of high water the sediments would be abundant and much coarse material would be brought down while in times of low water the sediments would be less abundant and finer grained. The effects on sedimentation of seasonal and periodic variations in rainfall would be accentuated in proportion as the relief of the land was high and rugged. As the sea bottom was aggraded by sedimentation at the river mouths the shallows advanced seaward instead of landward as happens when the sea encroaches on the land. The shore line was probably west and north of the area and this may explain the comparative coarseness of grain in the stratigraphically higher strata in the northern part of the district.

THE ROCKS FROM WHICH THE UPPER HURONIAN SERIES WERE DERIVED.

The Upper Huronian series were derived from the Archean complex of basic and acid rocks, mainly igneous, the rocks of the Lower (and Middle) Huronian series which on adjacent shores were quartzite, dolomite, some slate, igneous rocks of which probably the greater part were basic igneous extrusives, and contemporaneous basic igneous volcanics. These rocks were broken up on the land by decay and disintegration and transported to the sea by streams. The more resistant minerals such as quartz and feldspar reached the sea largely in the form of sand in less finely comminuted condition that the less resistant ferro-magnesian minerals and soluble silicates, the weathered residuum of which made mud. The former are abundant in the graywacke and arkose while the latter forms a main constituent of the slates. Iron, the alkalies, and the alkaline earths were partially dissolved and carried to the sea in soluble form. Sodium and potassium remained in solution in the sea water while the iron, calcium, and magnesium were precipitated mainly in the form of carbonate. Iron carbonate is the important original iron bearing mineral in the iron formation rocks and is also widely distributed with calcium-magnesium carbonate in slate associated with the iron formation.

The prevalence of graywacke and arkose in the Upper Huronian series is evidence of immature weathering of the rocks from which they were derived. It has been ascertained by careful calculation[1] that the slates of the Upper Huronian series as a whole are higher

[1] S. H. Davis. The Source of the Upper Huronian group of sediments of the Lake Superior region. Thesis, University of Wisconsin, 1909.

in feldspar and ferro-magnesian minerals than the average shale and slate showing that the material was not so thoroughly weathered before reaching the sea as the average mud. Perhaps the climate in Upper Huronian times was less favorable to decomposition than in later periods. Furthermore, volcanism was active in sea and on land. Enormous quantities of basaltic lava and ejectamenta were poured forth from fissures and craters and became intercalated with the sediments. Under ordinary atmospheric conditions basalt is rapidly disintegrated and decomposed. Great quantities of basaltic detritus were doubtless carried from the land to the sea in streams to be added to that which was poured forth in the sea to be broken up and worked over by the water. Volcanism was especially vigorous in the Iron River-Crystal Falls-Florence area and its products are widely distributed in the sediments as well as in breccias, tuffs and ellipsoidal flows.

CONDITIONS OF DEPOSITION AND ORIGIN OF THE IRON-FORMATION.

Conditions favorable to the deposition of iron formation were recurrent at intervals throughout the history of the Upper Huronian in the Iron River district. This is shown by the intercalation of iron formation strata at different horizons in the series. The iron formation is associated at different places with every type of rock known in the succession and passes by gradation in different places into all of the other sediments. So far as the purely physiographic factors are concerned it seems that the iron formation was formed under conditions not essentially different from those under which the associated sediments were deposited. It should be borne in mind that the characteristic minerals in the iron formation are abundant in some associated sediments which are classed as slate from which the iron formation differs only in the relative abundance of the essential minerals, viz., soluble silica and iron bearing carbonates or, to put it in another way, iron formation was frequently deposited with the mud and other detritus which forms the bulk of the sediments. At times when iron bearing carbonates and silica were abundant in solution precipitation of these minerals predominated over mechanical sedimentation and thus the iron formations were built up. Conditions for deposition of iron formation were recurrent, oscillating, and often local, as shown by the intercallation of thin bands of iron formation in slate. The variations in thickness of the different lenses are due in some measure to relative duration of conditions favoring deposition but probably in greater measure to fluctuations in supply of materials. Deposition was rapid in proportion to abundance of materials supplied. The iron formation lenses are to be regarded as a result of an unusually abundant supply of iron formation materials to the sea rather than to cessation of mechanical sedimentation during process of their accumulation.

SOURCES FROM WHICH THE IRON FORMATION WAS DERIVED.

We have now to inquire into the source of the iron formation materials and to explain the sudden influx of these materials contributed to the sea in large quantities at recurrent intervals. If the iron formation is a chemically precipitated rock, as it doubtless is, prior to deposition the silica and iron were in solution in sea water. There are two possible sources from which the sea may have derived its supply of materials. The more obvious of these is the rocks forming the land area which drained into the sea. It is a well known fact that iron is dissolved and carried in solution in both underground and overground run off. However, the amount which is carried today in the surface drainage is negligible except under local bog conditions where the waters are charged with carbonic acid and organic acids from the influence of decaying vegetation. Under ordinary weathering conditions iron is oxidized and remains in place as insoluble oxide or is transported in suspension in water with other insoluble weathered products. Some of the iron doubtless reached the sea in this form but we have no evidence in this district that iron oxide was an important original iron formation mineral.

The thickness and extent of the main iron bearing horizon together with the comparatively unweathered character of the associated sediments compared with the average shale or slate and perhaps the coarseness of grain shown by some of them indicate that the iron was not deposited under the well understood bog conditions of later times. It should be remembered that, (1) there are no known bog deposits comparable with these in thickness and extent, (2) drainage waters competent to bring down great quantities of rather coarse detritus are not those which

would under ordinary conditions carry iron in solution since the ability of the waters to hold soluble iron is dependent on slow movement through well vegetated low areas.

The quantity of iron carried in solution in rivers of today is negligible. In the analyses of the waters of 20 representative American rivers published by Chamberlain and Salisbury[2] traces of ferrous iron are found in only three, the Rio Grande Del Norte, the Ottawa, and the St. Lawrence and traces of ferric iron in but two, the Delaware and Maumee.

From the foregoing it seems that under the physiographic conditions which seem to have pertained only small quantities of iron could have reached the sea in solution in streams if the climatic and atmospheric conditions were similar to those which now prevail. What may have been the composition of the atmosphere in this early period we have as yet no means of knowing, but it seems probable that carbon dioxide was much more abundant in the earlier atmospheres than in those of later times. With the exception of water-vapor carbon dioxide is the most abundant gas emitted from volcanoes. It is abundantly occluded in meteorites and in igneous rocks. Under Chamberlain's planetesimal hypothesis of the earth's origin carbon dioxide was originally abundant in the rocks of the earth's interior whence it was extruded to form in large part the initial atmosphere through processes of volcanism which were dominant in the early periods of the earth's history. It is not unreasonable to suppose that the atmosphere of Upper Huronian times was heavily charged with carbon dioxide, especially as geologic processes involving abstraction of carbon dioxide from the atmosphere have since early times outbalanced those which restore it.[3] An atmosphere heavily charged with carbon dioxide would promote the weathering of rocks and especially the solution and transportation of iron as carbonate. It would also exert a favorable influence on the growth of plants and thus indirectly on rock weathering. In such an atmosphere the chief factors which now prevent the solution and transportation of iron on a large scale in streams would be inoperative.

Any acceptable theory of the origin of the iron formation must account satisfactorily for the source of the silica. That the silica

[2]Chamberlain, T. C., and Salisbury, R. D. Geology, Vol. I, table opposite p. 106.
[3]See Van Hise, Charles Richard. A treatise on Metamorphism. Monograph 47, United States Geological Survey, p. 974.

was deposited with the iron carbonate cannot be questioned. Through subsequent metamorphism it has been extensively rearranged in some of the rocks, some has been introduced from outside sources and some has been carried out of the formation but in the less altered rocks the even lamination of the chert with iron carbonate leaves no room for doubt that both were deposited together as a sediment. As in the case of iron carbonate, the more obvious source of the silica is the rocks forming the Upper Huronian land areas. Conditions favoring the solution and transportation of iron carbonate would favor solution and transportation of silica. Silica is more easily carried in solution in streams than is iron and is present in sea water from which it has been deposited since early times as chert in association with limestone and dolomite.

From the above we may conclude that under an atmosphere highly charged with carbon dioxide ordinary processes of erosion and transportation would contribute to the sea in soluble form important quantities of iron and silica.

We have now to consider whether the quantities of iron and silica contributed through the operation of the erosional processes discussed in above paragraphs would be an adequate supply under the physiographic conditions attending the deposition of the iron formation.

It will be recalled that the Upper Huronian series throughout has the characteristics of a delta deposit, in any event it was laid down in shallow water of varying depths. The rapid, oscillating, variations in conditions of sedimentation were due mainly to fluctuating supply of sediment. With the exception of non-fragmental sediments, i. e., the iron formation, fluctuating supply is easily accounted for by seasonal and periodic variations in precipitation without making appeal to oscillating earth movements affecting physiographic relations between land and sea. Under any prevailing combination of physiographic and climatic conditions, barring some unusual factor, it is, however, difficult to see why there should have been a greatly fluctuating supply of soluble silica and iron. These materials should have been contributed more or less uniformly throughout the period of sedimentation. If we embrace the assumption that silica and iron in soluble form were uniformly contributed to the sea, we face the question, why did not the precipitation of iron and silica, after having once begun, take

place uniformly and continuously? The readiest answer is, conditions for deposition were more favorable at some times than at others, but this answer is satisfactory only when the favorable conditions for deposition are fully explained. Obviously the most favorable condition for deposition is abundance of materials in solution and certainly great influx from time to time of materials in solution would be a strong factor in determining quantity of material deposited. There are reasons to believe that deposition of the iron formation was coincident with periods of unusual influx of abundant silica and iron as later shown.

It will be recalled that the iron formation is closely associated with black carbonaceous slate and is itself carbonaceous to varying extent. This close association with carbonaceous materials is probably not accidental and we are led to believe that it may have genetic significance. The occurrence of black carbonaceous slate and limestone has been considered strong evidence of the presence of life in the pre-Cambrian seas of the Lake Superior region. An early theory of Van Hise's[4] depends on the presence of carbonaceous matter (presumably organic) in the sea to explain the formation of iron carbonate. If the iron had been precipitated as ferrichydroxide and mixed on the sea bottom with decaying organic matter it would have been reduced to ferrous oxide which by uniting with carbon dioxide would form ferrous carbonate. The deposition of silica in the form of chert is presumed to have taken place through a process analogous to those of later times when extensive beds have been formed through the accumulation of siliceous tests of small organisms.

On the supposition that life was present in the Upper Huronian sea and that the atmosphere was heavily charged with carbon dioxide we may conclude, therefore, that with uniform accessions of iron and silica in solution, iron formation may have been deposited at recurrent intervals when the requisite kind of life, whatever its nature may have been, was unusually abundant. The lense-shaped discontinuous beds represent conditions of local development of these life forms. Under this theory deposition must necessarily have taken place very slowly and almost complete cessation of mechanical sedimentation was necessary to the accumulation of any considerable thickness of iron formation.

[4]Van Hise, Charles R. Monograph 19, United States Geological Survey, pp. 249-50.

While the theory above outlined, under the most favorable interpretation, accounts for the source of materials and the deposition of iron formation it is not an adequate explanation of all the phenomena of constitution, manner of occurrence and lithologic associations of the iron bearing formations of this and adjacent areas. The theory is not inclusive. It does not include all possible sources of iron and silica, does not recognize possible precipitation of iron formation through chemical processes unaided by organic life, does not account for rapid deposition in the face of evidence pointing to rapid accumulation and offers only partial explanation for the absence in post-Cambrian formations of iron bearing beds of similar constitution and equal extent.

The escape from some of these difficulties is afforded in appeal to the instrumentality of aqueo-igneous agencies in supplying iron and silica in solution to the sea and in direct chemical precipitation of both silica and iron to form the iron bearing beds. It has been shown that volcanism was active in this and adjacent areas throughout the Upper Huronian time both in sea and on land. Basic lava flows of submarine origin are abundant and in at least two known areas, viz., in the Atkinson and Jumbo belts, these rocks are closely associated with iron formation. Furthermore, the iron formation of the central area seems to have been laid down contemporaneously with or soon after an outbreak of volcanic activity recorded in the ellipsoidal flows and the volcanic breccias of the southern part of the district. Thus we have evidence that the periods of iron formation deposition were probably contemporaneous with periods of volcanism. The causal effects on iron formation deposition of great extrusions in the sea of hot basic lavas are too complex for satisfactory brief statement but it may be indicated here that iron and silica may have been contributed rapidly and directly to the sea in soluble form through pegmatitic action accompanying these extrusions especially during the cooling stages and also by chemical interaction between the sea water and the hot lavas. Furthermore, the quantity of iron contributed in solution in streams would doubtless be accelerated by reason of the sudden outpourings of hot basic lavas and ejectamenta on the land. Thus may be explained the field association of iron formation with basic extrusives, the coincidence of periods of pronounced volcanic activity and iron formation deposition, and

the apparent rapid deposition of iron formation under shallow water conditions.

This later addition to the theory of origin of the iron formations of the Lake Superior region has been established by Van Hise and Leith.[5] In view of the inadequacy of earlier theories, the writer has indicated the applicability of its basal ideas to the Iron River district in so far as may be inferred from physical relationships of the iron formation to associated rocks. The igneous relationships of iron formation are more clearly indicated in some other districts than in this one, especially in many Keewatin areas.[6]

The results of the investigation of the origin and deposition of iron formation by Van Hise, Leith, and assistants will soon appear in print in a monograph of the United States Geological Survey. In view of this it would not be profitable here to enter further into a discussion of the origin of the iron formation since little advance over present knowledge could be made without attacking the subject on broad lines and making appeal to data afforded only in a broad study of the iron bearing series of the pre-Cambrian rocks of the whole earth.

THE IRON ORES.

CHEMICAL COMPOSITION.

The iron ores are, without exception, medium to low grade, non-Bessemer hematites. The iron content of ores shipped from the different mines in 1909 ranges from 56.67% to 49.87%. In the following tables there are given complete average cargo analyses of Iron River ores for the season of 1909 and the average chemical composition of ores for 1907 with range for each constituent compared with same for the Crystal Falls and Florence districts. The latter was compiled by W. J. Mead and is published by permission of the United States Geological Survey.

[5]Unpublished manuscript.

[6]For description of igneous relationships of iron formation in a typical Keewatin succession in Canada, see Allen, R. C. Iron formation of Woman River area. Ontario Bureau of Mines. Eighteenth report, 1909, pp, 254-62.

COMPLETE AVERAGE CARGO ANALYSIS OF IRON RIVER ORES OF THE SEASON 1909.

Published by the Lake Superior Iron Ore Association.

[The upper line of figures opposite each ore represents its analysis when dried at 212° F.; the lower line when in its natural condition.]

Ore.		Iron.	Phos.	Silica.	Mang.	Alumina.	Lime.	Magnesia.	Sulf.	Loss by ignition.	Moist.
Baker	Dried	56.670	.313	7.460	.280	1.470	1.630	.920	.009	5.150	
	Natural	51.8750	.2860	6.8169	.2558	1.3432	1.4895	.8406	.0082	4.7060	8.620
Baltic (group). Including Baltic, Caspian, Fogarty	Dried	55.40	.493	7.88	.36	3.08	1.50	1.87	.033	5.01	
	Natural	49.83	.4435	7.088	3.24	2.770	1.349	1.682	.0297	4.506	10.05
Berkshire	Dried	54.45	.709	8.25	.18	4.23	2.79	2.40	.031	2.45	
	Natural	48.10	.626	7.29	.16	3.74	2.46	2.12	.027	2.16	11.66
Chatham including No.	Dried	54.50	.346	9.39	.21	2.73	.79	1.05	.088	6.71	
	Natural	51.37	.326	8.85	.20	2.57	.74	.99	.083	6.32	5.75
Dober Lump	Dried	55.8258	.6334	5.3536	.3493	.....	.....	.....	.....	.....	
	Natural	53.7605	.6100	5.1555	.3364	.....	.....	.....	.....	.....	3.6996
Hiawatha	Dried	49.87	.35	14.16	.234	4.20	1.30	1.75	.084	.....	
	Natural	46.34	.325	13.15	.217	3.90	1.21	1.63	.078	.....	7.08
James	Dried	54.89	.480	9.60	.30	.99	.40	.20	.015	9.02	
	Natural	50.50	.4416	8.832	.276	.911	.368	.184	.0138	8.298	8.00
Tully	Dried	56.100	.580	8.000	.360	2.200	2.120	1.650	.008	3.200	
	Natural	50.490	.5220	7.2000	.3240	1.9800	1.9080	1.4850	.0072	2.8800	10.000
Youngs	Dried	56.05	.50	7.60	.16	3.20	.82	.71	.04	5.45	
	Natural	52.1265	.465	7.068	.1488	2.976	.7626	.6603	.0372	5.0685	7.00

AVERAGE CHEMICAL COMPOSITION OF ORES FROM CARGO ANALYSIS FOR 1907, WITH RANGE FOR EACH CONSTITUENT.

(Ores dried at 212° Fahrenheit.)

	Crystal Falls district.		Iron River district.		Florence district.
	Average.	Range.	Average.	Range.	Average.
Fe	54.10	49.15 to 58.64	55.70	50.25 to 58.10	54.50
P	.437	.103 to 1.000	.396	.277 to .622	.32
SiO_2	6.27	5.62 to 10.00	8.62	4.28 to 19.29	6.72
Mn	1.27	.20 to 5.00	.20	.10 to .30	.26
Al_2O_3	2.94	1.04 to 4.98	2.54	.80 to 4.39	3.35
CaO	2.62	1.43 to 4.24	.92	.33 to 3.06	1.51
MgO	2.15	.30 to 4.09	.76	.16 to 1.82	2.46
S	.056	.030 to .161	.057	.011 to .105	.132
Loss in ignition	5.89	1.11 to 10.40	5.25	1.50 to 9.66	5.20
Moisture	8.46	3.00 to 12.02	8.23	3.19 to 12.00	10.86

MINERAL COMPOSITION.

The ores are mainly soft, red, hydrated hematite, and in subordinate quantity, brown and yellow limonite. The mineral impurities are quartz, some kaolin, calcium and magnesium carbonates, small amounts of carbonaceous matter, and minute amounts of iron sulphide. Manganese in the form of black oxide may occur up to 26% by weight as in the Barrass mine but its presence in amounts greater than a fraction of 1% is exceptional.

Quartz occurs in the form of chert intermixed with iron ore, in small veinlets cutting the ore, and in crystals lining the walls of cavities. In the latter forms it is secondary, in the former it is an unremoved portion of the original chert constituent of the iron formation. In 1909 the silica content of ores shipped ranged from 5.3536% to 14.16%. Kaolin occurs as a weathered product of aluminous impurities in the iron formation. It will be seen by reference to cargo analyses that lime and magnesia contents rise and fall together but either may be in excess, indicating that lime and magnesia are largely combined in the form of dolomite. Calcite occurs in crystal form on the walls of cavities, and the occurrence of magnesite is probable although this mineral was not seen by the writer. Carbon occurs in the form of graphite. Illustrations of the gradation of iron ore into highly graphitic rocks are given on pp. 81-82. Iron sulphide is rarely present in conspicuous amounts. It is occasionally present in the form of minute veinlets. In the old Sheridan mine it is reported that iron sulphide is so abundant at a depth of about 200 feet as to render the ore worthless. With this exception there is no evidence to show that the content of iron sulphide increases in depth. Magnetite is not known to occur in the Iron River ores although it is present in some parts of the Vulcan formation.

For the most part the ores are moderately hydrated, passing locally and in varying degree in different deposits into more highly hydrated varieties which may be termed "limonitic." The "limonitic" ores differ from the hematites only in having a higher percentage of combined water but not necessarily in proportion to form the mineral limonite ($H_2O = 14.5\%$). In the limonitic ores doubtless there occur the whole series of hydrated oxides from turgite ($H_2O = 5.3\%$) through göethite ($H_2O = 10.1$) to limonite and possibly xanthosiderite ($H_2O = 18.4\%$) but average cargo analyses indicate that of these the lower hydrated varieties are much more abundant.

The color of the ore depends to large extent on the combined water content. The slightly hydrated hematites are dark blue, as in the Dober lump ore, while the more highly hydrated varieties are red to brown and yellow. All of the variously hydrated ores may be associated in the same deposit, in fact they usually are, but some deposits are characterized by an average relatively low or relatively high combined water content. In a given deposit more hydrated ores may follow layers or bands which are separated by others of less hydrated variety. The degree of hydration may also vary irregularly in the deposit. There are no available data to indicate whether the tops of the deposits are more highly hydrated than the bottoms.

PHYSICAL CHARACTERS.

Taking the district as a whole the ores may be graded as medium soft hematite. The less highly hydrated ores are usually but not invariably harder than the limonitic ores. In some mines a hard blue hematite is found. This ore runs higher in iron than the softer varieties. At the Dober mine it is separated in handling from the softer varieties and graded as "Dober lump ore." The hard blue ore breaks out in large fragments which may be readily crushed to a mixture of small hard blocks and soft ore. Hard stalactitic, botryoidal, and mammillary forms are common on the walls of cavities.

The banding of the ferruginous cherts is often retained in the ores, especially in the highly siliceous varieties which may be regarded as enriched iron formation. As the process of concentration continues, by abstraction of silica and replacement of silica with iron oxide, the banding becomes faint and indistinct and frequently disappears. In those cases where, prior to concentration of the ores, the iron formation has been brecciated the banding in the broken and displaced fragments may be preserved in the ore. In ore where concentraction seems to have been effected mainly by leaching of silica the banding in the iron formation is more likely to be preserved than in ore showing in abundance of cavities lined with botryoidal and mammillary forms that iron has been dissolved and extensively rearranged in process of concentration. Much of the hard lump ore is of the latter variety.

On the whole the ores are very porous. As calculated by Mead the pore space ranges from 5% to 40% of volume, and the volume of a ton of ore varies between 8.5 to 15 cubic feet with an average of about 11 cubic feet.

THE ORE DEPOSITS.

SHAPE AND STRUCTURE.

The shapes of the ore bodies are determined by (1) the general steep dip of the iron formation, (2) thickness of the iron formation, (3) minor structural features such as brecciation, minor folding, banding, jointing, etc. Of these the first and second factors are decidedly the most important in determining the shapes of the ore bodies. The iron formation is in most places vertical or highly inclined and enclosed in walls of slate. Examining the ore bodies from the three dimensional view point, the two components in the direction of bedding are much greater than the transverse component, i. e., normal to the bedding. Even if the ore body extends from wall to wall transversely across the iron formation, a maximum distance of perhaps 300 feet, as for instance in the Caspian mine, the other two components are sufficiently greater to give the ore body a *tabular* shape. Some of the ore bodies follow foot wall slates and grade transversely across the bedding into ferruginous chert thus being thinner than the iron formation in which they occur. Such gradation also takes place laterally along the bedding. The Berkshire is a good example of this type of deposit. If the iron formation contains *interbedded* slate layers one or more of these may function as a foot wall slate, in which case there may be two or even more ore bodies lying one above the other as for instance in the Fogarty, Youngs, and Riverton mines. But the ore bodies are not invariably related to slate walls. They may occur in the body of the iron formation separated from foot and hanging walls by ferruginous chert, as in Chatam No. 1 mine and to large extent in the Hiawatha mine. If the bedding has not been much broken and disarranged by brecciation the ores follow the banding in the iron formation and the shapes of the ore bodies are essentially the same as those which follow slate walls. If the iron formation is shattered and brecciated with destruction of all parallel structures the ore bodies are apt to be of various irregular shapes and sizes varying from the smallest "pockets" of a few tons of ore up to bodies containing thousands of tons. This type of occurrence is best illustrated in the Baker mine as shown by the workings in the fall of 1909. These ore bodies are not related to slate walls or major structural features of the iron formation. They are irregular concentrations of ore in ferruginous chert into which they grade by decrease in iron and corresponding increase in silica. Their extreme irregularity of shape, size, and manner of occurrence is of course reflected in high mining costs. The occurrence of "ore pockets" is, however, not by any means confined to highly brecciated, large masses of ferruginous chert. They may occur in minor folds of slate or in local brecciated masses associated with minor folds in the iron formation. Relatively large minor folds may affect the shape of an ore body of considerable size as in some parts of the James mine (fig. 14). But the *tabular ore body* standing in inclined position, usually very steeply inclined, with the two greater dimensions in the plane of bedding of the iron formation is the type deposit of the district.

RELATIONS TO WALL ROCKS.

The relations of the ore bodies to wall rocks have been referred to repeatedly in preceding pages. A brief summary of these relations follows.

The ore bodies very commonly lie on relatively impervious slate foot walls. In many cases the foot wall slate is of the black graphitic variety. The foot wall slate is in some instances basal to the iron formation, in others it lies within the iron formation. In some instances the ore body is limited by slate on both foot and hanging walls, either or both of which may lie within the iron formation. The wall slates may in places assume the characters of ferruginous graywacke (reported from the Chicagon mine) or quartz-chlorite-schist as in the Riverton mine.

A common type of ore body is bounded on all sides by iron formation rocks, viz., ferruginous chert and slate.

Lateral gradations to black slate (Dober) and ferruginous graywacke (Riverton and Chicagon) are known.

At Atkinson iron ore is closely associated with volcanic greenstone and also in the Jumbo belt east of Saunders.

Thus the ore bodies are in juxtaposition in different places to nearly all the rocks with which the iron formation is associated.

DEPTH TO WHICH ORE OCCURS.

Many of the ore bodies, in fact nearly all of the larger ones, are exposed at the rock surface. All of the older mines started to mine by the open pit method. Those deposits which are not exposed at the rock surface are connected with this surface by lean ore or ferruginous chert or slate. In no case is an ore body known to be cut off from the surface by intervening iron formation rocks which have not been altered by katamorphism, that is to say, by processes which if completed would result in ore concentration. This is a fact of fundamental significance to the accepted theory of the concentration of the ores and has a practical bearing on exploration which will be discussed later. To date ore has not been mined at depths greater than 700 feet. The Dober and Hiawatha mines are operating on the lower levels at between 600 and 700 feet. Ore is known to occur in both these properties at greater depths. In a vertical drill hole on the Michaels exploration 100 feet south of the center of Section 29, T. 43 N., R. 34 W., ore running above 50% in iron was encountered between 1,360 and 1,712 feet. The bottom of the hole is reported to be in ore. Subtracting depth of overburden, 230 feet, we have 1,482 feet as the greatest depth below rock surface at which ore is known to occur in this district.

Speculation as to the ultimate depth of mining is hazardous. Large deposits of rich ore occur on the Gogebic range below 2,000 feet. Ore concentration is limited by the depth to which a vigorous circulation of oxidizing waters may penetrate from the surface but theoretical calculations of such depth are invalidated by the uncertainty of factors involved. No reasons are known why ore should not occur here at depths as great as in other districts of the Lake Superior region. Past experience in exploration and known favorable structural conditions invite to exploration at depths greater than those now attained.

TOPOGRAPHIC RELATIONS.

In considering the relation of the ore bodies to hills and valleys it should be borne in mind that the present topographic forms bear only slight relation to those which existed in post Huronian and pre-Ordovician time. It was during this time that the ores were mainly formed. If there is any significant relation between ore deposits and topographic forms such can be discerned only in reference to the pre-Ordovician erosion surface and not to the present surface. Except in those cases where the covering of glacial drift only partially masks the character of the underlying rock surface any observed relationships between ore bodies and hills and valleys as they exist today are purely accidental and have no significance. This will be made clear in the following brief outline of the post-Huronian physical history of the district.

At the close of the Upper Huronian period of sedimentation the bottom of the sea became land and thence to Middle Ordovician time, so far as we have evidence, this district was not again submerged but remained part of a land area which was subject to the processes of erosion which are in operation on the land areas of today. Accompanying the withdrawal of the sea, and probably the cause of its retreat, the area was uplifted and the rocks were folded into anticlines and synclines. It is not probable that all nor perhaps the major part of the folding in the Upper Huronian series was accomplished at this time. In the Gogebic range to the west the main deformation took place in post Keewenawan times but is is certain that long before the Middle Ordovician submergence the Upper Huronian rocks had been folded as we now see them and had been eroded for long ages with the removal of many hundreds and perhaps thousands of feet of strata. As the plane of erosion worked downward the folds were truncated, exposing at the surface the upturned edges of the iron formation and other rocks in belts of curving and sinuous form. During this long period of erosion the ores were mainly formed as shown in the Menominee district on the east where iron ore is found in the conglomerate at the base of the Cambrian sandstone in such relations as to show that the ore had been formed prior to the Cambrian submergence. The Paleozoic sea did not cover this area until Middle Ordovician time. The Cambrian formations of the Menominee district and the Ordovician formations of this district are about flat lying and undeformed. In both districts the Paleozoic seas advanced over a rugged, hilly country. The valleys were first filled with sediment and gradually even the tops of the hills were buried. The covering of Paleozoic rocks put an end, or at least a great check, to the formation of iron ores. When the Paleozoic sea finally withdrew the area was again subject to erosion. Streams were formed and began the work of removing the flat lying limestone and sandstone. The pre-Cambrian rocks are much harder and more resistant to erosion than the Paleozoic rocks. Wherever these rocks were uncovered in the valleys the streams were shifted to the softer rocks after a well known principle of erosion under which streams tend to follow lines of least erosive resistance. As erosion went on the pre-Cambrian topography was uncovered and the streams finally adjusted themselves to the old valleys which they found ready made in the harder rocks. The topography of the rock surface is thus of pre-Ordovician origin modified only by erosion since the mantle of Paleozoic rocks was removed. As the Huronian series were uncovered the conditions for ore concentration here were gradually re-established and ore concentration has continued without interruption to the present day if we except locally the retarding effect of a glacial cover in some places above 300 feet thick. The process of ore concentration is an extremely slow one, so slow in fact that the part which has been accomplished since glacial times is insignificantly small.

It is now clear that we must examine the pre-Ordovician rock surface for significant relationships between ore deposits and topographic forms. This should be emphasized here for the reason that many prospectors look with favor on a "draw" or a swamp as a promising locality for exploration. In fact it was largely the success attending exploration in the vicinity of the Baker mine that induced to further exploration up the Baker "draw" resulting in discoveries of ore as far northeast as the S. W. 1/4 of the S. W. 1/4 of Section 21, T. 43 N., R. 34 W. Another "draw" which has attracted some attention extends north of east through the James mine property. This small valley is crossed by the James and Konwinski belts of iron formation. In the former case Baker Creek seems to follow in a general way a deep pre-glacial valley which doubtless carried the bed of a pre-glacial stream flowing northeast while in the latter case the "draw" or valley is entirely in drift and has no relation to the topography of the underlying rock surface. In the former case it may be that the ancient stream bed followed in a general way the strike of an iron formation belt which formed the north side of its valley, since drill holes in iron formation are thus far all on the north side of the depression. The two illustrations above given emphasize the importance of the exercise of discrimination and care in the application of a well founded principle of exploration.

On the general map of the district (Plate 1) the general outlines of the topography of the rock surface in the producing part of the district are indicated to the extent of known data. It cannot be expected that results based on inaccurate data can be more than approximately correct. The contours in green have been drawn from data furnished by several hundred drill holes, rock exposures, shafts and pits, and a small scale topographic sheet. It will be seen by reference to this map that the ore bodies show a decided preference for valleys and hill slopes rather than upland areas. With the exception of the deposits on the James belt every producing deposit in the district is either in a valley or under a decided slope. The same relation seems to hold in large measure for occurrences of ore known only from drill records. The great Caspian deposit lies in the bottom of an ancient drainage course trending northeast through the Baker property and carrying the ore of Sections 29 and 31 in T. 43 N., R. 35 W. The relations of the Berkshire, Fogarty, Youngs, and Baltic deposits to high ground on the east are seen at a glance. From the Caspian to the old Beta mine a

depression followed by the Iron River carries the Dober, Isabella, Hiawatha, Chatam and Riverton mines.

To what extent the location of ore bodies in valleys and under decided slopes is a matter of pure accident and to what extent is governed by natural laws is difficult to determine. That the ores have been secondarily concentrated by oxidizing meteoric waters has not recently been seriously questioned. Obviously those parts of the iron formation most happily situated to receive a vigorous circulation of oxidizing waters are more apt to carry ore deposits than those parts not so situated. In general, such locations are to be found along natural drainage lines and under hill slopes, and it is safe to assume that, barring adverse structural conditions, ore deposits are more apt to be formed in these places than elsewhere.

CONCENTRATION OF THE ORES.

The processes involved in the concentration of the ore deposits in the Lake Superior region were early discerned by Van Hise in his studies of the Penokee-Gogebic iron range and fully discussed by him in 1892.[7] The principles of iron ore concentration laid down by Van Hise for the Penokee-Gogebic range have been found to have general application in the Lake Superior region with such modifications and additions as are demanded by the varying structural conditions in the different areas. The discussion which follows is mainly an application of these now well known principles to the concentration of iron ores in the Iron River district.

At the close of Michigamme (Upper Huronian) time this and adjacent areas were uplifted, the ocean receded and the rocks were exposed to erosion. There is evidence in the schistose character of the slates and graywackes in many parts of the district and the folding without fracture in some parts of the iron formation that the rocks now exposed at the surface were deformed under a considerable thickness of strata which has since been removed by erosion. During deformation under load the iron formation underwent a more or less complete recrystallization. It is not possible to conceive that the brittle layers of cherty iron carbonate could be bent and contorted without breaking except through internal molecular rearrangement in the mineral constituents. In different places the iron formation was deformed mainly by brecciation, by

[7] Van Hise, C. R., and Irving, R. D. The Penokee Iron Bearing Series of Michigan and Wisconsin, Monograph 19. United States Geological Survey.

folding combined with brecciation, and by folding unaccompanied by prominent brecciation. The conditions of deformation varied from place to place from those of the zone of flow to those of the zone of combined fracture and flow depending perhaps on the variations in the intensity and rapidity of application of the deforming forces. It is certain that the deformation was a slow process and that the intensity of deformation was variable in time as well as place. There was also doubtless more than one period of general deformation. A rock which was earlier folded in the zone of flow may have been brecciated at a later period in the zone of fracture due to removal of load by erosion of overlying rocks. Under any conditions the iron formation would respond less readily to anamorphic changes in mineralogical composition than the associated sediments of more complex constitution. Locally, as for instance on Stambaugh hill, the effects of anamorphism are seen in the development of magnetitic slates but on the whole the iron formation was not mineralogically altered where folded in the zone of flow.

The iron formation was folded prior to the concentration of the ores which was inaugurated only after the folds had been truncated by erosion exposing the iron formation at the surface. That this is true is shown beyond the shadow of a doubt by the relations of the ore bodies, (1) to the surface, (2) to structural features such as folds, breccias, and joints, (3) to natural channels of downward underground circulation.

(1) It has already been shown that all of the ore bodies connect with the surface either directly or indirectly through ferruginous chert or slate which for present purposes may be considered as lean ore. It is equally true that the ore bodies do not extend downward indefinitely but are limited to a relatively shallow depth. It has been shown by drilling that the vertical range of the zone of oxidation varies greatly up to above 1,712 feet. Unoxidized, cherty iron carbonate rocks are frequently found in drilling at depths of less than a hundred feet from the rock surface and less often at only a few feet. Explorers have been taught by experience, entirely aside from reasoning based on theoretical grounds, that ore deposits are not found under a cover of unweathered iron formation rocks and when such rocks are encountered in drilling work is usually discontinued. Of course there are cases where a considerable thickness of unaltered iron formation may lie beneath a protecting impervious slate cover and it is customary to drill to sufficient depths to make sure that the limit of the zone of oxidation has been reached in the direction in which the hole is pointed. The irregularity in depths to which oxidation has extended is illustrated in fig. 16, which is a section constructed from borings made by Mr. Wm. Connibear for the Cleveland Cliffs Iron Co.

It has been shown that the ores were not originally deposited as oxide but as ferrous carbonate which was subsequently altered to ferric oxide. Oxidation is one of the characteristic reactions of the belt of weathering, less conspicuously of the belt of cementation, and with one or two unimportant exceptions does not take place under deep seated conditions.

In the light of the above considerations it is certainly more logical to believe that the ores were formed in *consequence* of the descent of the zone of oxidation on the original ferrous carbonate rocks as the overlying strata were removed than to assume that the ores had been formed under deep seated conditions and later simply exposed at the surface by erosion.

(2) That the relation of the erosion surface to the ore bodies is a causative and not an accidental one becomes more strongly apparent from a study of the relations of the ore bodies to structural features in the iron formation forming natural trunk channels of underground circulation of waters descending from the surface. Where the iron formation is in practically vertical position the ores may not show decided preference for bounding slate walls but may occur in lenses and bands anywhere in the formation or may occupy the width of the formation from wall to wall but where the rocks are inclined the ore bodies show decided preference for impervious slate foot walls and, wherever they occur, for pitching troughs. The ores are also characteristically associated with brecciated parts of the iron formation. The selective preference of ore bodies for these structural features indicates that the structures antedate the ores, and have exercised a causative influence on ore concentration. On no other assumption can the observed relations be explained.

(3) If the iron ores have been formed from an original cherty iron carbonate by oxidation of the ferrous iron and removal of silica, the only known agency competent to effect the alteration is that

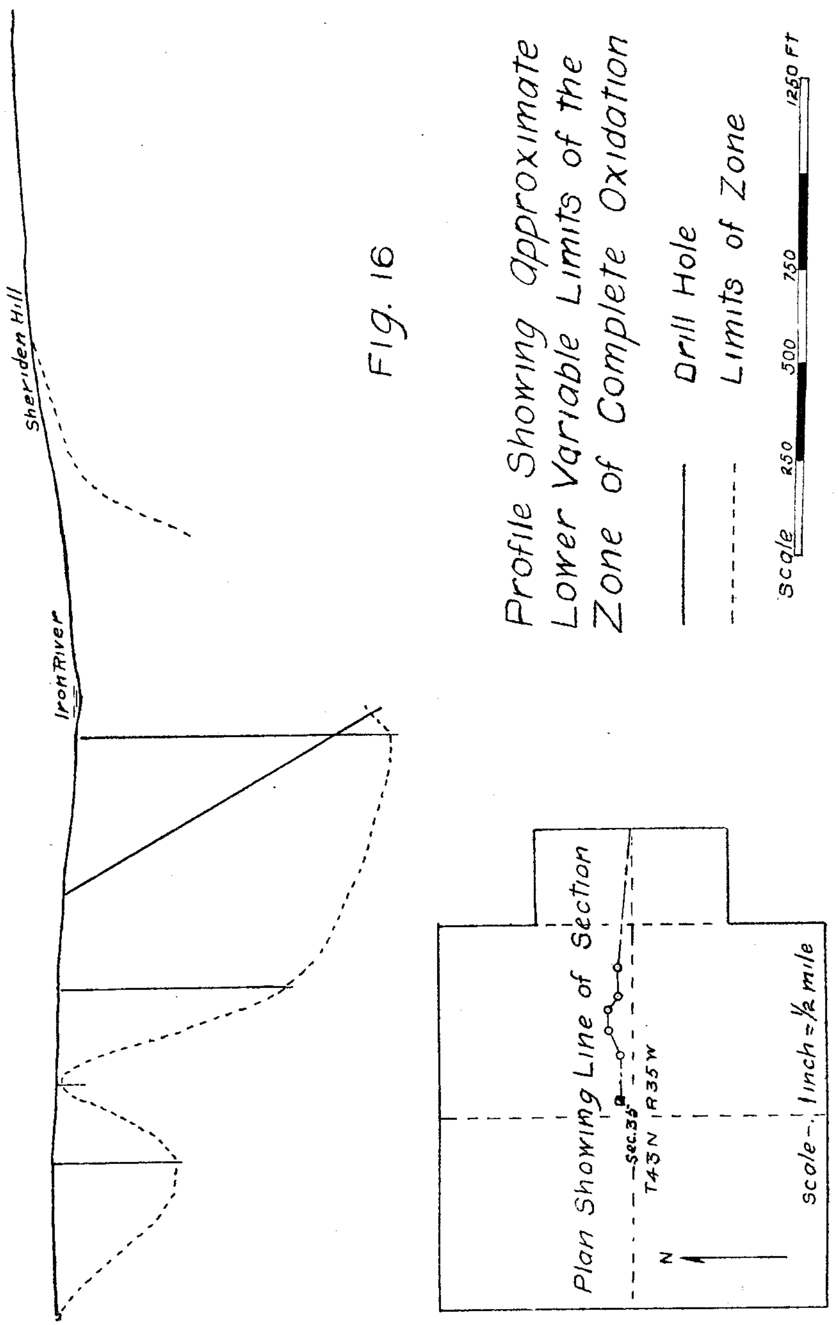


Fig. 16

Profile Showing Approximate Lower Variable Limits of the Zone of Complete Oxidation

of circulating aqueous solutions. The occurrence of ore on foot-walls rather than under hanging walls, and in pitching troughs rather than under pitching arches, is evidence that concentration was effected not by waters *rising* from depths but by waters *descending* from the surface. Meteoric waters descending from the surface carry abundant oxygen while those rising from depths are characteristically reducing.

Starting with the basal premises (1) that the deformation of the iron formation preceded the concentration of the ores, (2) that ore concentration followed the truncation and exposure at the surface by erosion of the folded iron formation, (3) and that concentration was effected by downward-moving, meteroic, oxidizing waters, we have now to consider briefly in sequence the various physical and chemical agencies which resulted in the formation of the ore bodies in their present positions.

Meteoric waters enter from the surface by innumerable openings in the rocks. In the iron formation these openings are afforded by fracture and bedding planes and minute pore spaces. Of the water which enters the rocks some reappears at the surface in springs and as seepage on the land and under streams and water bodies while the remainder is returned directly to the atmosphere by evaporation from the surface, capillary action in the rocks combined with evaporation, and through exhalation and evaporation from plants. Most of the water which is returned to the surface by capillarity, evaporation, and plant action has not penetrated far from the surface and its effect on ore concentration is therefore negligible.

It is obvious that the movement of water descending from the surface to join the underground circulation and to finally reappear at the surface has a downward and a lateral component and in the majority of cases an upward component. Having shown that concentration of the ores has been effected by downward moving waters it will be necessary for present purposes to consider only the downward component including therein downward lateral movement.[8]

It has been shown that the alteration of cherty iron carbonate

[8]For full treatise on movements of ground water see Slichter, C. S. "Theoretical Investigation of the Motion of Ground Water," 19th Ann. Report U. S. Geol. Survey, 1897-98, pt. No. 2, and Water Supply and Irrigation Papers No. 67. For general application of movements of underground water to ore deposition, see Van Hise, Chas. R., Some Principles Controlling the Deposition of Ores. Genesis of Ore Deposits, A. I. M. E. 1901, pp. 282-432.

to iron ore involves oxidation of the ferrous carbonate and removal of silica. Waters entering the iron formation at the surface carry oxygen and carbon dioxide in solution. The oxidation of the iron carbonate takes place under the following reaction,

$$4FeCO_3 + 3H_2O + 2O = 2Fe_2O_3 + 3H_2O + 4CO_2,$$

with production of hematite and carbon dioxide. Hematite is insoluble in oxidizing solutions and is thrown down at the place where the reaction occurs. Waters bearing carbon dioxide take iron carbonate into solution. It will be noted that the reaction producing hematite sets free carbon dioxide which is added to waters from the surface bearing carbon dioxide derived from the atmosphere thus increasing their solvent effect on iron carbonate. It is therefore evident that some of the iron carbonate was taken into solution and carried downward. Precipitation of iron carbonate from solution as iron oxide would occur in places where the solutions become strongly oxidizing. This may have occurred by intermingling of waters bearing iron carbonate in solution with waters which were oxidizing by reason of having come more directly from the surface or having traveled more rapidly through open channels or through rocks in which oxidation had been earlier effected.

It is well known that silica is soluble to some extent in pure water but it is much more readily soluble in waters bearing carbon dioxide. In so far as organic acids were carried downward from the surface they would aid in the solution of silica. Silica which was taken into solution was carried downward thus enriching the iron formation by its abstraction. It is evident that oxidation of iron carbonate and solution of silica would take place at the surface and continue downward to the limits of the circulation of oxidized and carbonated waters.

The downward movement of water in the iron formation is affected, (1) by the attitude of the beds, vertical or inclined, (2) by the character of the openings in the rocks, (3) by occurrence of slate layers in the iron formation, below it or above it (4) by the folding, producing pitching troughs and breccias, and (5) by the effective head.

(1) If the iron formation be in vertical position the waters move downward along available openings such as joints and bedding planes but do not show tendency to localization in any particular horizon unless such horizon is generally more porous, jointed, or brecciated. The influence of the bedding planes on movement of water is illustrated in ore deposits bounded by planes parallel to the bedding in middle horizons of the iron formation and also in alterations often occurring along joints and bedding planes while at slight distances from these openings the rock remains unaltered or only slightly altered.

(2) Where the iron formation is much fractured and brecciated, offering easy passage for downward moving waters, the conditions for ore concentration are more favorable than in those parts of the formation not thus affected. The preference of ore bodies for brecciated parts of the iron formation has already been illustrated.

(3) If the iron formation be in inclined position, downward circulation is concentrated on such impervious slate beds as may occur in the formation or directly below it. The water moves vertically downward, except as deflected along bedding planes, until an impervious slate layer is encountered on which it is concentrated and moves downward along the dip. The occurrence of ore bodies on slate footwalls is illustrated in most of the mines of the district, notably in the Youngs, Fogarty, Berkshire, Riverton, and James.

(4) Pitching troughs in slate or other relatively impervious rocks would obviously afford the most favorable conditions for concentration of downward moving waters. Such troughs are of common occurrence but unless of large dimensions their effect on ore concentration is often obscured by the extention of ores across the accompanying arches. (See fig. 14.)

The process of ore concentration by downward moving meteoric water is beautifully illustrated in miniature in the James mine. In the fall of 1908 a stream of water carrying perhaps 20 to 25 gallons per minute issued from an opening in the trough of a small, tightly compressed syncline of ferruginous chert plunging S. E. into the main drift on the third level. The trough of the syncline adjacent to the water channel was completely altered to high grade ore which became leaner away from the opening and passed gradually into ferruginous chert. This phenomenon is a perfect illustration on a small scale of the concentration of ore in a pitching trough. (Fig. 17.)

(5) The downward extention of ore is limited to the depth to

which an active circulation of oxidizing waters may penetrate. Meteoric water which is returned to the surface in flowing springs or as seepage has somewhere entered the rocks at an altitude which is higher than the point of escape. The difference in altitude between the points of entry and escape is the *head*. The effective head is the difference in altitude between the point of escape (which is at ground water level) and the level of ground water beneath the catchment area, and the *force* which produces circulation of water at depths below the points of escape is the pressure exerted by a column of water whose length is the effective head. The movements of ground waters are complex but it has been shown by Slichter that ground water in moving under head from place to

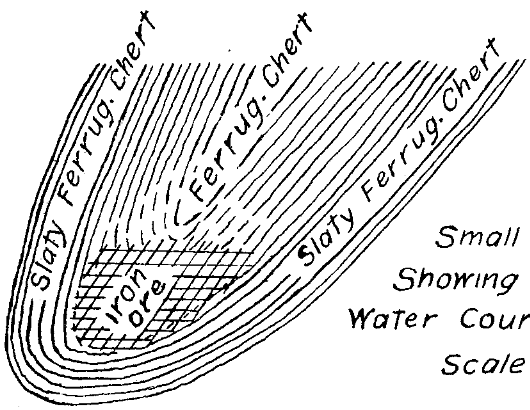


Fig. 17

Small Fold in James Mine Showing Influence of Local Water Course on Ore Concentration

Scale— 1 inch = 2½ Feet

place through the rocks utilizes the entire available cross section and under favorable conditions, i. e., if the rocks contain continuous openings through which the water may freely pass, a slight head is sufficient to cause circulation at great depths. Under any conditions the circulation will be active at depths in proportion to effective head, and oxidizing waters coming from the surface will be more apt to carry oxygen to great depths in an active circulation than in a sluggish one. The effective head in the Iron River district at the present time is inconsiderable, in the producing area being nowhere above 200 feet. Ore occurs at depth of approximately 150 feet below sea level and probably at still greater depths. The ground water level is near the surface and though there is no way of making satisfactory calculation it has been

questioned that active circulation of oxidizing water under slight head pertains at such depths below ground water level as are reached by the ore bodies. However, bearing in mind that oxidation proceeds from the surface downward it is evident that water will retain its oxygen content to gradually increasing depths as oxidation is effected in the rocks at higher levels and that in time oxidizing waters may penetrate to great depths. Furthermore, the change from ferrous carbonate to limonite involves a reduction in volume of 18.22% and to hematite 49.11%[10], consequently, as oxidation progresses the iron formation is made more porous; the ores are more porous than ferruginous chert and unaltered iron formation, therefore, as alteration progresses the descending waters are able to retain their oxygen content to increasingly greater depths by reason of the oxidation previously effected in the rocks at higher levels and by reason of the greater porosity of the altered rocks offering the means of easier and more rapid movement through them.

It is certain that in past times this area exhibited greater surface relief and stood much higher above sea level than it does now. There is evidence in the occurrence of schistose rocks at the surface and the truncation of folds that great thicknesses of strata have been removed by erosion. This is also indicated in the occurrence of ore bodies at the surface. If the ore bodies which are now exposed at the surface have been concentrated by downward moving waters it is evident that much of the iron must have been carried downward from rocks which have since been cut away by erosion for the reason that the increase in porosity of the ores over the porosity of the original iron bearing rocks and allowances for slight slump in the ore bodies only partially accounts for the space occupied by the silica which has been leached out of the original rocks in the process of ore concentration. In so far as the surface was elevated and deeply furrowed by valleys the depth of active circulation of ground water would be great. As the surface of the land was lowered the ore deposits that had been formed would suffer by erosion at the surface and doubtless large quantities of ore have been removed in this way. That ore bodies exist today is proof that downward concentration has in the end kept pace with removal of ore at the surface by erosion.

[10] Van Hise, C. R. A treatise on metamorphism. Mon. 47 U. S. Geological Survey. p. 391.

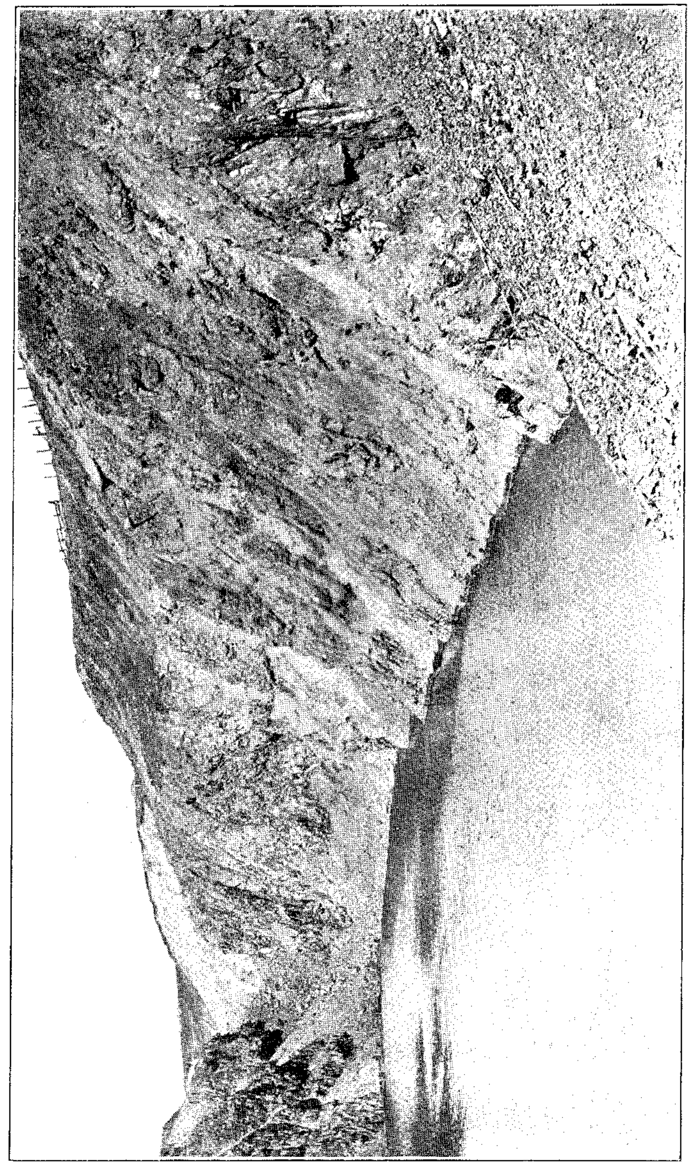
EXPLORATION.

So far as known the occurrence of ore bodies is limited to the Upper-Middle Huronian formations. The Saunders (Lower Huronian) formation has been prospected to some extent but the results have been uniformly negative. The Lower Huronian is not known to bear ore elsewhere in the Lake Superior region and we have as yet no reason to believe that it is ore bearing in the Iron River district. The writer has drawn the approximate north limit of the Saunders formation on the map. (Plate 1.) North of the Saunders formation the possibility of the occurrence of ore bearing iron formation can be excluded only in those areas which have been proved barren by adequate exploration and in those where exposures are abundant enough to disclose the barrenness of the underlying rocks. All other territory must be *deemed explorable ground.* Of course it is certain that only a small fraction of the unexplored territory is underlain by iron formation.

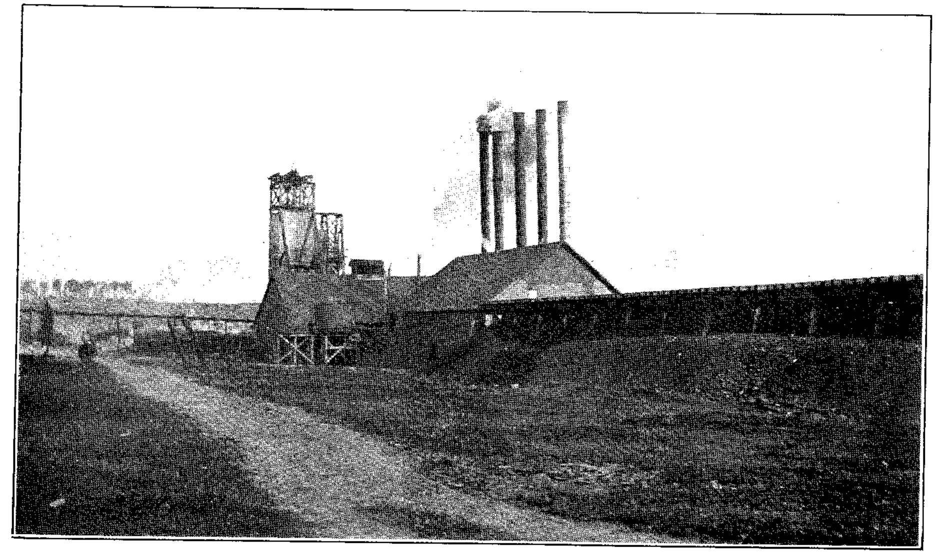
Where information is entirely wanting it is necessary to begin exploratory work blindly. This, however, is seldom done by conservative and well advised interests. Exploration usually begins on areas adjacent to known occurrences, usually on the strike or the inferred strike of known iron formation. In this manner the known iron formation belts are gradually traced into virgin ground.

No other district in the Lake Superior region presents greater difficulties in the way of exploration. The iron bearing rocks seldom outcrop; they are not magnetic; the overburden varies up to above 300 feet in thickness; the iron formation is usually steeply dipping and its surface width is therefore often not much greater than the thickness; the iron formation is not stratigraphically related to any rock which by retention of uniform characters over large areas can be used as a key to structure and distribution. Under these conditions it is not possible for any one to predict the presence or absence of iron formation in virgin territory very far in advance of actual exploration. The elimination of barren areas is accomplished only by "testing ledge" in a sufficient number of places to demonstrate the absence of iron formation.

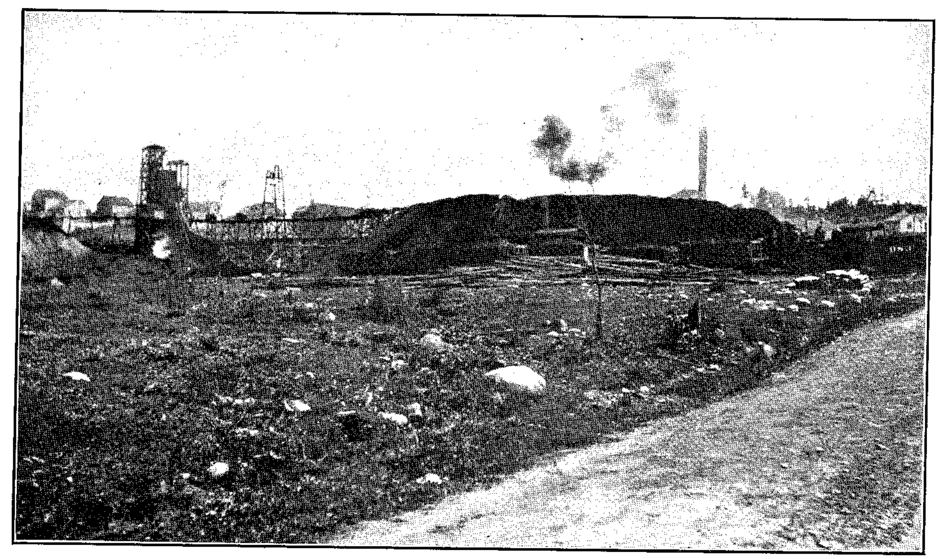
The element of chance enters largely into the problems of exploration in any iron bearing district but in the Iron River area perhaps more largely than in any other known Michigan range.



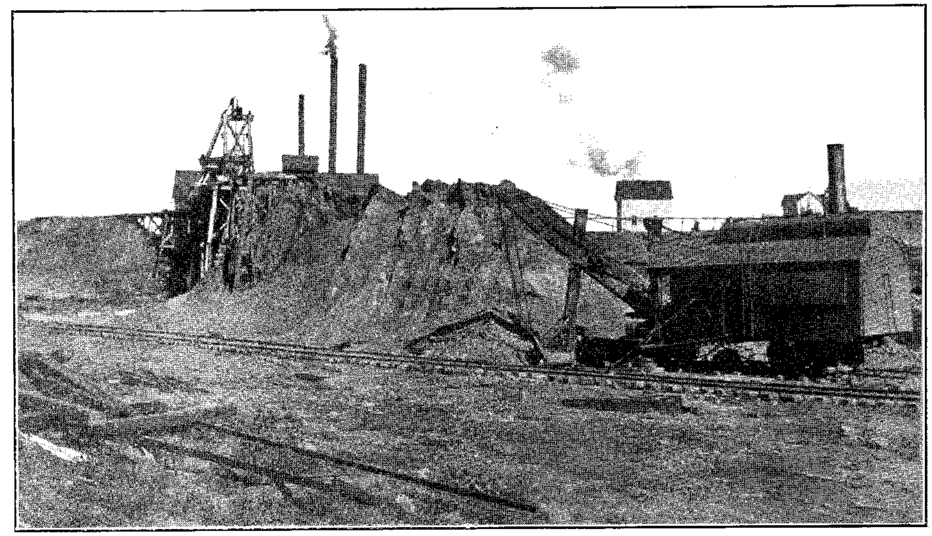
OPEN PIT OF THE RIVERTON MINE. LOOKING NORTH.



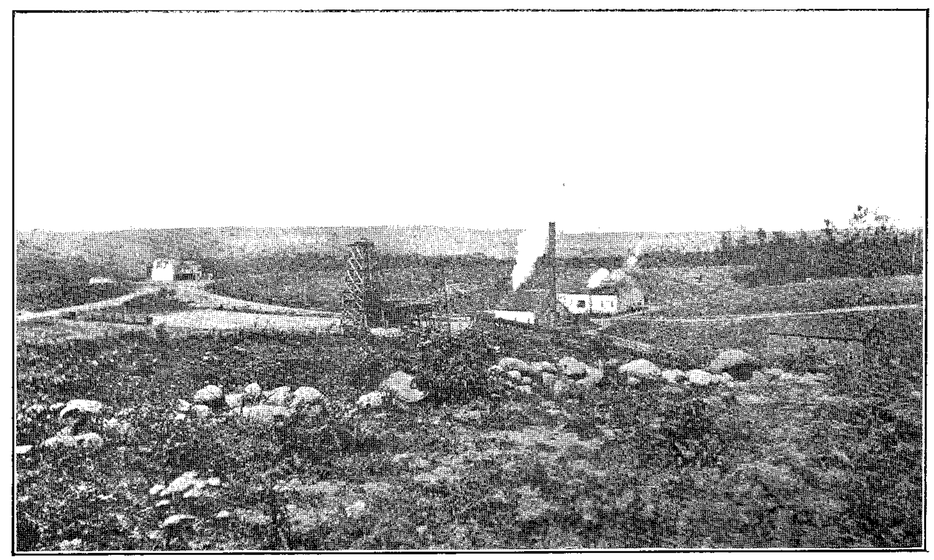
(A) CASPIAN MINE.



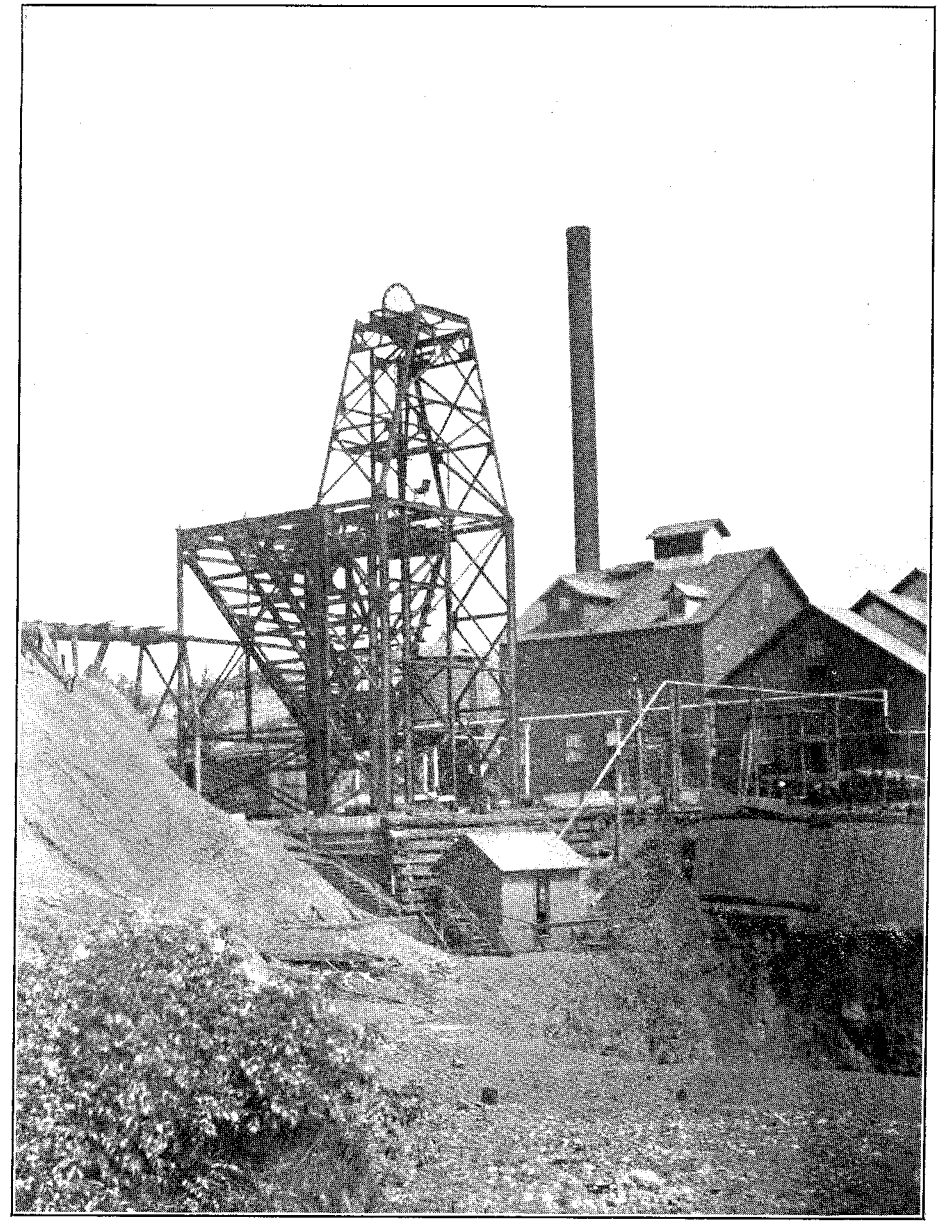
(B) STOCK PILE AT BALTIC NO. 1 SHAFT IN 1908. LOOKING SOUTH.



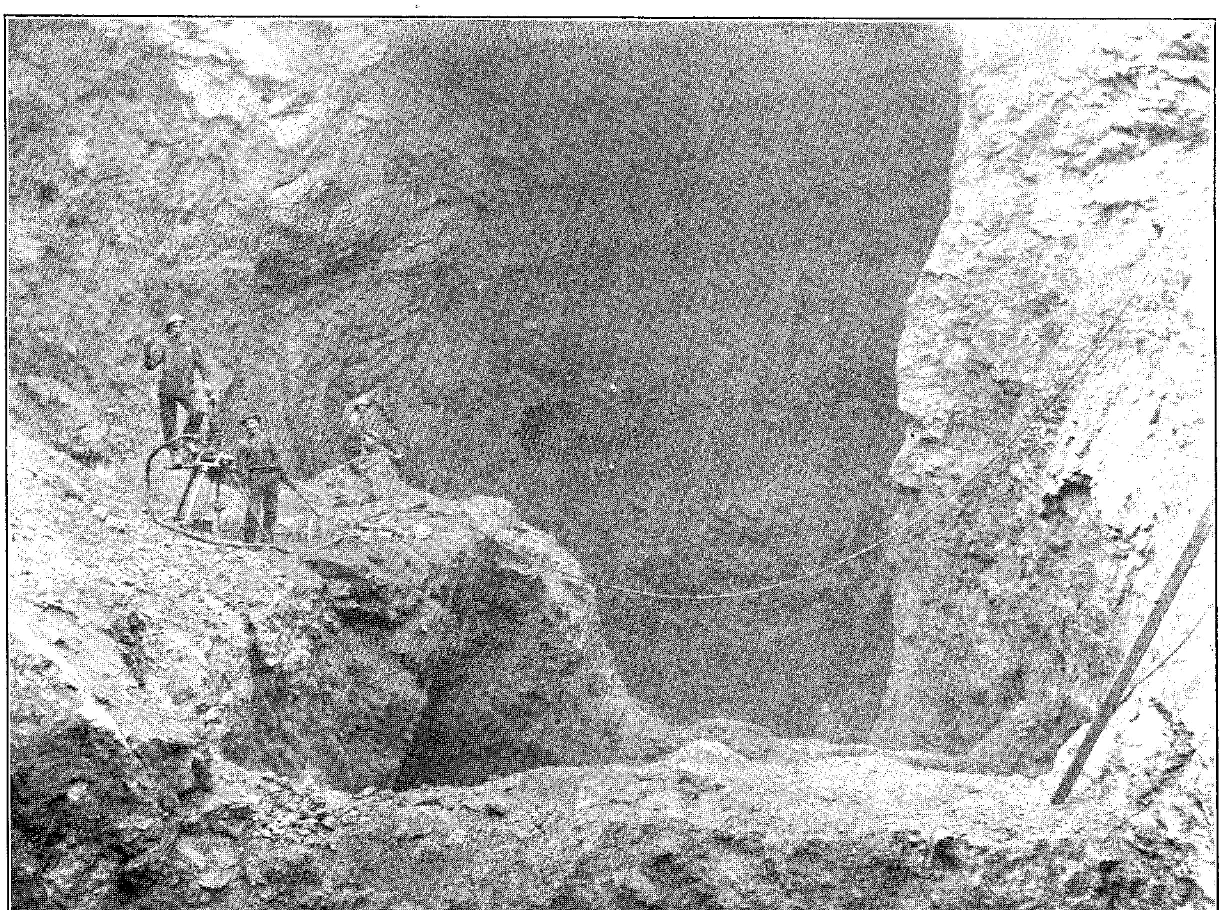
(A) STOCK PILE AND SHAFT OF THE YOUNGS MINE IN SEPTEMBER, 1908.



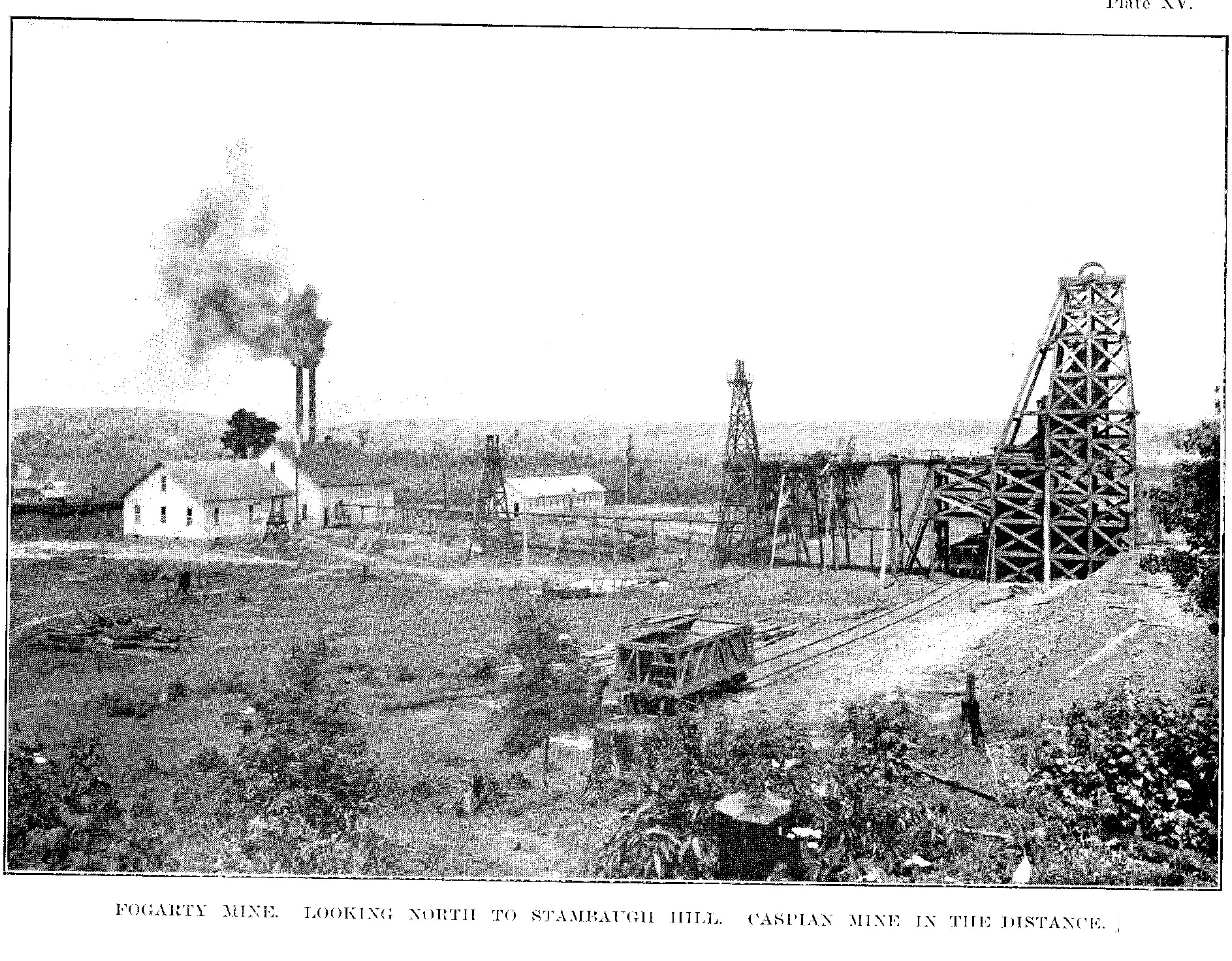
(B) BALTIC NO. 2 SHAFT. LOOKING NORTHWEST FROM THE ZIMMERMAN MINE.



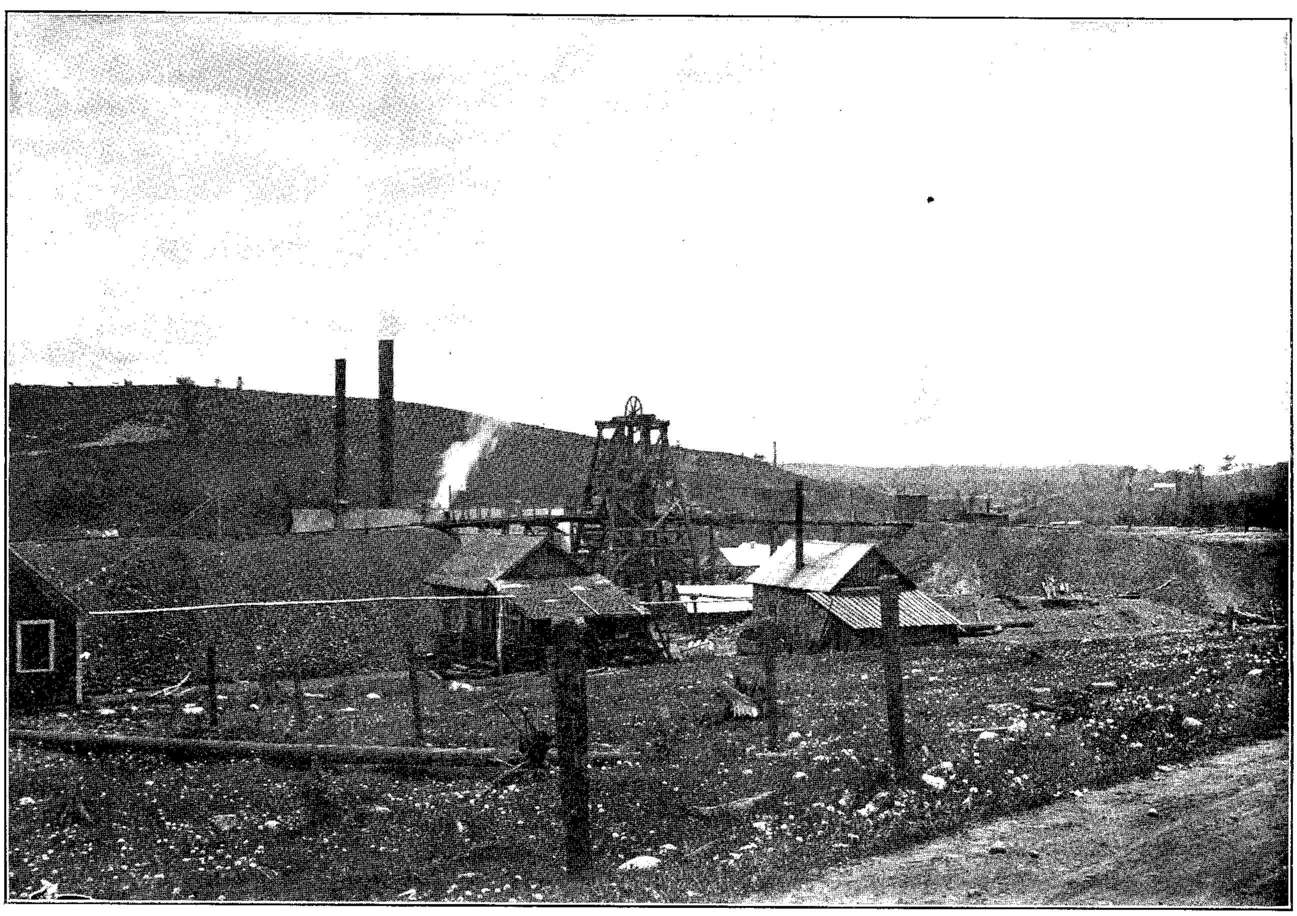
NO. 1 SHAFT AND OPEN PIT OF THE DOBER MINE.



UNDERGROUND IN THE BALTIC MINE.



FOGARTY MINE. LOOKING NORTH TO STAMBAUGH HILL. CASPIAN MINE IN THE DISTANCE.



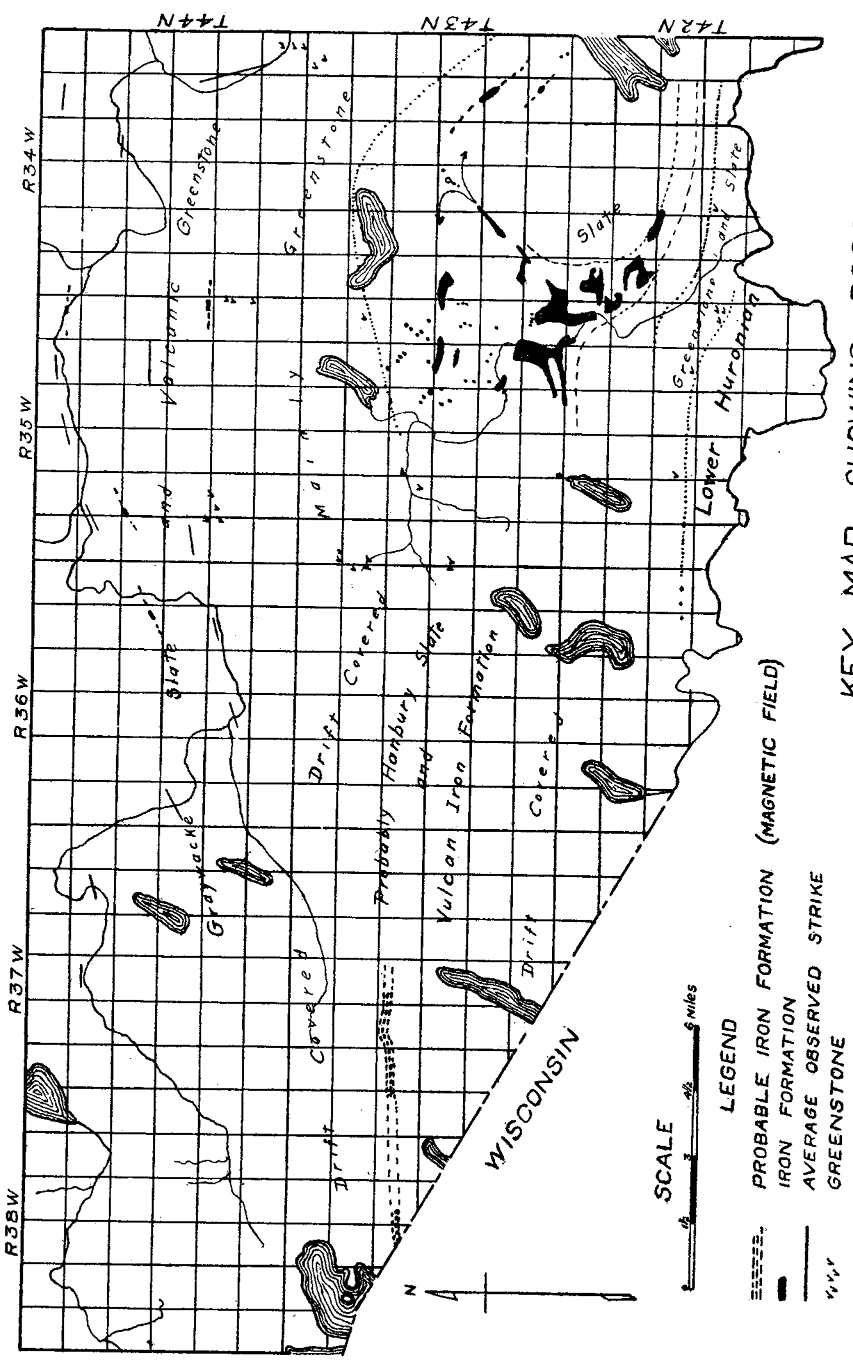
CHATAM MINE. NO. 2 SHAFT. LOOKING ACROSS VALLEY OF IRON RIVER. CHATAM NO. 1 IN THE BACKGROUND.

STEEL HEAD FRAME AT NO. 2 SHAFT OF THE JAMES MINE.

The writer will doubtless be criticized by persons not familiar with the district for not attempting to indicate on the map probable extentions of the known iron formation belts but it is believed that the map is fully as useful in its present form as it would be had such attempt been made. The facts of geology are plainly shown and will readily suggest to the experienced prospector the more favorable areas for exploration. However, in figure 18 possible extentions of known iron formation belts are indicated to the extent that is warranted by available data.

In beginning exploration the prospector usually confines his efforts to "testing ledge" until the iron formation is located. The methods used depend largely on the thickness of the overburden. If the drift is thin the rock may be reached by test pitting but if the level of ground water is reached before "ledge" is encountered a stand pipe from 2½ to 3 inches in diameter is driven from the bottom of the pit. Frequently the stand pipe is driven from the surface. The pipe may be driven with a striking hammer operated by hand or steam power. A churn bit is operated inside the pipe. If boulders are encountered it is necessary to break them up by blasting; in case many boulders are encountered it is usually cheapest in the end to pull the pipe and begin sinking in a new location. When "ledge" is encountered a drill hole is started. Shallow holes may be put down with a churn bit, but in deeper drilling and in angle holes a diamond bit is used.

The ore deposits are associated with ferruginous chert and slate, i. e., with the altered phases of the iron formation. In general, exploration should be confined to the portions of the iron formation thus altered. Experience has shown that ore bodies are not found under any considerable thickness of unaltered iron formation. A drill hole which encounters cherty iron carbonate near the surface or after having penetrated ore or ferruginous slate or chert should be discontinued. Of course instances may be cited where ore or highly altered iron formation has been found *under* practically unaltered cherty iron carbonate but it should be borne in mind that *alteration proceeds from the surface downward* and in the end it is cheapest to "test ledge" until the altered phases of the iron formation are located at the surface. Deep drilling in unaltered cherty iron carbonate has given uniformly negative results. On the other hand deep drilling in ferruginous chert is



KEY MAP SHOWING POSSIBLE EXTENTIONS OF KNOW IRON FORMATION

FIG. 18

warranted by experience. Ore bodies may occur anywhere in ferruginous chert and it is generally wise to push a drill hole where possible to the limit of the zone of complete oxidation in the direction in which the hole is pointed. If slate is encountered below ferruginous chert or ore the hole should be sunk in it to a depth great enough to make sure that the slate is not merely a layer in the iron formation but is basal to it.

Mining engineers and explorers in general are divided in opinion as to the best methods of prospecting for ore bodies after the iron formation has been located by drilling or "testing ledge." Some favor drilling while others prefer underground work. Whether the one or the other of these methods is followed in a given instance is controlled largely by local conditions. If the overburden is deep the sinking of a shaft is often a difficult and expensive undertaking and is not often done unless ore has been previously located by drilling.

Practically all of the mines are operated under lease. The royalties range from 10 cents to 50 cents per ton of ore shipped. The lower figure is paid by two of the older mines, the latter is reported to have been stipulated in a recent lease on a developed property. During 1909 options to explore in virgin ground were freely given on royalties ranging from 20 to 35 cents.

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