated with the ores may represent a concentration from many hundreds, or even thousands of feet of rock which have been swept away, just as the ore-bodies are concentrations from the iron carbonates which these same rocks contained. A portion of the silica may have come from the alteration of the dyke-rocks contained in this removed material, but doubtless most of it came from the original cherty carbonate.

The only exceptions of moment to the facts as assumed in the above discussion, are the occurrence of iron ore at a higher horizon than the foot-wall quartzite, and the ore-bodies east of Sunday Lake, which, so far as present developments go, are not known to be associated with dyke-rocks. It has been said that those ore-bodies in the main part of the range which are north of the fragmental quartzite have a well-defined cherty quartz foot-wall of a regular character. In these cases, this quartz-rock has served as the plane which checked the waters in their downward passage before reaching the fragmental quartzite. Here the relation of the ore to the dykes, and its other characters, are the same as when the ore is found upon the fragmental quartzite. It is of interest to note that in one of the largest mines of the region, the Colby, as shown by Fig. 4, the north and south deposits have as their basement the same great dyke, the two ore-bodies being separated merely by a gigantic horse of rock which served as the impervious layer to form the foot-wall of the north deposit. The explanation given of the origin of the ore found upon the fragmental quartzite, applies perfectly to these north deposits with the modifications above indicated. That there are layers of the iron-bearing formation which are not readily pervious, and therefore become basements along which the down-flowing waters passed, is not at all strange. It would be stranger if, in a thickness of water-deposited sediments of 800 feet, there were no layers which, at least for a short distance, were effectual barriers to the passage of percolating waters. The chemistry of the process of concentration of the ore-deposits east of Sunday Lake, in all

probability, is like that of the typical deposits of the range. Their concentration is apparently, however, more nearly analogous to the narrow seams of ore described in the early part of this paper than to the typical deposits. The formation here apparently being cut by no impervious dykes, the waters have not been carried over to the quartzite, thus forming main channels of percolation, but the comparatively small ore-bodies have developed here and there as favorable conditions for concentration occurred.*

The above explanation of the origin of the ore-deposits accords well with the facts of their occurrence, and also with the idea that the iron formation deposits were originally an impure cherty carbonate of iron. It explains perfectly the peculiar position of the ore-bodies with reference to the dykes and the foot-wall quartzite; it explains their presence in a similar position in the few instances in which the deposits are north of the fragmental quartzite; it explains the flat wedge-shaped character of the ore-deposit; it explains the nature of the ore, a soft somewhat hydrated hematite, bearing more or less of manganese; it explains the excess of manganese which the ore carries beyond the amount found in the unaltered carbonates, and its relatively greater abundance in the south deposits; it explains the presence of large quantities of unaltered carbonates in the upper horizons of the iron formation, the gradual lessening of this carbonate in passing to lower horizons, and its absence at the base of the formation; it explains the large percentage of silica contained in the greater part of the lower horizons and the low percentage at the apices of the troughs.

Probable extent in depth of ore-bodies.—This explanation of the origin of the ores may throw some light upon the depth to which the ore-bodies extend. The fact that all of them have been traced to the erosion surface, is favorable, rather than otherwise, to their extending to a considerable depth. The ore-bodies, at the depths now penetrated, must have formed almost wholly before the sweeping away of the rocks of the iron formation above them. They could, then, have received but little of the iron they contain since the end of the Glacial epoch, for erosion was then terminated by the mantle of drift dropped over the region. The deposits, with some degree of probability, may be said to continue to a depth at which the agencies of concentration could effectively work. Whether this distance will be found to be measured in hundreds or thousands of feet, the data at present are too scant to indicate. I am inclined to believe, however, that they may be depended upon to con-

* As bearing upon the truthfulness of the above theory as a whole, it is an interesting fact that the practical miners, in prospecting, eagerly follow underground water channels, hoping that they will lead to ore-deposits.

tinue for a considerable depth. While they may extend in unimpaired richness and magnitude to a depth as great as can be penetrated by workings, it is certain that they do not continue to an indefinite distance. There is also a possibility that the deposits may become poorer than at the surface at comparatively small depths; for it may be that percolating waters, since the termination of the Glacial epoch, have been able to remove from the upper parts of the deposits a small percentage of silica. Such a removal, even to the extent of five per cent, or less, would have an important influence upon the value of the deposits.

Emmons on Ore-deposits.—It is of interest to compare the conclusions reached, to those of Emmons* as to the origin of the silver-lead-deposits of Leadville, Colorado. He finds that the ore did not form in pre-existing cavities, but by a gradual replacement of the rock materials by substances brought in solutions; and also that these solutions did not come up from below, but have reached their "immediate locus" by passing downward through the rocks above. In his discussion upon ore-deposits in general, he maintains that a like origin is much more common than has been believed. It will be seen that my conclusions as to the origin of the iron ore of the Penokee-Gogebic Series, arrived at independently of Mr. Emmons's work, are in exact harmony with his general conclusions.

Iron ores in other parts of the Lake Superior country.—Before closing this paper, some allusions must be made to the nature and origin of the iron ores which are found in other regions in the Lake Superior country. Large deposits of ore are found in rocks remarkably like those of the Penokee-Gogebic series, in the Vermilion Lake, Marquette and Menomonee regions. These ores are associated in almost every mine with a somewhat varying peculiar rock, universally known as soapstone. The connection between the ore and these soapstones is so constant that the appearance of this peculiar greasy altered material is considered as a very favorable indication in prospecting. It is true that the rock which miners denominate soapstone, in different localities has quite different appearances, and frequently schists are called soapstones which have no essential likeness to the material with which the ore is found associated. These so-called soapstones, in the regions referred to, are at times peculiar green banded schists, at other times are compact strongly foliated sericite-schists, and only occasionally do they retain the structure of

* U. S. Geol. Survey; Monograph XII; Geology and Mining Industry of Leadville; Samuel Franklin Emmons, pp. 375-379. Trans. Am. Inst. Min. Eng., vol. xvi, pp. 804-839. Structural Relations of Ore Deposits, S. F. Emmons.

an eruptive rock; but in the few cases of which we have definite knowledge, the manner in which the soapstones cut the adjacent rocks is that of dykes. This is particularly well shown at the large open pits at the Jackson Mine, Negaunee, Michigan, and at the Champion Mine, Champion, Michigan. This same dyke-like character of the peculiar schistose rock at one mine in the Vermilion Lake series is described and figured by Professor Alexander Winchell.* Mr. James R. Thompson, Mining Engineer for the Iron Cliffs' Mining Company, of Negaunee, Michigan, also finds in quite a number of mines in the Marquette region, that the soapstones have a dyke-like character. With most of the soapstones of these regions, the only evidence that they are of eruptive origin is their relations to the rocks which they intersect. They have not been shown in many cases, as in the Penokee-Gogebic region, to have the typical structure of eruptive diabbases; but the transition phases between these much altered rocks and the comparatively unaltered massive eruptives have in some instances been found, and it is probable that many of them are altered eruptives. At any rate, the close association between the soapstones and the ores can hardly be accidental, and, taken in connection with what has been given in reference to the Penokee-Gogebic ores, it is very suggestive that they, in some way, and perhaps in a way similar to that in the Penokee-Gogebic region, have influenced the concentration of the iron in the ore-bodies at the places found. To certainly determine the origin of all these "soapstones," and their stratigraphical and other relations to the ore-bodies will require a detailed investigation. It would, however, be an interesting illustration of the uniformity of nature's processes, if such future investigation should show that the iron ores in the other regions of the Lake Superior country have an origin like those of the Penokee-Gogebic series.

Madison, Wisconsin, October, 1888.

DESCRIPTION OF FIGURES. PLATE II.

FIGURE 1.—Cross-section of the Penokee-Gogebic series at Penokee Gap, showing the relations of this series to the underlying Laurentian and the overlying Keweenaw series. The figure also shows the conformable succession of the four members of the series itself. At this particular place, the quartz-slate member, as compared with the iron-bearing member, is thicker than usual. Scale 1"=4000'.

FIGURE 2.—Elevation of First National mine, looking south. The eastern pitch of the dyke is shown, and the resultant greater depth of the ore in passing to the eastward. Scale 1"=130'.

FIGURE 3.—Cross-section of same mine, looking east. Scale 1"=130'.

* Geol. and Nat. Hist. of Minn.; 15th annual report, pp. 24-25.

FIGURE 4.—Cross-section of Colby Mine through both north and south ore-deposits. The perpendicular line running through the figure is drawn because the two parts of the section are not exactly upon the same plane. They differ from this so slightly, however, that the true relations of the ore-bodies to the surrounding rocks are shown by the combined figure. Scale 1"=210'.

FIGURE 5.—Elevation of Pence Mine, looking north. The eastern pitch of the dyke is again observable. The right-angled trough made by the dyke-rock and quartzite is in this case not filled with ore throughout the whole figure. At the eastern end of the figure after passing through a heavy bed of drift, the ore constitutes the rock surface. Scale 1"=210'.

FIGURES 6, 7 and 8.—Cross-sections of same at No. 1, 2 and Father Hennepin shafts respectively. In figure 8, the shaft has not yet passed through the ore. Scale 1"=210'.

FIGURE 9.—Section designed to show the variation from unaltered carbonate to ferruginous chert and ore-bodies in passing from higher to lower horizons, and to illustrate the manner of ore-concentration: S=Upper Slate, Q=Quartzite, FQ=Feldspathic Quartz-slate. Scale 1"=1230'.

Figures 2 to 8 inclusive are from surveys made and blue-prints furnished by Messrs. J. Parke Channing and C. M. Boss, of Bessemer, Mich.

IRON ORES OF THE PENOKEE-GOGEbic REGION.