The University of Minnesota

MINNESOTA GEOLOGICAL SURVEY

WILLIAM H. EMMONS, DIRECTOR

BULLETIN NO. 19

CONTRIBUTIONS TO THE GEOLOGY OF THE MESABI RANGE

WITH SPECIAL REFERENCE TO THE MAGNETITES OF THE IRON-BEARING FORMATION WEST OF MESABA

BY

JOHN W. GRUNER

MINNEAPOLIS
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THE GEOLOGY OF THE MESABI RANGE

CHAPTER I

INTRODUCTION

This paper treats the geology of that portion of the Mesabi Range that lies west of the town of Mesaba (Fig. 1). The Mesabi Range east of Mesaba was recently surveyed by Grout and Broderick,[1] and the Gunflint Range by Broderick.[2]

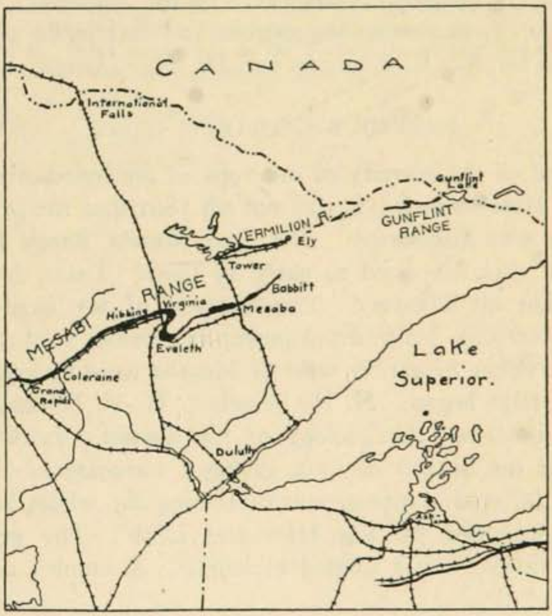

FIGURE I. SKETCH MAP SHOWING THE LOCATION OF THE MESABI AND GUNFLINT RANGES

The subjects treated include (1) the stratigraphic subdivisions and structure of the iron formation, (2) the occurrence of large magnetite bodies, possibly ore reserves for the future, (3) the origin of the formation and of the ores. The geologic setting of the district as a whole is briefly reviewed.

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[1] Grout, F. F., and Broderick, T. M., The magnetite deposits of the eastern Mesabi Range, Minnesota: Minn. Geol. Survey Bull. 17, 1919.

[2] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geol., vol. 15, 1920, pp. 422-50.

FIELD WORK AND ACKNOWLEDGMENTS

The writer's work in the district was begun in the summer of 1919, with Dr. T. M. Broderick in charge. It was continued by the writer with the assistance of Mr. S. C. Lin, and Mr. H. A. Schmitt, in the summers of 1920 and 1921.

In gathering the data all of the mining companies of the range co-operated heartily. Special thanks are due to Mr. W. J. Olcott, president, and Mr. J. Uno Sebenius, general mining engineer, of the Oliver Iron Mining Company, who gave permission to examine all their drill cores and maps used in the construction of the plates accompanying this report; also to the E. J. Longyear Company. In the laboratory work and in writing this paper, numerous suggestions and invaluable assistance were received from Dr. W. H. Emmons and Dr. F. F. Grout.

PREVIOUS GEOLOGIC WORK

On account of the scarcity of outcrops of the iron-bearing formation on the West Mesabi Range, it was not till 1891 that the productive part of the range was discovered. The East Mesabi Range had attracted explorers and was described as early as 1866.[3] Later this region was described again by Chester.[4] The leanness of the hard iron-bearing formation (taconite), made development impossible at that time.

When the richer hematites west of Mesaba were discovered the rush of 1891 and 1892 began. N. H. Winchell, H. V. Winchell, and J. E. Spurr[5] have described the geology of the district. Leith[6] published a monograph of the district in 1903, giving a summary of the history of the district. In 1912 a monograph describing the whole Lake Superior region was published by Van Hise and Leith[7]. The genesis of the iron-bearing formations is treated at length. A number of papers and

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[3] Eames, H. H., The metalliferous region bordering on Lake Superior: First Rept. of the State Geologist of Minn., St. Paul, 1866.

[4] Chester, A. H., The iron region of northern Minnesota: Minn. Geol. and Nat. Hist. Survey Eleventh Ann. Rept., 1884, pp. 154-67.

[5] Winchell, N. H., and Winchell, H. V., Iron ores of Minnesota: Minn. Geol. and Nat. Hist. Survey Bull. 6, 1891.

Winchell, N. H., Some problems of the Mesabi iron ore: Minn. Geol. and Nat. Hist. Survey Twenty-first Ann. Rept., 1893, p. 134.

Winchell, H. V., The Mesabi Iron Range: Minn. Geol. and Nat. Hist. Survey Twentieth Ann. Rept., 1891.

Spurr, J. E., The iron-bearing rocks of the Mesabi Range: Minn. Geol. and Nat. Hist. Survey Bull. 10, 1894.

[6] Leith, C. K., The Mesabi iron-bearing district of Minnesota: U. S. Geol. Survey Mon. 43, 1903.

[7] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, 1911.

reports have been published since 1912. Those by Wolff[8] are of special interest because they give a classification of the iron-bearing formation into subdivisions. Grout and Broderick[9] carried the subdivisions still farther on the East Mesabi Range and found several good horizon markers. Lately a new mining camp has sprung up at Babbitt on the East Mesabi Range, where the Mesabi Iron Company is actively engaged in extracting magnetite from the richer beds of the taconite.

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[8] Wolff, J. F., Ore bodies of the Mesabi Range: Eng. and Min. Jour., vol. 100, 1915, p. 93.

Wolff, J. F., Recent geologic developments on the Mesabi Iron Range, Minnesota: Proc. Lake Superior Mining Inst., vol. 21, 1917, pp. 229-57; Am. Inst. Min. Eng. Trans., vol. 56, 1917, pp. 142-69.

[9] Grout, F. F., and Broderick, T. M., Organic structures in the Biwabik iron-bearing formation of the Huronian in Minnesota: Am. Jour. Sci., vol. 48, 1919, p. 109.

Broderick, T. M., Detail stratigraphy of the Biwabik iron-bearing formation, East Mesabi district, Minnesota: Econ. Geol., vol. 14, 1919, p. 441; *op. cit.*

CHAPTER II

GENERAL GEOLOGY

STRATIGRAPHY

All the rocks of the Mesabi district have been described in great detail by the Minnesota and the United States Geological Surveys. The present study is confined to the iron-bearing formation. A short review of the stratigraphy is given below.

Quaternary system	
Pleistocene series	Glacial drift
Unconformity	
Cretaceous system	Conglomerates and shales
Unconformity	
Algonkian system	
Keweenawan series	Duluth gabbro and associated diabase sills and dikes
Unconformity	
Huronian series	
Upper Huronian (Animikie group)	Virginia slate Biwabik formation (iron-bearing) Pokegama quartzite
Unconformity	
Lower-Middle Huronian	Giants Range granite Slate-graywacke, conglomerate formation
Unconformity	
Archean system	Greenstones and schists

ARCHEAN SYSTEM

Greenstones and Schists

The greenstones are mostly green to gray schists, and represent much altered basic igneous rocks and, to a minor extent, sediments. Where foliation of the rocks is pronounced the name schist is preferable to greenstone. The greenstones occupy relatively small areas north of the iron-bearing formation between Mountain Iron and the Spring Mine in R. 14 W. They are not directly in contact with the Biwabik formation, but are separated from it by the Pokegama quartzite and commonly also by Lower-Middle Huronian graywacke and schist.

ALGONKIAN SYSTEM

Lower-Middle Huronian Series

Graywackes and slates.—To the casual observer the graywackes and slates look somewhat like the Archean greenstones and schists, but their sedimentary character is shown by bedding planes in many places. Slaty

A. MICRO-ORGANIC STRUCTURES (ALGAE?) IN CHERT PEBBLES. THE CHERT SHOWS LARGE COLLOFORM OUTLINES. THE BROWNISH GREEN ORGANISMS (BLACK IN PICTURE) OCCUR ALONG THE OUTSIDE OF THE "SCALLOPS" IN A MATRIX OF THE SAME KIND OF CHERT. ORDINARY LIGHT. x 88. SLIDE M 904 a

B. A PART OF STRUCTURES IN A, HIGHLY MAGNIFIED. THE DARK MATERIAL IS OF A GREENISH COLOR (PROBABLY A FERROUS IRON SUBSTANCE) AND CONSISTS OF MINUTE RODS OF UNIFORM SHAPE AND SIZE. x 660. SLIDE M 904 a

cleavage is common. The graywackes and slates are found in the area north of the Pokegama quartzite between Biwabik and Virginia. They are not in direct contact with the iron-bearing formation. Pokegama quartzite separates the two.

Giants Range granite.—Granite intrudes the greenstone, the graywacke, and the slate and forms most of the hills which make up the Giants Range. East of Mountain Iron the granite is hornblendic; west of Mountain Iron biotite predominates. The granite is coarse except near intrusive contacts. Pegmatite dikes are very common in it.

Upper Huronian Series (Animikie Group)

Pokegama quartzite and conglomerate.—The Upper Huronian sediments lie on the truncated edges of the Lower-Middle Huronian graywackes and slates. The Pokegama quartzite consists of a conglomerate as its base and a micaceous gray, green, or pink quartzite above the conglomerate. Pokegama quartzite, though very thin in places, underlies the Biwabik formation practically everywhere.

The conglomerate at the base of the quartzite was studied in a number of places where it is in contact with the older rocks. It is persistent though thin (a few inches to 6 feet). Its pebbles consist chiefly of graywacke, slate, greenstone, quartz, granite, and chert. Usually pebbles of the rock immediately underlying the conglomerate predominate. In size the pebbles vary from a fraction of an inch to one foot in diameter. The matrix may be quartzite or may consist of soft chloritic material where weathered.

A special study was made of patches of conglomerate in the SW¼ sec. 29, T. 58 N., R. 18 W., about half a mile northeast of Eveleth, in the NW¼ sec. 34, T. 59 N., R. 18 W., about one mile north of Mountain Iron, and in the SE¼ sec. 26, T. 58 N., R. 18 W., about two and a half miles northwest of North Hibbing. In these places the conglomerate was deposited on a rather uneven and broken erosion surface, and also fills fissures and cracks in the older rocks. Most of its pebbles are graywacke and slate of flat shapes. Quartz and chert pebbles which are present are usually fairly well rounded. The matrix consists of crystalline material resembling chloritic schist. Often the pebbles are so numerous and so close together that there is little room for matrix.

Cutting through the conglomerate and extending into the older underlying rocks are small veins and irregular areas of chert. The occurrence of this chert in the older rocks was described by the writer in 1922,[1]

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[1] Gruner, J. W., The origin of sedimentary iron formations; the Biwabik formation of the Mesabi Range: Econ. Geol., vol. 17, 1922, p. 417.

and is discussed later in this report. At that time it was not known that this chert also penetrates the conglomerate at the base of the Pokegama quartzite. The chert is green, light gray, dark gray, or reddish in color and in places shows peculiar markings as small rings or spots the size of greenalite granules. It may be much decomposed and looks "worm-eaten." Pyrite in minute cubes is common in it. The chert is indistinguishable either in the hand specimen or under the microscope from any other cherts of the Lake Superior region. This chert contains fossil micro-organisms. As noted, the conglomerate at the base of the Pokegama quartzite contains well-rounded chert pebbles. The chert of these pebbles resembles the "vein" chert just described. It is possible, but hardly probable, that the chert was formed in the same body of water in which the conglomerate was laid down, that the chert was broken up immediately and pieces of it carried into the conglomerate then forming. Organic structures have been found in two pebbles from sec. 26, T. 58 N., R. 21 W., about two miles northwest of Hibbing. Plates III and IV are photographs of these fossils. Somewhat similar structures have been found in other pebbles of the conglomerate north of Mountain Iron and northeast of Eveleth. (See Pl. V.)

Overlying the conglomerate there is a varying thickness (a few feet to 200 feet) of quartzite most of which is micaceous. Only toward the top of the formation does it become a coarse-grained massive quartzite.

Biwabik iron-bearing formation.—Overlying the quartzite practically conformably is found the Biwabik iron-bearing formation, about 400 to 750 feet thick. Its detailed description is presented in Chapter III.

Virginia slate.—The Virginia slate overlies the Biwabik formation conformably on the south side of the range. The two formations are separated by a persistent layer of impure crystalline limestone with an average thickness of about 10 feet. Drill cores in places show traces of a limestone conglomerate at the contact of the limestone with the Virginia slate. The slate is usually gray and varies in hardness. Much of the rock easily splits along the bedding planes but some breaks with difficulty and shows conchoidal fracture. The total thickness of the slate is probably several thousand feet. From a deep drill hole we know that it is at least 1900 feet thick in the central part of the range. In the examination of many thousands of feet of drill cores of Virginia slate no indication was found that deposition of iron-bearing formation, even on a very small scale, took place after the slate had begun to form.[2] Very small lenses of light gray chert, however, are found occasionally in the slate.

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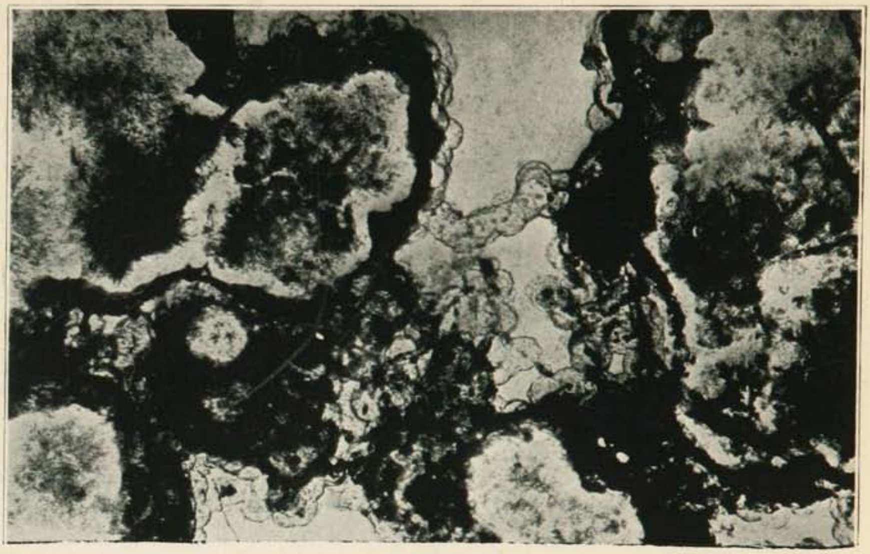
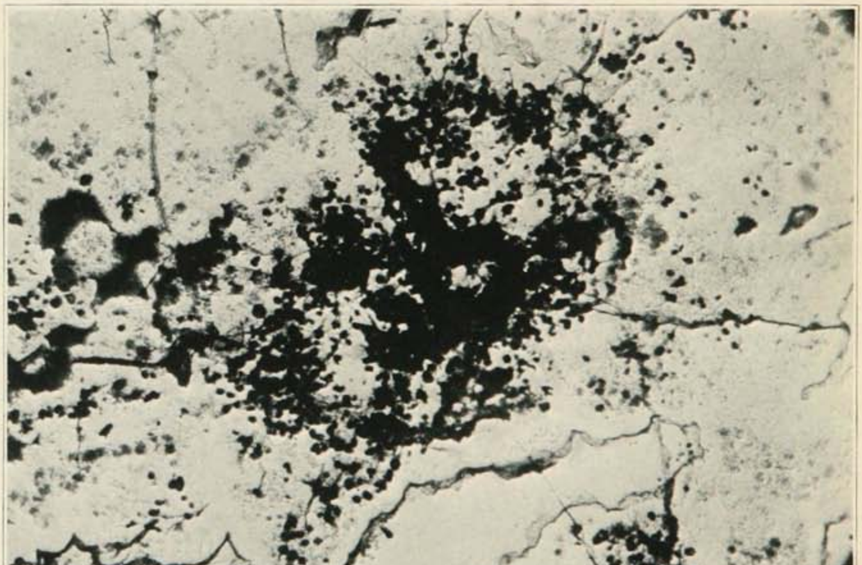
[2] In sec. 12, T. 56 N., R. 23 W. (Pl. II) some greenalite is interstratified with slate, but on account of the predominance of the slate this portion is included in the Virginia slate.



A. PECULIAR CHAINS OF MINUTE CONCENTRIC STRUCTURES IN CHERT PEBBLES. THE BLACK IN THE PICTURE CONSISTS OF IRON AND GREENISH MATERIAL WHICH RESEMBLES ALTERATION PRODUCTS (AMPHIBOLE-LIKE) OF GREENALITE. ORDINARY LIGHT. x 88. SLIDE M 904 d



B. "COLONIES" OF MINUTE, ROUND GRAINS IN THE CHERT PEBBLE WHICH CONTAIN THE ORGANISMS OF PLATES III A AND B, AND PLATE IV A. THESE GRAINS CONSIST OF BROWNISH MATERIAL AND STRONGLY SUGGEST ORGANIC ORIGIN IN THEIR ARRANGEMENT. x 77. SLIDE M 904 x

Keweenawan Series

The encroachment of the Duluth gabbro and the intrusion of sills of basic rock in the iron-bearing formation east of Mesaba are well known. During recent years drilling and underground mining have disclosed a number of intrusive dioritic masses near Aurora and dikes of highly altered igneous rocks in the Miller, Mohawk, Belgrade, and "Corsica-80" mines. There are indications that intrusions occur as far west as Virginia. (See p. 27.)

Diabase dikes and gabbro in larger masses occur north of the Biwabik formation, intrusive into the Giants Range granite as far west as Nashwauk.[3]

CRETACEOUS SYSTEM

Conglomerates and shales overlie a number of ore bodies west of Eveleth. Cretaceous fossils have been found in the shales west of Hibbing, but east of this town the age of the conglomerates can only be inferred from their similarity with those west of Hibbing.

QUATERNARY SYSTEM

Pleistocene Series

On the Mesabi Range, from Mesaba westward, probably not more than half a dozen exposures of the Biwabik formation can be found. In all other places a mantle of glacial drift, ranging from one to three hundred feet thick, or more, conceals the formation. The drift is thickest at the western end and thinnest at Mesaba, east of which outcrops of the iron-bearing formation are very numerous.

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[3] Observed by G. A. Thiel, I. S. Allison, and the writer.

CHAPTER III

DETAILED DESCRIPTION OF THE IRON-BEARING FORMATION

MINERALS OF THE IRON-BEARING FORMATION

The minerals noted in the following paragraphs are those easily observed in the hand specimens.

Greenalite and *amphiboles,* ferrous silicates with some magnesium, are found in many beds of the iron formation, as dull green or grayish green granules that rarely exceed one and one-half millimeter in diameter. The green microscopic needles of amphibole silicates which occur as metamorphic products of greenalite, retaining its granule shape, are included in the term greenalite as used here. The granules as a rule are embedded in a matrix of chert or dark slaty material. In the overlying Virginia slate greenalite is absent. It is the opinion of many geologists that by far the largest portion of the iron oxides and cherts is derived from this mineral in the processes of alteration and decomposition.

Chert is by far the most abundant mineral in the iron formation. It is usually white or light gray. When it has the characteristic greenalite structure it may be greenish gray. Most of the chert has been recrystallized and it is now a very fine aggregate of quartz crystals. Chert resembling flint in appearance occurs as very small lenses in the slaty phases of the iron formation. Coarsely crystallized quartz is common as filling in fissures and joints.

Magnetite was recognized for many years in the Biwabik formation, but its abundance has only recently attracted attention. In very small amounts it may be seen with the aid of the microscope in almost any fresh phase of the formation. It is present in amounts sufficiently large to attract an ordinary horseshoe magnet either as granules the size of those of greenalite with chert as matrix, or as dense fine-grained bands between cherty or slaty material. Its dark gray or black color and metallic luster, as a rule, are conspicuous. There are also mixtures of hematite and magnetite that look reddish brown or purple and attract the magnet. The eye alone cannot be relied upon in identifying the magnetite. Other less common phases of the occurrence of this mineral will be described later.

Hematite and *limonite* are very abundant in the iron formation. They are commonly mixed. In the following pages such mixtures are sometimes referred to as "ferric oxides" or "oxidized material." These oxides are recognized by their conspicuous purple, red, brown, and yellow colors. Black oxides are not all magnetite; some are hematite. Much of the hematite is derived from magnetite and its texture and distribution are much the same.

Carbonates of various composition are common in many beds that have not been decomposed. The abundance of carbonates has probably not been sufficiently emphasized heretofore. They occur especially with greenalite and slaty material, but are also common in the cherty beds. They occur as patches or bands, and also as individual crystals scattered through the rock. The sparkling of cleavage faces generally makes their recognition possible. In exceptional cases large crystals or aggregates may be noted. In color the carbonates range from white to brown and grayish, and their composition probably varies accordingly, though most of them are brownish yellow and appear to be siderite. An exception to this is the limy carbonate which is found at the top of the iron formation. This resembles a white, fine-grained, recrystallized limestone in every respect.

Kaolinite is present in the decomposed slate, the so-called paint rock. It is mixed with oxides of iron and therefore is usually some shade of red.

Graphite has been seen as very thin grayish black seams or films. The seams are often irregular and jagged in cross section, and are typical stylolites. (See Fig. 2.) At some places they form the dividing line between greenalite and slaty material or carbonates.

FIGURE 2. STYLOLITIC SURFACE BETWEEN CARBONATE AND SLATE IN THE BIWABIK FORMATION, NATURAL SIZE

Pyrite in very small quantities is widely distributed in the iron formation, especially in the greenalite and slate. It everywhere occurs as a replacement. A few large cubes were found in cherty taconite.

Marcasite was observed in fissures in ore bodies as a very late mineral.

Chalcopyrite has been noted in and near minute quartz veinlets in drill cores.

Manganese oxides and *hydroxides,* as black coating and probable replacement of iron oxides, are found locally in some ore bodies, especially near or in quartz veins.

Minerals in the slate must be treated as a whole, for individually they are indistinguishable as such to the naked eye. They are very fine grained and their aggregates are dull green, gray, brown, or black. All minerals that were mentioned in the preceding paragraphs are present in the slate. Amphiboles, chlorites, and carbonaceous material also occur in the slates.

ROCKS OF THE IRON-BEARING FORMATION

Taconite is a term which locally is applied to nearly any phase of the Biwabik formation. No better term has been suggested for a rock which has the characteristic granule texture and consists chiefly of chert and iron oxides. Ferruginous chert is another name used for the main phase of taconite. According to the phase of the formation the term taconite may be modified by a word expressing the physical properties or chemical composition. Slate is another convenient term for certain beds and in this report refers to a dense, very fine-grained rock which usually shows distinct banding. True slate, that is, a rock with slaty cleavage due to metamorphism, does not occur in the Biwabik formation. Paint rock is a local term that is used for the red-banded decomposed slate.

In the following paragraphs various kinds of taconite and slate will be described. The classification is based on the physical properties and the composition of the rocks as they may be seen without the aid of the microscope. An ordinary horseshoe magnet was used to detect magnetism and its intensity. Drill cores furnished most of the information regarding the magnetic taconite. Detailed descriptions, necessary for the interpretation of the maps and sections, are given below.

GREENALITE AND GREENALITE SLATE

Greenalite and greenalite slate have been described by Winchell, Spurr, Leith, and others, in papers already mentioned. Greenalite commonly is closely associated with the slaty beds of the Biwabik formation. The layers of greenalite are usually thin—rarely a few inches thick. Siderite is often associated with these layers, especially on the western half of the range.

The greenalite and greenalite slate as a whole are dark grayish green and are considerably softer than the greenalite taconite mentioned later on page 12. The greenalite granules are usually a little lighter in color than the groundmass. They are soft and in the polished specimens appear somewhat duller than the matrix. They may be very abundant with little groundmass, or very scattered in a large field of groundmass. Few have a greater diameter than one millimeter. The larger ones resemble small pebbles in some specimens. When the matrix is siliceous and the greenalite granules are partly replaced by chert and iron oxide, the rock is a transition to greenalite taconite and cherty taconite. On the other hand, where granules of greenalite are few there is a gradation into slate.

Weathered phases of greenalite and greenalite slate have not been distinguished from those of greenalite taconite with certainty, but it has been observed that the layers next below the layer known as Intermediate Slate which usually are greenalite when unaltered, form yellow limonitic ore on decomposition.

SLATE

The term slate has been used to describe dense, banded rocks in which the grains are of microscopic size. Slaty cleavage is not developed, but the banding and ease of splitting parallel to the bedding planes is pronounced. It may be brought out by color contrasts, or by layers of somewhat coarser grained material interstratified with the very fine-grained. Unless specified otherwise, the slate contains no considerable portions of magnetite or other minerals that could be easily identified in the hand specimen. It generally is dark green, gray, or black, breaks parallel to the bedding, or with conchoidal fracture across it. Its hardness varies with its composition. Very siliceous hard slate is almost as common as softer slate consisting mostly of iron and aluminum silicates. Carbonates are important constituents of the slate. Slaty varieties of taconite are common in any horizon of the Biwabik formation, but slate as defined here is found only in the Lower Slaty and Upper Slaty divisions. In the former it is best developed in the so-called "Intermediate Slate" which forms the bottom beds of the Lower Slaty division. It is dark gray to black in color and is always softer than the other phases of the undecomposed formation. It presents a uniform appearance, and contains much less greenalite than in any other slate beds.

The decomposition of the slates results in the formation of kaolin, hematite, and limonite. The slate first becomes lighter colored and crumbles easily. Where decomposition is far advanced there develop the well-known paint rock layers of which the altered Intermediate Slate forms the most prominent one. Some layers of slate appear to decompose much more readily than any phase of taconite. In the mines these slates may have become paint rock before the taconite in contact with them has lost its silica by leaching.

CHERTY TACONITE

Cherty taconite is a massive variety of taconite without any banding or slaty layers. As used here this term can be applied only in the study of drill cores in which only relatively short pieces of core are available. In the field exposures banding can be seen in most taconite, though the bands may be comparatively far apart. Therefore, strictly speaking, cherty taconite is a banded taconite, but its bands cannot be seen in drill cores

(Pl. V, D). All taconite is more or less cherty, but other features, such as banding for example, may be present and allow a more rigid classification of the phase.

Cherty taconite most resembles the irregularly banded taconite, but the latter phase can be distinguished by the twisted and wavy bands practically everywhere present. Cherty taconite has retained its original granule texture, but the granules consist of light gray or white chert and of iron oxides. This combination gives a grayish or brownish color to the rock as a whole, unless, as is rarely the case, a considerable portion of the granules consists of red jasper. The latter reddish phase has been called "jaspery taconite."

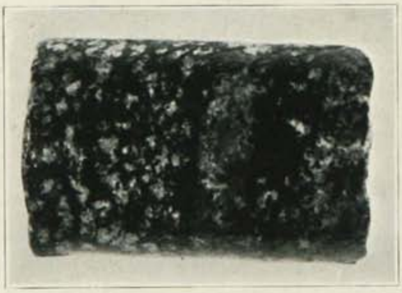
In weathering and leaching of cherty taconite, as in the similar banded and mottled varieties, pores and cavities develop. The rock becomes red or brown as a whole, but nearly white cherty areas may form where the taconite originally was very siliceous. It is especially noticeable in this phase of alteration that in some portions the silica is leached out and the iron oxides remain, while a short distance from such an area the reverse process seems to have taken place. Correlations of drill cores and field observations lead the writer to believe that in the case where white cherty areas have remained while the iron was leached, the iron was present in the pore spaces as iron carbonates or greenalite, both of which seem to be more easily attacked than the iron oxides.

GREENALITE TACONITE

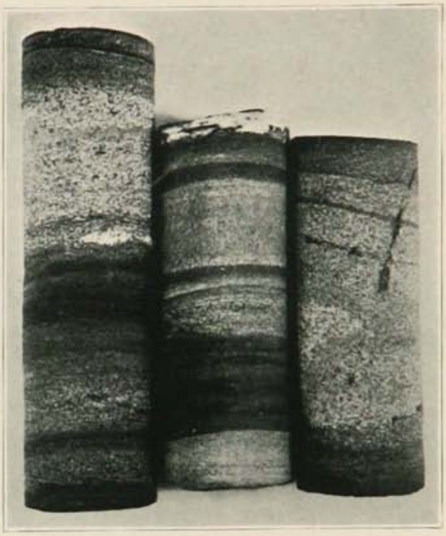
The distinction between greenalite taconite and cherty taconite is somewhat arbitrary and in the examination of cores was based on the color of the granules contained in the rock. The rock as a whole has a light greenish gray color due to the color of the granules which are chiefly made up of green amphiboles. The matrix of the granules, however, is chert as in cherty taconite, which differs from the greenalite taconite by the fact that its granules consist chiefly of darker iron oxides. All gradations from cherty taconite to greenalite taconite may be observed in drill cores, the classification depending entirely on the amount of the green silicates in the form of granules. Carbonates are also very common in the greenalite taconite.

As a rule greenalite taconite is rather uniform throughout, though frequently a band of dense dark cherty or slaty material is interbedded with it. The greenalite taconite usually has little magnetic oxide, but some shiny specks may be seen in most specimens. In some they are plentiful and such phases represent the gradations to the cherty or mottled taconite.

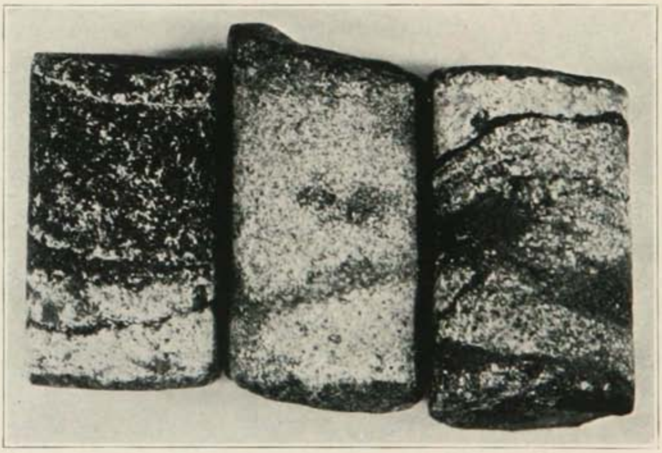
A. STRUCTURES PROBABLY ORGANIC IN A CHERT PEBBLE. DARK MATERIAL IS GREEN AND RESEMBLES GREENALITE. WHITE IS CHERT. X 26. SLIDE M 947



B. DRILL CORE OF MOTTLED TACONITE. DARK MATERIAL IS MAGNETITE.
NATURAL SIZE



C. BANDED TACONITE. THE BANDS CONSIST OF MAGNETITE AND SLATY MATERIAL. THREE-FOURTHS NATURAL SIZE



D. DRILL CORES OF CHERTY TACONITE. BLACK MATERIAL IS MAGNETITE. ONE AND ONE-FOURTH NATURAL SIZE

While the greenalite taconite may occur anywhere in the Biwabik formation, it is very rare in the lower 30 feet of the Lower Cherty division. It is much more common in the western half of the range than in the eastern. Decomposed phases are not easily distinguished from those of cherty taconite. They are sandy greenish yellow in the unbroken cores, and the crumbled material looks similar. The ore derived from greenalite taconite is not high grade.

SLATY TACONITE

The slaty taconite consists of layers which are similar to the slate described, but is much richer in oxides of iron. Therefore it is heavier in weight, and sparkling grains of magnetite or hematite may be observed in it. The individual bands may be yellow, red, purple, green, gray, or black and combined in such a way that the color contrast of adjoining bands is rather conspicuous. The bands may be very thin, or they may reach a thickness of one inch. Equally thin layers of greenalite, greenalite taconite, or cherty taconite are commonly interstratified with the slaty material.

In decomposing the greenalite layers generally become porous and disintegrate, and the slaty bands become softer and lighter in color. On still further decomposition the slaty bands become paint rock and the material interstratified becomes friable. The quality of the ore from this phase depends upon the amount of paint rock present.

The slaty taconite occurs in all of the divisions of the Biwabik formation and may locally be fairly rich in magnetite.

MOTTLED TACONITE

Mottled taconite has a characteristic spotted or mottled appearance (Pl. V, B). The spots range in size from one-sixteenth to one-half inch in diameter. Frequently they are of very irregular outline, not at all like greenalite granules. They are generally lighter colored portions of chert or more rarely of yellowish carbonate. The matrix consists generally of dark gray or brownish cherty taconite, especially rich in iron oxides around the lean "spots." They have no sharp borders like pebbles, but are apparently due to irregular replacement of the original minerals. Where leached, this rock has the peculiar "worm-eaten" appearance.

BANDED TACONITE

The banded taconite is intermediate between cherty taconite and slaty taconite. It contains too many bands of very fine-grained slaty material to be classed as cherty taconite, and too much of cherty taconite with granule texture to be called slaty taconite. (See Pl. V, C.)

The bands consist of very dense fine-grained material commonly containing much magnetite. Magnetite, however, is also abundant in the cherty material between the bands. The bands are straight but not quite as regular as in the slaty taconite. In the Upper and Lower Cherty divisions the banded taconite is important. Whether banded taconite forms high grade or medium grade ore depends on the composition of the bands. The more they approach slate in composition, the lower grade is the ore.

IRREGULARLY BANDED TACONITE

Irregularly banded taconite usually occurs in the Lower Cherty division in which it is the thickest magnetite-rich member.

This taconite differs from the banded taconite in which the banding is parallel by the irregular arrangement of the bands which are often not continuous, but pinch out or split, and curve in the most irregular manner or end abruptly. (See Fig. 3 and Pl. VI, A.)

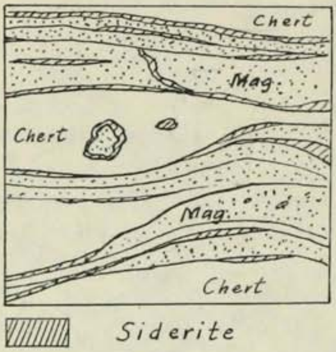
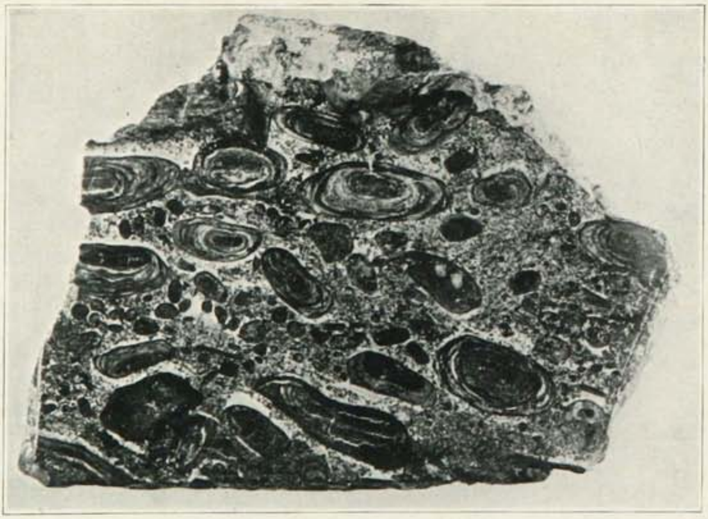


FIGURE 3. IRREGULARLY BANDED TACONITE. MAGNETITIC BANDS (DOTTED) WITH NARROW SEAMS OF SIDERITE (SHADED) BETWEEN MAGNETITE AND CHERT. NATURAL SIZE. THICKNESS OF CARBONATE SEAMS SLIGHTLY EXAGGERATED

In iron-rich portions of the formation the bands are dark gray to black in color and consist of magnetite mixed with dense chert and carbonate. Between the dark bands lighter colored lenses and irregular areas of chert or carbonate are seen. Magnetite or hematite is sprinkled through these lenses and areas, giving a kind of "salt and pepper" effect. The dark bands hardly ever exceed two inches in width except on the East Mesabi, and generally are less than one inch wide.

Usually three fourths of the iron oxides of the irregularly banded taconite are concentrated in these bands. The areas between the bands are considerably wider than the bands and are commonly lean in magnetite. In weathering or leaching the cherty portions turn white and

A. DRILL CORES OF IRREGULARLY BANDED TACONITE. BANDS CONSIST OF MAGNETITE AND CARBONATE. THREE-FOURTHS NATURAL SIZE



B. CONCENTRIC ALGAL STRUCTURES FROM THE BOTTOM OF THE LEONIDAS PIT. NATURAL SIZE

C. A MORE COMMON TYPE OF ALGAL STRUCTURE FROM THE TOP BENCH OF THE ADAMS PIT. NATURAL SIZE

innumerable holes up to the size of a match head form in it. Not uncommonly the cherty portions are disintegrated to a considerable extent, while the oxides of iron retain their magnetism. In such samples the magnetic iron runs especially high. On further decomposition the magnetite present is oxidized to hematite and most of the silica is removed. The resulting blue ore consists of bands of hard, heavy hematite, and sandy crumbling brownish or bluish portions between the bands. This is the best coarse blue ore of the Mesabi Range. The core from the irregularly banded taconite is usually very hard and well preserved in drilling.

CONGLOMERATES

Conglomerates may be divided into (1) that at the base of the Biwabik, (2) that in the Upper Cherty division, and (3) some scattered conglomeratic beds.

1. The basal conglomerate represents a break in deposition. This break may not have been caused by actual exposure of the sediments to erosion above the sea, but by a change of the conditions of deposition. The pebbles that can be seen in drill cores are naturally limited in size, and probably much larger ones exist that were not recognized in the samples. The pebbles comprise a great variety of rocks. In order of abundance, there are quartz, slate, chert, jasper, and a few magnetite pebbles. The slate pebbles are usually elongated, but the shapes of the others are varied. Subangular ones are as common as well-rounded ones. They are embedded either in a cherty or sandy matrix. Algal structures are closely associated with the conglomerate. They are found immediately above it and in the cherty matrix which surrounds the pebbles. The thickness of the conglomerate including the algal structures probably is never more than 10 feet, usually not more than 5 feet.

2. The conglomerate of the Upper Cherty division was first described by Wolff.[1] Grout and Broderick[2] found it a prominent horizon marker on the East Mesabi Range, and the present writer saw it east of Nashwauk in practically every drill hole and in many pits that penetrate the Upper Cherty division. It loses its significance as horizon marker west of Chisholm because it occurs in scattered layers at different horizons in the Upper Cherty division and even in the upper beds of the Lower Slaty division.

The pebbles of this conglomerate are small, as far as could be seen in the cores, and all consist of one of the phases of the iron formation. The most conspicuous are jasper and magnetite, though gray chert is also abundant. Their shapes are very irregular. Some are perfectly

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[1] *Op. cit.*, p. 243.

[2] *Op. cit.*, p. 20.

round and others very flat elongated. Usually their long diameters are more or less parallel to the bedding, but there are some striking exceptions.[3] The groundmass of the pebbles is usually cherty taconite or some gradational phase to greenalite taconite. Closely associated with the conglomeratic bed and adding to its value as horizon marker, are algal structures. The combined thickness of the conglomerate and algal structures west of Mesaba rarely exceeds 20 feet and may be as little as 2 or 3 feet.

3. The scattered conglomerates are very erratic in occurrence. The size of the pebbles does not exceed half an inch. In places they seem to grade into granules of the size of greenalite. Their shapes differ widely. They are not angular, however. In composition they are like the phase of taconite in which they are embedded. A piece of drill core 2 inches long frequently may contain only one or two pebbles.

ALGAL STRUCTURES

Algal structures of the Biwabik were first described by Leith as "contorted banding."[4] The engineers of the Oliver Iron Mining Company had noticed these peculiar structures at an early date, but Grout and Broderick[5] were the first who assigned an organic origin to them. Photographs of outcrops of these structures in their paper show them much better than illustrations of drill cores could. The algal structures found in open pits are shown in Plates VI, B and C. The structures may be recognized by the fine contorted lines which resemble the grain of an especially gnarled and knotty piece of wood.

The lines are always thin and according to the way the structures are cut by the drill, they may appear as concentric bands enclosing very irregular cores or form little arches in which the lines converge on both limbs. Mineralogically the structures consist of very narrow red jasper or whitish chert bands which alternate with brown, gray, or black bands. Greenalite structures were not seen with these bands. All of them are surrounded by some cherty phase of taconite or conglomerate. Algal structures occur in the lower part of the Biwabik formation from one end of the range to the other without any apparent break, and also in the Upper Cherty division where they were observed as far west as Hibbing. (See Pl. II.)

Between Chisholm and Hibbing the algal structures of the Upper Cherty division are only locally seen. West of Hibbing they disappear entirely.

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[3] For illustrations, see Grout and Broderick, *op. cit.*, Pls. V, VI, and IX.

[4] Leith, C. K., Mon. 43, Pl. XII, A.

[5] Am. Jour. Sci., vol. 48, 1919, pp. 190-205.

While these structures are associated with some of the richest magnetite beds on the East Mesabi Range, this is not the case from Eveleth westward. Magnetite, while still present in these beds, becomes rather "spotty," and is not abundant west of Eveleth.

In the mines the algal structures, after they are once found in a bed, are not difficult to trace through the workings. The beds in which they occur are light, often almost white in color. They are dense and hard because they are composed of massive chert or jasper. The beds are very resistant to weathering, so that boulders of them are found even in the most highly concentrated ore in which other primary structures are destroyed. It is this property which makes the algal structures very valuable as horizon markers.

A word of caution is added here. Lines simulating algal structures often occur at the surfaces of joints. The true structures always penetrate the rock. It may be at first difficult to find the beds in place, but if one will look for "boulders" and broken pieces of them at the foot of the ore benches, one will soon discover the places where they were broken off.

SUBDIVISIONS OF THE IRON-BEARING FORMATION

Tabular Section of Divisions of the Biwabik Formation West of Mesaba Station

	Thickness in Feet
UPPER SLATY DIVISION	
Limy carbonate, with greenalite, greenalite slate, and slaty taconite	0 to 25
Slaty and cherty taconite, greenalite and slate	0 to 145
UPPER CHERTY DIVISION	
Cherty, banded, slaty, and greenalite taconite with layers of conglomerate. Algal structures. Some beds rich in magnetite	95 to 250
LOWER SLATY DIVISION	
Slaty taconite, greenalite, greenalite slate, banded and cherty taconite, carbonates and scattered conglomerates. Some rich magnetite beds	0 to 250
"Intermediate Slate." Black slate, greenalite slate, and paint rock	½ to 40
LOWER CHERTY DIVISION	
Lean member. White cherty and greenalite taconite, greenalite and greenalite slate	12 to 52
Member rich in magnetite. Irregularly banded, mottled, and greenalite taconite	90 to 250
Member with iron in ferric state	
Beds of cherty and banded taconite with slate and slaty taconite on top	8 to 70
Red basal taconite	0 to 40
Basal conglomerate and algal structures	0 to 12
Total	400 to 755

A tabular section of the thickness and character of the divisions is given above.

In subdividing the Biwabik formation, the divisions as introduced by Wolff are used. Grout and Broderick have given essentially the same divisions for the East Mesabi Range. Textural and mineralogical changes along the dip and strike in beds may lead to apparent discrepancies locally, and yet, taking into consideration the great thickness and length of the iron-bearing formation, its uniformity is remarkable.

LOWER CHERTY DIVISION

The Lower Cherty division is the most uniform division of the iron formation. This may be seen in Plate II, which is a longitudinal vertical section parallel to the strike of the iron formation. The thickness of the Lower Cherty division which is small in the eastern part of the range, is 140 feet at Mesaba and becomes progressively greater toward the west, reaching its maximum of 340 feet between Keewatin and Calumet, and from there to Prairie River it does not fall below 260 feet.

Prominent outcrops of the Lower Cherty division may be seen in the extreme northeastern extension of the Virginia Horn, 3 miles northeast of Virginia, (SE¼ sec. 28, T. 59 N., R. 17 W.), in the NW¼ sec. 34, T. 59 N., R. 18 W., 1 mile north of Mountain Iron, and along the high bluff north of Eveleth in sec. 20 and 29, T. 58 N., R. 17 W. It also has been exposed in the excavation along the road from Eveleth to Gilbert in sec. 5, T. 58 N., R. 17 W., and a few hundred feet northeast in the shallow cut of the Mesabi Electric Railway. A new cut may be found in the town of Eveleth where the concrete road to Virginia branches off from the city streets.

The Lower Cherty division may be subdivided into (1) the lower member with most of the iron in the ferric state, (2) the middle member rich in magnetite, and (3) the upper lean member.

1. The lower member includes the basal conglomerate and algal structures, the red basal taconite and cherty beds which nearly always have slate or slaty taconite beds on top. This member is usually 40 to 60 feet, but may become 80 feet thick. It is unimportant as a prospective magnetite horizon. The basal conglomerate, including the inseparable algal structures, is well developed from Buhl westward. From Buhl eastward to the big bluff between Virginia and Eveleth, it was observed in relatively few places. Farther east to Mesaba it gradually regains its prominence.

The so-called red basal taconite is easily traced from Aurora to the west end of the range. It may consist of any phase of taconite, usually of a combination of several, which are reddish in color. In spite of its gradual transition downward into the basal conglomerate and upward into the cherty beds, it is not easily overlooked because its color is so conspicuous and there are no other similar beds in the Lower Cherty division.

The cherty beds overlying the red basal taconite are also relatively easily identified, provided one knows that one is examining beds below the Intermediate Slate. These cherty beds also contain ferric iron, but so coarse as to be dark colored. They are separated from the usually magnetic beds above by a few inches of slate and a number of feet of slaty taconite which are almost invariably present at this horizon. The characteristic feature then is that a thin slate and slaty taconite as a rule separate the ferric oxides below from the magnetic oxides above them. There are places, however, in which some magnetite occurs in the beds below this slate.

2. The member rich in magnetite is of greatest economic interest on account of its possible availability in the future as low grade ore. It consists of irregularly banded taconite, mottled taconite, and greenalite taconite. The irregularly banded taconite is by far the most abundant. The amount of magnetite in the unoxidized parts of this member is probably 27 to 33 per cent, or in other words as much as on the East Mesabi Range. There is a difference, however, in the size of the grains and thickness of the bands of magnetite, in the two parts of the range, the East Mesabi magnetite being coarser and in thicker bands.

Not all of this member is as rich in magnetite as one might suppose after studying the longitudinal section, Plate II. In this section only deep holes are shown in which the Lower Cherty division is buried to considerable depth. Nearer the surface oxidation has affected large areas of this member. In some places almost all of it has been oxidized and little magnetite remains. Every gradation between the two extremes is found, though west of Snowball oxidation seems to have altered most of the magnetite that is close to the surface. At some places there is a leaching of the cherty material of the cores in advance of oxidation, with a corresponding increase in magnetite due to the removal of silica. As a whole, this member is the hardest part of the formation and therefore furnishes good, solid cores.

3. The "lean member" of the Lower Cherty division consists either of white cherty taconite and much decomposed material including yellow ore; or of greenalite taconite and yellowish carbonate.

The oxidation of this member is more advanced on the western half of the range as indicated in the longitudinal section. The white cherty taconite owes its color to the lean condition of the original beds and also to the extensive leaching out of the iron carbonate and green silicates.

The unoxidized beds of this member have a grayish green color due to the presence of much greenalite. Conglomerates are found in places but are neither conspicuous nor continuous. This member grades into the underlying rich magnetite beds. On the other hand, the contact between it and the overlying Intermediate Slate is the most definite line and horizon marker of the whole formation.

LOWER SLATY DIVISION

The Lower Slaty division has the very well-defined Intermediate Slate at its base, but the rest of the division has no horizon marker save conglomerates that occur either at the top of the division or much more often at the base of the Upper Cherty division in parts of the range. West of Nashwauk all conglomerates become very obscure or are absent altogether. At most places the presence of any cherty conglomerate will indicate the Upper Cherty or top of the Lower Slaty division.

The lack of a definite marker between the Lower Slaty and Upper Cherty divisions makes the dividing line between the two somewhat arbitrary. In this report, beds with a preponderance of slaty taconite were assigned to the Lower Slaty division; those beds with more cherty taconite than slaty were classed as belonging to the Upper Cherty division.

A discrepancy on account of this manner of dividing the Biwabik formation with the divisions introduced by Wolff[6] will be noticed for example in the drill hole from sec. 27, T. 57 N., R. 22 W. It was believed that the larger portion of the beds listed by Wolff as "Lower Slaty Horizon" were too cherty to be included in the Lower Slaty division, and they were classed with the Upper Cherty division. Wolff, on the other hand, makes the conglomerate shown at the base of the Upper Cherty horizon the dividing line. As these conglomerates are very erratic or are missing entirely at the western end of the range, they were not used as definite markers.

The Intermediate Slate consists of black slate, greenalite slate, and paint rock, or a mixture of these, and ranges from a few inches to nearly 40 feet in thickness. Its lower contact is almost always sharp and is usually marked by some black slate or paint rock. The upper contact is indefinite and a gradual change to other slaty phases takes place. The Intermediate Slate was seen in nearly all drill holes.

The Lower Slaty division, above the Intermediate Slate consists of layers of slaty taconite, greenalite, greenalite slate, and lesser amounts of banded and cherty taconite. These types are commonly interbedded in no definite order, save for the fact that the amount of iron in them decreases toward the bottom. As mentioned before, scattered conglomerates are common in the upper layers. The total thickness of the division is great in Range 15 and from Eveleth to Range 18. From there westward it gradually decreases and beyond Hibbing it is below 50 feet.

[6] *Op. cit.*, p. 246.

West of Nashwauk only the Intermediate Slate is slaty enough to be included in this division.

Between sec. 6, T. 57 N., R. 17 W. (near Eveleth), and sec. 1, T. 58 N., R. 18 W. (near Virginia), a lens of cherty, banded and irregularly banded taconite rich in magnetite, and having a maximum thickness of 140 feet, occurs in the Lower Slaty division. In some respects its beds resemble the member rich in magnetite in the Lower Cherty division, but a great deal of the banded taconite is different from any other listed under this name. It consists of very thin, light colored, straight bands of cherty taconite which alternate with thin dark bands of cherty taconite in which magnetite has been concentrated. Therefore this phase has little resemblance to the ordinary banded taconite in which the dark bands are dense slaty material. This lens is 7 or 8 miles long.

Much of the high grade blue ore mined around Virginia and Eveleth is derived from this lens, while the rest of the Lower Slaty division produces yellow or brown ore. As a source of magnetite in this division only the lens of cherty taconite just mentioned deserves consideration.

UPPER CHERTY DIVISION

The Upper Cherty division is more nearly uniform in its general features than the Lower Slaty division. Its thickness ranges from 95 to 250 feet. Usually it is more than 140 feet thick, but west of Nashwauk it thins rather abruptly and regains a thickness of nearly 200 feet only at the town of Taconite. West of Taconite the cores of this division are insufficient and difficult to interpret. Between Kelly Lake and Nashwauk it cannot be distinguished from the Upper Slaty division, for the latter seems to have as much cherty taconite as the Upper Cherty division, which here is exceptionally slaty. Therefore the two have not been differentiated on the map for a distance of five miles.

The gradation of the Upper Cherty into the Lower Slaty division has been described. Besides cherty taconite and minor amounts of slaty taconite, the Upper Cherty division contains banded taconite, greenalite taconite, conglomerates, and algal structures. The conglomerate beds and algal structures are of chief interest. It was stated in describing the algal structures that they were generally found in, or very close to, a well-developed layer of conglomerate. The latter is really the most conspicuous conglomerate above the basal conglomerate, though probably not everywhere the thickest. The algal structures of the eastern half of the range are closer to the top, those of the western half nearer the bottom of the Upper Cherty division, though always at least 50 feet from either dividing line. The longitudinal section (Pl. II) should be seen for the exact location of the algal structures. West of Hibbing they enter beds included in the Upper Slaty division, and disappear altogether within a short distance. The conglomerate associated with the algal structures also becomes indefinite west of Hibbing.

There are other conglomerate beds above and below the algal structures in the Upper Cherty division, but none of them seems to be continuous over large areas. Correlation of them is impossible with the data available. All conglomerates become obscure and probably disappear entirely west of Nashwauk. The change from the Upper Cherty division to the overlying one is very gradual. As a source of magnetite the Upper Cherty division is out of consideration west of Eveleth. Oxidation and decomposition have converted most of the magnetite to hematite to considerable depths. The ore derived from this division is a high grade blue or brown ore.

UPPER SLATY DIVISION

The Upper Slaty division consists of slaty taconite, greenalite taconite, cherty taconite, and greenalite slate. A layer of limy carbonate occurs, usually interstratified with a little slate, at the top of the Biwabik formation. The carbonate where present in the solid cores forms a very good horizon marker. It is a well-crystallized, fine to medium-grained, white or gray rock, but evidently due to its inferior hardness, it has been lost in the drilling of many holes. Its greater solubility, also, probably caused more rapid decomposition. Without the carbonate as a guide no sharp lines can be drawn between the Biwabik formation and Virginia slate at some places, but the absence of any greenalite texture in about 10 to 15 feet of drill cores is almost always a sure sign of the Virginia slate. The limy carbonate was not seen west of Nashwauk. From there on no Upper Slaty division could be mapped, for while a thin layer of it may exist in places it was not possible to distinguish it in the disintegrated and decomposed material which predominates in the cores on the western end of the range.

The Upper Slaty division at most places is not thicker than 60 to 70 feet, though there is a marked increase near Hibbing. A few miles farther west it merges into the Upper Cherty division. (See map, Pl. I.)

Many layers of the Upper Slaty division are completely decomposed. Where silica has been leached out a low grade ore has formed. The beds of this division were originally lean in iron and they are valueless for purposes of magnetic concentration.

CORRELATION OF THE BIWABIK WITH THE GUNFLINT FORMATION

Broderick[7] has clearly stated the numerous points of similarity between the Biwabik and Gunflint formations. The fact that both can be divided into the same members, that both have two algal structure layers at corresponding horizons, and also the septaria bed, show that they were probably deposited at the same time as a continuous formation. For comparison a vertical section of the Gunflint area is included in Plate II. Broderick has proposed that the name Gunflint formation be dropped and Biwabik formation substituted, for the sake of simplifying nomenclature.

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[7] Broderick, T. M., Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Econ. Geol., vol. 15, 1920, pp. 435-37.

CHAPTER IV

STRUCTURE OF THE IRON-BEARING FORMATION

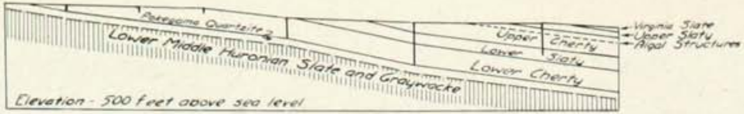
GENERAL STRUCTURE

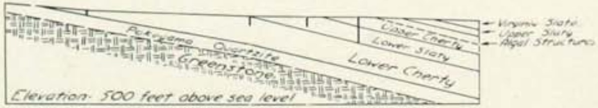
The Upper Huronian rocks of the Mesabi Range are simple in structure as is shown by maps and cross sections of Winchell, Leith, and others. The beds of the iron formation as a whole have been slightly inclined from their originally nearly horizontal position. They dip to the south and southeast at an angle of 4 to 7 degrees west of Eveleth (see cross sections Nos. 3 to 10, Pl. VII), and from 6 to 12 degrees east of Eveleth (see cross sections Nos. 1 and 2, Pl. VII). Between Aurora and the town of Mesaba, however, the dip is nearly zero in some areas. Due to this flattening of the beds between Aurora and Mesaba, the outcropping belt of iron formation in places becomes as wide as two miles.

The direction of dip in the Z-shaped bend of the Biwabik formation between Gilbert and Mountain Iron, which is called the Virginia Horn, is west and southwest for a few miles. The outlier of the iron formation 4 miles northeast of Virginia (sec. 35, T. 59 N., R. 17 W.) shows that the now eroded portion of the iron formation which covered the area of the Virginia Horn was nearly flat. This flattening of the dip is also indicated by the fact that the outcrops of the lower divisions of the formation are relatively wider than those of the upper divisions east of Eveleth as shown in Plate I. A flattening of the dip of the iron formation is also indicated by deep drill holes south of the range through the Virginia slate. In other words, there exists (partly eroded) a monoclinal flexure of the iron formation east of Eveleth, and the outcrops of the upper divisions of the iron formation are on the portion of the monocline which dips most steeply. This is shown diagrammatically in Figure 4. This monoclinal structure is simply an extension of the structures shown in reports by former investigators. Whether it exists, or once existed, west of Virginia is not known. The relatively great width of the outcrops of iron formation west of Virginia is due mainly to the slight dip of the formation. Rapid changes locally in this width may be due to either local changes in dip or changes in the thickness of the iron formation.

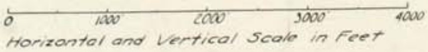
As would be expected in a brittle rock like taconite, joint and bedding plane cracks are exceedingly numerous throughout the formation. The joint surfaces as a rule are straight and, in places, of considerable length. The strike of the joints was taken on most exposures of the range and the following generalization has been derived from these measurements;

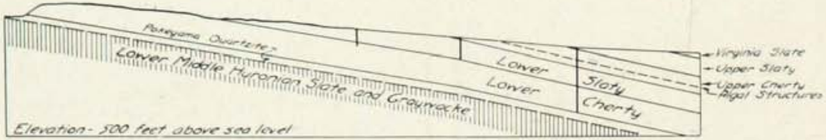
PLATE VII

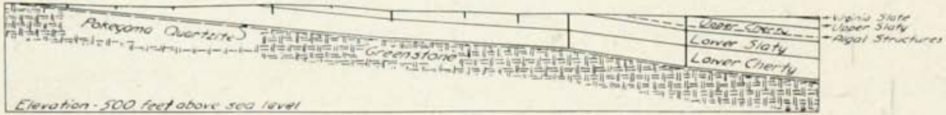


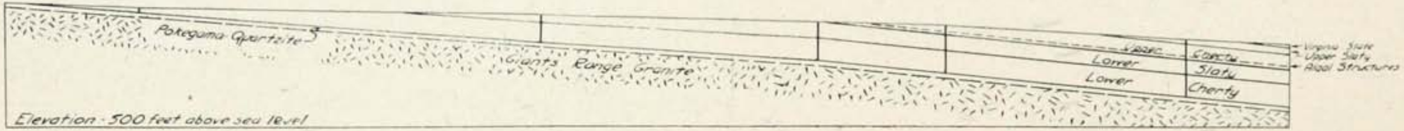


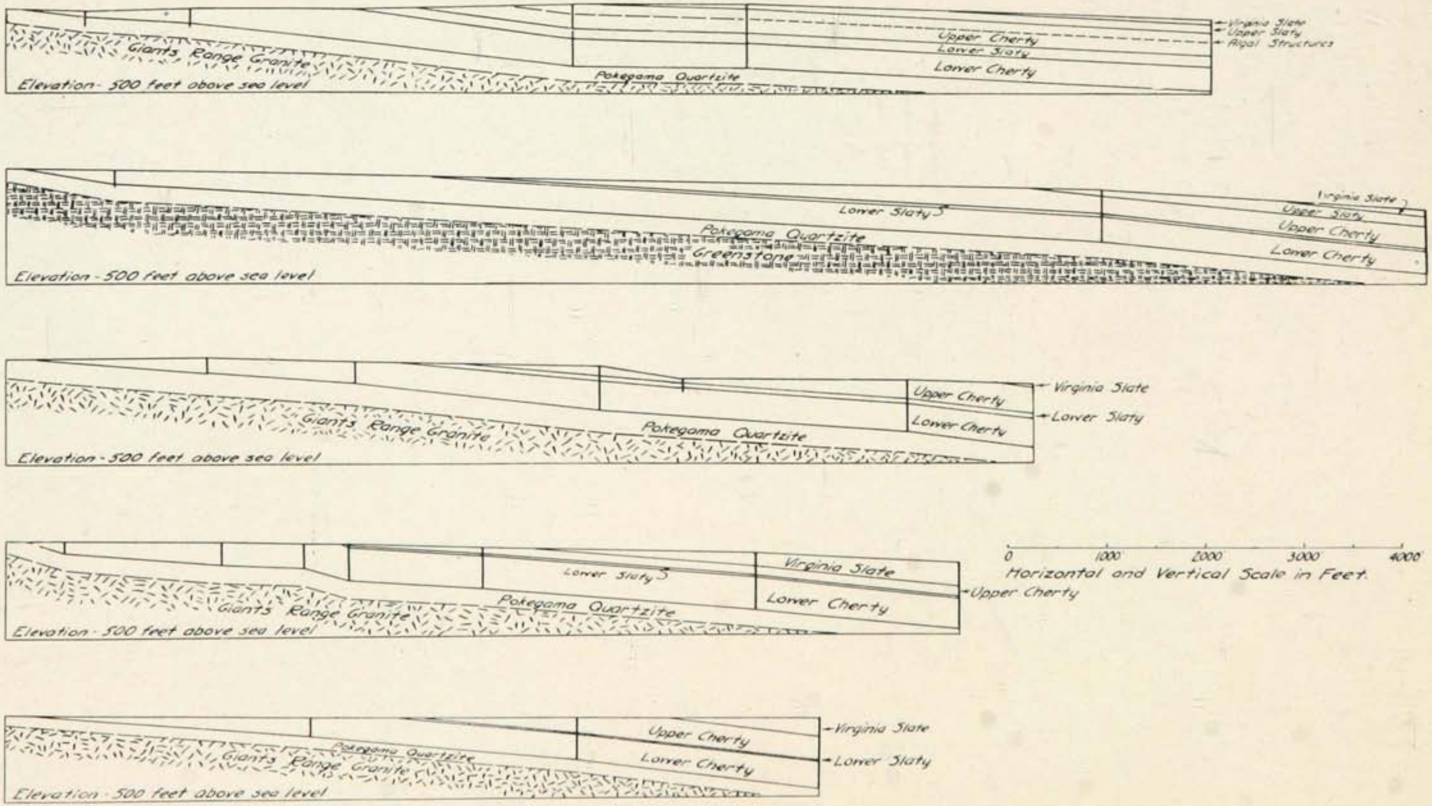
Number cross sections consecutively
from top to bottom of plate.











CROSS SECTION OF THE IRON-BEARING FORMATION. NUMBERS I TO X

1. With relatively few exceptions, as in the case of exceedingly dense cherty taconite phases, three joint planes are present.
2. They are either at right angles, or nearly at right angles, to the bedding planes.
3. The directions of strike are approximately N. 10° E. for one set, east-west for another, and N. 45° W. for a third. Naturally there are many variations, but as a whole the agreement is conspicuous.
4. In slaty phases of taconite there may be two more sets of joints.
5. Joints in the underlying Pokegama quartzite are similar.

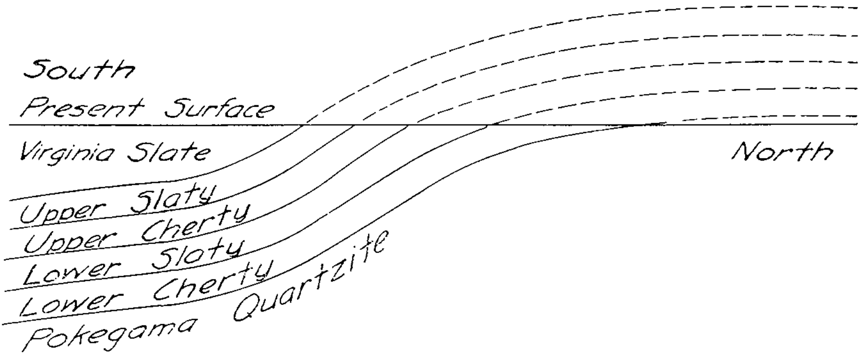


FIGURE 4. IDEAL NORTH-SOUTH CROSS SECTION OF THE IRON FORMATION BETWEEN GILBERT AND BIWABIK. VERTICAL SCALE TWICE THAT OF HORIZONTAL SCALE

SPECIAL STRUCTURES

A prominent monocline is exposed in the Alpena pit at Virginia. (See Fig. 5.) Its axis strikes north. The beds on the east of the monocline are about 400 feet higher than the corresponding ones on the west side. This fold was for a time regarded a reverse fault in earlier reports.

A normal fault is exposed in the Biwabik pit north of Biwabik. The strike of the fault appears to be nearly east-west along the north edge of the Biwabik formation. It has been traced eastward into sec. 5, T. 58 N., R. 15 W. The dip of the fault plane is steeply south. The displacement is at least 200 feet. Greenstone on the north is now in contact with iron-bearing rocks on the south side of the fault plane.

There are some special structures found in ore bodies which are discussed later. Some of them are due to slumping, but others originated before the concentration of the ore by weathering.[1] Among these are kaolin dikes, originally igneous intrusives. They are found as far west as Elba (sec. 18, T. 58 N., R. 16 W.). One dike has been reported from an old mine at Nashwauk, but its occurrence could not be verified.

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[1] A fault or monocline appears to be located between the La Rue and Hawkins mines at Nashwauk. Mr. John Edwin, engineer of the La Rue Mine, also called the writer's attention to this structure.

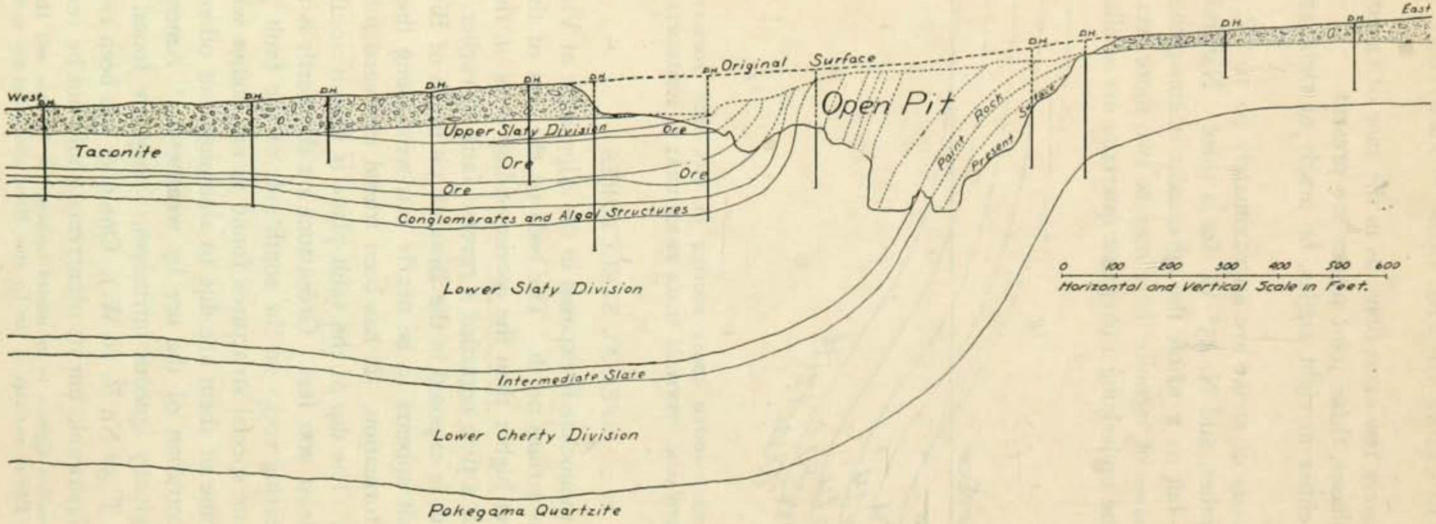

FIGURE 5. MONOCLINAL STRUCTURE OF THE ALPENA AND SLIVVER MINE AREA

Large quartz veins have caused local structures in ore bodies. These quartz veins may be as wide as 15 feet, and in extreme cases 1500 to 2000 feet long. They may branch at higher levels. Besides quartz they contain much biotite,[2] in needles, chlorite, and a little apatite.[3] One vein near Buhl contained crystallized native copper. It is highly probable that these veins were formed by ascending hot solutions. These veins and dikes in connection with acidic and basic intrusives in the Giants Range granite, north of the iron formation, suggest that possibly there is a larger batholith younger than the Upper Huronian rocks beneath the Biwabik formation.

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[2] This is probably stilpnomelane, a mineral closely resembling biotite in optical properties. Personal communication by F. F. Grout and G. A. Thiel.

[3] Manganese oxides are commonly associated with the ore near quartz veins.

CHAPTER V

THE MAGNETITE DEPOSITS

MINERALS AND CHEMICAL COMPOSITION

The minerals in the areas rich in magnetite are essentially the same as those found in the unweathered formation as a whole. (See p. 8.) The magnetite frequently contains minute specks of hematite as inclusions. As hematite ore bodies are approached the amount of magnetite decreases usually abruptly, and hematite takes its place. This change is especially abrupt in the areas east of Mountain Iron.

The chemical composition of the average taconite as given by Van Hise and Leith[1] is as follows:

Fe	25.71
SiO_2	58.70
P	0.021
Al_3O_2	0.54
Loss on ignition	1.96

The present writer made a partial analysis of a typical sample of irregularly banded magnetite taconite and found

Fe	29.39
SiO_2	44.09

On the East Mesabi Range[2] the average sample of magnetite taconite from the Upper Cherty beds near Babbitt is: Fe 33.80, and SiO_2 45.17. This closely resembles the West Mesabi taconite. As on the East Mesabi, the amount of phosphorus in the magnetite taconite is very low as shown in the table on page 32.

TEXTURE

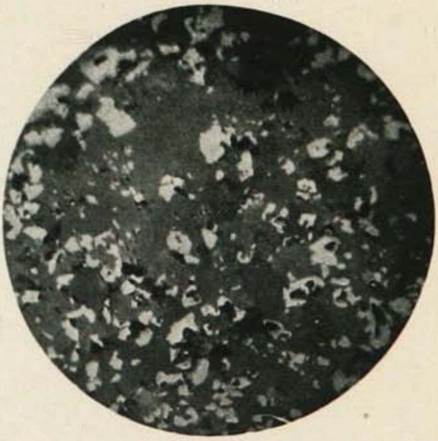
The magnetite in the taconite is practically all very fine grained. The individual grains are of microscopic size and as a rule show octahedral outlines of magnetite, though magnetite pseudomorphs after hematite are not uncommon.[3] The minute grains of magnetite may form aggregates with the outlines of greenalite granules (Pl. VIII, A.), or be concentrated into dense bands (Fig. 3). The dense bands, when viewed under the microscope, consist of minute grains of magnetite similar to those shown on Plate VIII, B, which are embedded in a matrix of carbonate and chert. Most of the carbonate is siderite. Plate VIII, B, shows the average size of the magnetite grains. In this photograph the grains are, however, only half as abundant as in the average dense band.

[1] Van Hise, C. R., and Leith, C. K., U.S. Geol. Survey Mon. 52, 1911, p. 181.

[2] Grout and Broderick, *op. cit.*, p. 29.

[3] Gruner, J. W., Paragenesis of the martite ore bodies and magnetites of the Mesabi Range. Minnesota: Econ. Geol., vol. 17, 1922 pp. 1-14.

A. EUHEDRAL MAGNETITE (WHITE) IN FORM OF GREENALITE GRANULES. X 40



B. EUHEDRAL MAGNETITE (LIGHT GRAY) IN GANGUE OF CARBONATE AND CHERT. X 200

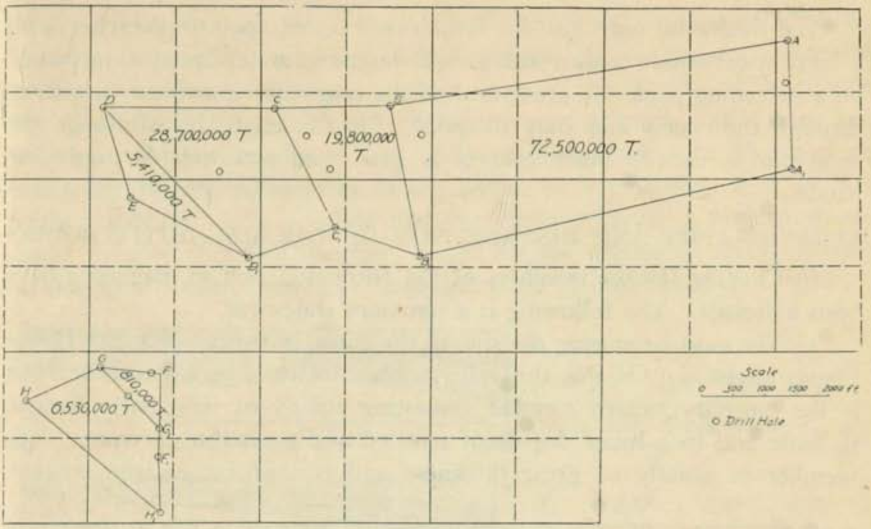


FIGURE 6. APPROXIMATE OUTLINE OF A MAGNETITE BODY BETWEEN MESABA AND BIWABIK

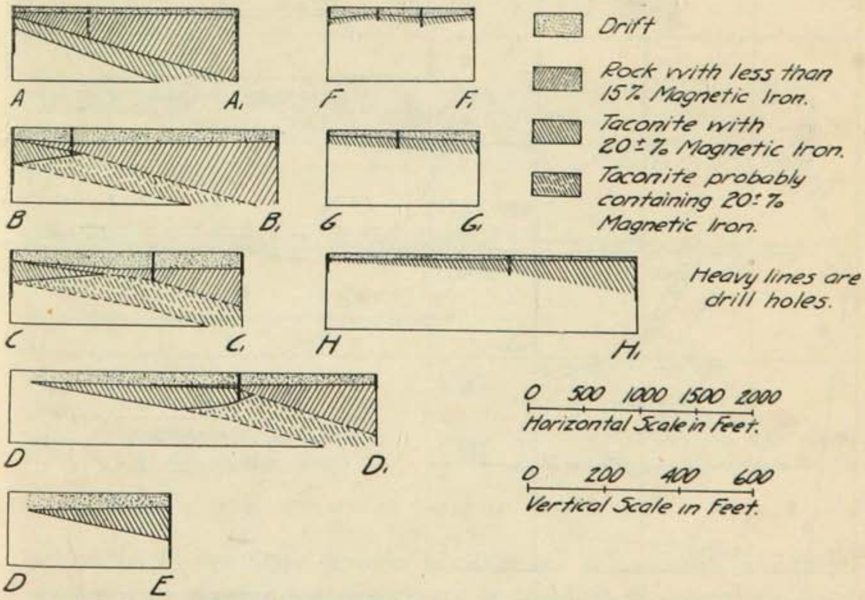


FIGURE 7. CROSS SECTIONS OF MAGNETITE BODY OUTLINED IN FIGURE 6

The magnetite may also be found as rounded spots or blotches with a chert or carbonate center, such as was described under "mottled taconite," on a preceding page. A great deal of the magnetite also occurs scattered through the cherty and slaty material. On the East Mesabi Range the magnetite is usually much coarser in grain and concentrated in thicker bands.

STRATIGRAPHY AND DISTRIBUTION OF THE MAGNETITE BODIES

In Chapter III the members of the formation rich in magnetite have been indicated. The following is a summary statement.

1. The most promising division of the Biwabik formation is the Lower Cherty division. Of this the only member which deserves consideration is the centrally located member consisting chiefly of irregularly banded taconite and to a lesser degree of mottled and greenalite taconite. This member is usually of great thickness and is uniform in iron content.

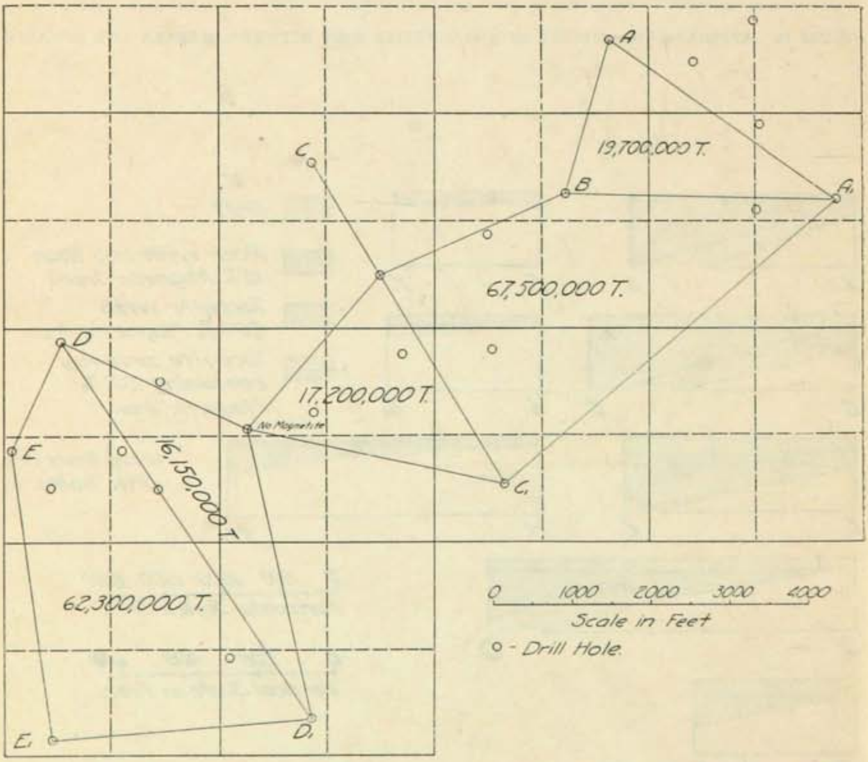


FIGURE 8. APPROXIMATE OUTLINE OF A MAGNETITE BODY BETWEEN CHISHOLM AND KEEWATIN

While it extends throughout the whole range (it is thin east of Mesaba) it holds no promise west of Snowball, because the magnetite is changed to higher oxides close to the surface west of this town. This change has also affected large areas in other parts of the range and it must not be expected that magnetite ore bodies will be found at the surface wherever this central member of the Lower Cherty division is in contact with the drift. It is possible that the exploration of a magnetite ore body, even in this rich member, would require almost as much drilling as that of a hematite body of an equal tonnage of metallic iron.

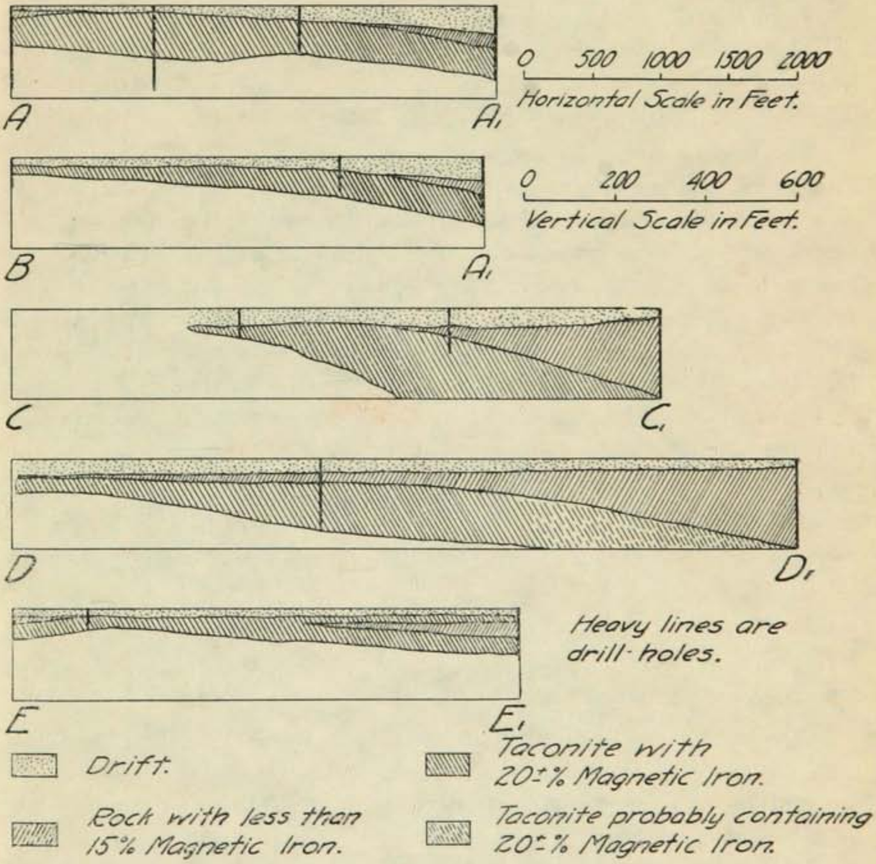


FIGURE 9. CROSS SECTIONS OF MAGNETITE BODY OUTLINED IN FIGURE 8

2. The Lower Slaty division is either too thin or too lean to be a prospective magnetite horizon, except in the lens of irregularly banded and of banded taconite between Mountain Iron and Eveleth (p. 21). This lens is almost as high in magnetite as the rich member in the Lower

Cherty division. It also resembles it in texture in certain portions. It is of considerable thickness (Pl. II), and is low in phosphorus.

3. The Upper Cherty division is much less uniform in magnetite content than its stratigraphic equivalent of the East Mesabi Range, where it is mined at Babbitt. On the Central and West Mesabi Range magnetite occurs in it in a very erratic manner and changes of this mineral to hematite are very extensive. There is little promise of finding magnetite deposits of considerable size and thickness in it near the surface west of Gilbert. East of this town the possibilities are somewhat better, especially near Mesaba.

4. In the Upper Slaty division magnetite is scattered and is present in relatively small amounts. There is small probability that it will ever be mined.

GRADE AND SIZE OF THE DEPOSITS

The amount of iron as magnetite in the good sized taconite beds which are richest in magnetite varies between 20 and 30 per cent. The average is about 22 per cent iron in the form of magnetite. Five magnetic concentration tests were made on average samples of irregularly banded and mottled taconite of the Lower Cherty division. Each one of the samples represents five feet of drill core. The samples are from widely separated localities west of Mesaba. The tests were made by the Minnesota School of Mines Experiment Station, according to the method developed in testing East Mesabi taconite. The samples were crushed to pass through 150 mesh. The amounts are given in per cent.

Sample No.	Fe in Taconite	Fe Recovered by Magnetic Concentration	Fe in Concentrate	P in Concentrate
1............	31.34	30.90	67.94	0.007
2............	25.32	19.13	65.77	0.014
3............	31.12	22.97	68.68	0.005
4............	28.75	23.07	67.11	0.007
5............	31.57	17.65	66.44	0.007

Sample No. 5 is the only one which was leaner than was estimated with the aid of a horseshoe magnet. The writer had an opportunity to see analyses of other samples of cherty taconite. All were extremely low in phosphorus.

The size of the magnetite bodies depends on the limits placed on the quality of ore, the amount of overburden to be removed, and the depth to which open pit mining could be carried on. It is safe to assume that these bodies will not be drawn on soon, but it is not unlikely that they will be utilized some day. The available drill holes are insufficient to make any reliable estimates of the size of the magnetite bodies, but an attempt has been made to estimate the amount of iron that could be extracted from certain areas containing taconite with 20 or more per cent magnetic iron. The lower limit in these estimates was fixed arbitrarily as 200 feet below the top of the drift, but only taconite containing 20 per cent or more iron as magnetite was included in the estimates. Where drill holes stopped in such ore the probable total depth of the ore was estimated from the dip of the beds and included in the tonnage. Figures 6, 7, 8, and 9 are the bodies for which the tonnages were computed. The distortion of section lines was disregarded in the diagrams. The thin straight lines represent the boundaries of the areas, the small circles, the drill holes. It is not improbable that the areas are much larger than shown and the drift cover is less at some places, but there are not enough drill records available for exact determinations. As may be seen, the quantities of taconite with 20 per cent or more of iron in the magnetically recoverable condition range from 100,000,000 to 200,000,000 tons in each area. At greater depth than 200 feet the hematite becomes rarer and the ores contain the original amount of magnetite. Figure 10 is an actual cross section through the central part of the range. It illustrates how the magnetite bodies follow the dip of the beds.

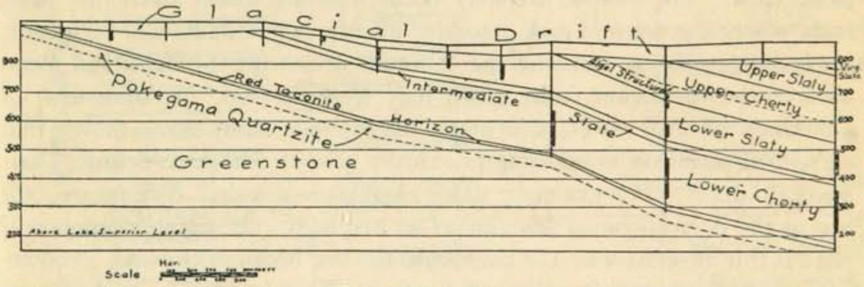


FIGURE 10. CROSS SECTION THROUGH CENTRAL PART OF THE MESABI RANGE SHOWING SUBDIVISIONS OF THE BIWABIK FORMATION AND ABUNDANCE OF MAGNETITE

It has been known for some time that the glacial drift is thinner above the Lower Cherty division than above the Upper Slaty division. In other words, the drift cover becomes thicker as a rule toward the south side of the iron-bearing formation. This fact is especially important for future exploration of magnetite bodies.

It was the practice in former years to keep only part of the drill cores in order to save storage room. It seems highly desirable to save all of the cores for future reference. Such a policy would undoubtedly repay the property owners and operators ultimately. Another common practice has been the dumping of strippings on the portions of the iron-bearing formation containing low grade ore and magnetite. It would be to the advantage of future generations to place the dumps on rocks older than the iron-bearing formation wherever possible.

CHAPTER VI

THE HEMATITE-LIMONITE DEPOSITS

ORES AND THEIR CHARACTERISTICS

In the papers by Winchell, Spurr, Leith, and Wolff the Mesabi ores are described in detail. According to Wolff[1] there are three kinds of ore: (1) a high grade blue or brown ore averaging, dry, 59 per cent of iron; (2) a medium grade brown or yellow ore averaging, dry, 55 to 56 per cent of iron; and (3) a low grade yellow or brown ore averaging, dry, about 50 per cent of iron.

The blue ore is a Bessemer ore found in the Lower Cherty division, in the Upper Cherty division, and in parts of the Lower Slaty division. The brown ore occurs in the various divisions except possibly in the Lower Cherty division. The yellow ore occurs at the top and, in parts of the range, at the bottom of the Lower Cherty division. The ore at the top is easily recognized where it is in contact with the red intermediate paint rock. The yellow ore may occur also anywhere above the paint rock, where the original rock consisted mainly of greenalite and carbonate.

It is possible to correlate the different ores with the unaltered members of the formation from which they were derived.[2] Examination of thousands of drill cores, and much microscopic study have shown that certain minerals on weathering practically always change to definite alteration products. For example, much magnetite in a drill core means blue ore in the corresponding horizon of an ore body. If a larger amount of slate is interlayered with the magnetite the ore becomes brown. Predominating greenalite or siderite in the rock, on the other hand, nearly always produces yellow ore. Much slate with the greenalite may make the yellow ore derived from them non-merchantable. Very lean greenalitic taconite, as it occurs in most parts of the Upper Slaty division, very rarely yields a commercial lean yellow ore. Black slate alters to ore only under exceptional conditions. Usually it forms the paint rock which is high in alumina and correspondingly low in iron.

Mineralogically stated, we may say that, in the decomposition of taconite, magnetite yields martite. Hematite remains unchanged. Greenalite and siderite alter to limonite which is brownish yellow when finely divided. Ferromagnesian minerals, which usually carry the iron contained in the slaty phases, yield limonite on decomposition, though it seems to be the rule that aluminous slates alter to hematite paint rock.

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[1] Wolff, J. F., Recent geologic developments of the Mesabi Iron Range, Minnesota: Lake Sup. Min. Inst., 1917, pp. 245-47.

[2] Gruner, J. W., *op. cit.*

Minerals in iron formation before weathering		Minerals in iron formation after weathering	Kind of ore
Virginia Slate		Slate or light colored paintrock	
Upper Slaty	Amphiboles Greenalite Slate Chert	Limonite Paint rock	Yellow ore
Upper Cherty	Amphiboles Chert Magnetite	Limonite Martite	Brown and blue ore
	Algal structures	Cherty boulders	
	Chert Magnetite Hematite Some slate	Martite Hexegonal hematite Paint rock	Blue and brown ore
Lower Slaty	Amphiboles Magnetite Slate	Limonite Martite Paint rock	Brown and yellow ore
	Amphiboles Greenalite Slate	Limonite Paint rock	Yellow ore
	Intermed. slate	Paint rock	
Lower Cherty	Greenalite Carbonate Amphiboles Chert Magnetite	Limonite Some Martite	Yellow and brown ore
	Chert Magnetite Some amphiboles and carbonates	Martite Some limonite	Blue and brown ore
	Slate	Paint rock	
	Chert Hematite Slate	Hematite Paint rock	Brown and yellow ore
Pokegama Quartzite		Quartzite stained by iron oxide	

FIGURE II. DIAGRAM SHOWING KINDS OF MINERALS AND ORES DERIVED FROM TACONITE BY WEATHERING

The alumina itself combines with silica and water and forms kaolinite. These changes are shown in Figure 11, which shows an ideal case of alteration.

It was stated that blue ore occurs in three different divisions of the iron formation. The question arises whether it is possible from the physical characteristics of the blue ore, to identify the subdivision of the iron-bearing formation from which it is derived. It is believed that with some exceptions a fairly accurate determination can be made. The blue ore of the Lower Cherty division is coarser than most of the other blue ore, and it has very heavy, hard layers in it which are not straight but irregular and rough, and usually close together. They represent the originally magnetic layers of the irregularly banded taconite. The blue ore from the Upper Cherty division also contains layers but the layers are more porous and therefore lighter in weight. They are relatively smooth besides being comparatively straight and easily broken by hand. They represent original bands of a somewhat more evenly banded primary material.

The blue ore which is found in the Lower Slaty division in the central part of the range may be in part so similar to that of the Lower Cherty that it cannot be distinguished, but a great deal of it is finely banded. The bands are due to very narrow straight layers of hematite which formerly alternated with fine bands of silica. The latter have been removed, but the original structure has been fairly well preserved.

With regard to the wash ores of the western part of the range it is possible to use the same classification, if one bears in mind that the sandy silica still present gives a much lighter color to the ore. This silica is in the form of minute quartz grains, as can be seen with the aid of the microscope. It is possible that much of the cement between these quartz particles was originally a carbonate, which is more abundant in the unweathered cores on the western end of the range than farther east.

SHAPES AND STRUCTURES OF ORE BODIES

From the standpoint of the engineer ore bodies may be classified into the trough shaped ore bodies, fissure ore bodies, and flat lying ore bodies. This classification was given by Wolff.[3] To quote from his paper:

> While the trough ore body is the typical one, there are two other types, namely, the flat-layered body and the fissure-type ore body. The former is either the remnant left by the erosion of a former trough-body or it is an ore layer continuing down the dip from a trough-body. Usually a layer has a rock (slate) capping. The fissure-type ore body is an incompletely developed trough-body and is usually associated with a larger trough ore body.

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[3] Wolff, J. F., Trans. Lake Sup. Min. Inst., 1917, p. 236.

The most important type is the trough shaped body. In size it varies from that of a large fissure type to some that have a length of nearly one mile, a width of 1000 feet, and a depth of 200 to 400 feet. At some places two or more troughs run parallel for a distance, then converge and ultimately unite into one body. Some of the troughs intersect. These troughs are formed by the leaching of the silica out of the taconite and the creation of much pore space. The porous residual masses of iron oxides are unable to support the overlying burden of ore and rock and slump, with the consequent elimination of a large part of the pore space. As the original bedding planes are preserved to a considerable extent in spite of the movement of the ore downward, there is formed an easily recognizable synclinal structure of the ore between the rock walls which remain in their original position. Figure 12 is an ideal cross section through such a body.

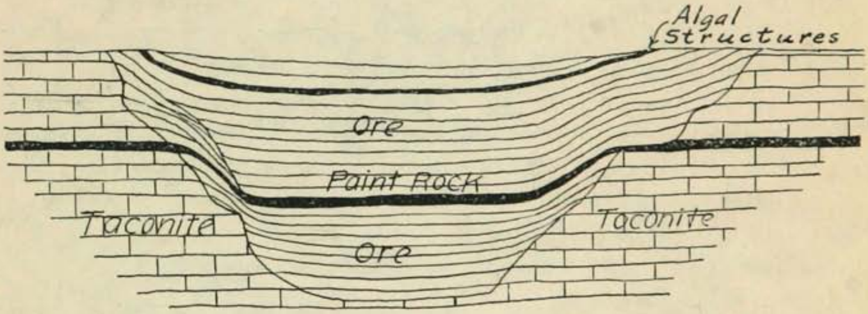

FIGURE 12. IDEAL CROSS SECTION THROUGH A TROUGH ORE BODY SHOWING SLUMPING OF ORE

The slump in the ore bodies is very considerable.[4] In a vertical column of solid taconite, originally 100 feet high, the shrinkage amounts to 40 feet if all the taconite is converted to ore. In other words, a thickness of 60 feet of ore is formed from 100 feet of taconite. There is some variation, of course, for slaty taconite, which undergoes less leaching and therefore less slumping than cherty taconite.

Paint rock layers in the ore at the edge of the trough ore bodies frequently form ideal planes along which slipping will take place. Such planes then resemble real slickensided fault planes characterized by gougelike material. Leaching has commonly affected a much larger area of taconite at the top of an ore body than near the bottom. This results in the narrowing of bodies toward the bottom. The slump under such

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[4] Leith, C. K., and Mead, W. J., U. S. Geol. Survey Mon. 52, p. 188.

conditions may be steplike and characterized by terraces or offsets as shown in Figure 12. The direction and elongation of the troughs is practically always parallel to one of the major sets of jointing of the taconite.

The fissure ore bodies are very similar to the trough shaped bodies in every respect except size. The fissure bodies are also parallel to joint sets and were formed by the leaching of the taconite along joint fissures. Slumping is observed in them, but on a smaller scale than in the trough bodies depending upon the width and depth of the fissure body. The width may be only 2 or 3 feet, or even less, and the depth as much as 50 feet. The length may exceed 200 feet. These fissures do not necessarily reach the contact of the iron-bearing formation with the glacial drift. In places the ore body may have a roof of unleached taconite, and may not have slumped where the fissure is narrow.

Naturally the fissure bodies are commonly arranged in parallel lines like the joints which determined their position. Since there are several joint sets which intersect each other, fissure ore bodies also commonly intersect one another at corresponding angles. The best example of this type (Fig. 13) may be seen in the Malta pit near Sparta. Every intermediate stage between fissure bodies and trough bodies may be observed on the Mesabi Range. The numerous rock islands or horses seen in the larger pits represent the still unweathered taconite between former fissure bodies. There seems to be no doubt, then, that the trough body originated from fissure bodies by prolonged leaching between the fissures till most of the taconite had been converted into ore.

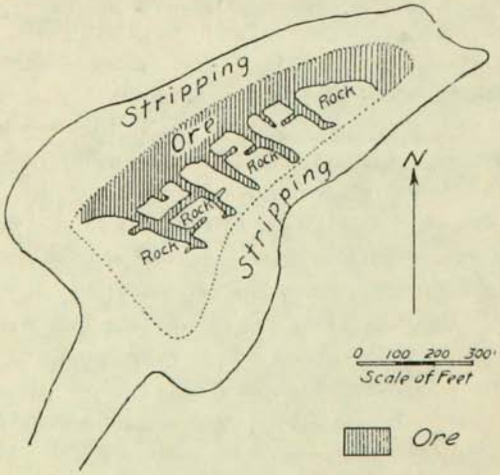


FIGURE 13. SKETCH PLAN OF FISSURE ORE BODIES IN MALTA PIT NEAR SPARTA

The flat lying ore bodies have been described by Wolff as "troughs cut off." As the name implies, they are of relatively great horizontal extent as compared with their thickness. In outline they are very irregular. Slumping, while present, is not conspicuous because the ore bodies are shallow and their transitions to the unleached taconite walls are gradual. It appears that leaching in these bodies followed chiefly the bedding planes of the sediments, while in the fissure and trough bodies leaching was most pronounced along the vertical joints. Due to the nature of the deposits it is impossible, however, to make any more specific statement. Many of the wash ore bodies of the western part of the range are flat lying bodies.

POSITION OF ORE BODIES IN THE IRON-BEARING FORMATION

In exploration work, only that part of the iron-bearing formation is included in the ore body which is commercially valuable. Much taconite, however, has undergone the same alteration though it is not far enough altered to form ore.

As previously reported, there is only a little ore south of the northern boundary of the Virginia slate. Where ore is discovered under the Virginia slate the slate is thin and highly decomposed to paint rock, which is very light in color on account of the small amounts of iron oxides in it. The thick Virginia slate being impervious to leaching solutions protected the iron-bearing formation effectively. Slaty phases of the Biwabik formation as a rule are too thin to have been of much influence in the guiding of solutions. They do not form the footwall or roof of ore bodies except in a few deposits. Usually the paint rock is highly fractured so that it is not impervious to solutions. In a few deposits, however, it appears as if the Intermediate Slate had prevented solutions from passing from the Lower Cherty division upward to the Lower Slaty, for at places yellow ore is found under the paint rock and taconite above the paint rock.

All other attempts to correlate the upper or lower limits of ore bodies with certain beds of the Biwabik formation show that the bottom and top of an ore body usually are very irregular, except that glacial drift commonly overlies a flat surface of ore. At a few places ore bodies extend into the Pokegama quartzite to a depth of several feet. Small vertical fissure bodies following joints may be traced between the flat lying beds for considerable distances, but then the roof above the ore fissure practically always shows some leaching and oxidation of the iron-bearing minerals to limonite and hematite.

LOCAL STRUCTURES OF THE ORE BODIES

For the discussion of local structures it is convenient to divide the range west of Mesaba into four groups:

1. The eastern group, the deposits between Gilbert and Mesaba.
2. The east central group, those between Gilbert and Mountain Iron inclusive.
3. The west central group, the deposits between Mountain Iron and a line half way between Keewatin and Nashwauk.
4. The western group, the deposits around and west of Nashwauk.

THE EASTERN GROUP

A number of rather irregularly shaped deposits belong in this group. Their longer axes seem to lie commonly in a northwest direction, which corresponds to the direction of prominent jointing, N. 40° to 50° W. The size of the deposits is relatively small with the exception of the Stephens and Biwabik properties. The structure of the Biwabik deposit is controlled by the east-west fault to which it is parallel. A number of decomposed dikes have been found in the various deposits. In the Stephens, one strikes northeast, and in the Miller, another has a similar trend. In the Mohawk, a dike strikes northwest; in the Belgrade, the direction of a dike is N. 30° to 40° W. The strike of the dike in the "Corsica-80" is not known.

The deposits seem to show no preference for any particular horizon of the iron formation, but are as common in the higher as in the lower divisions. The transition from the ore to unaltered country rock is fairly abrupt, resulting in steep rock walls as far as can be seen in the present open pits. Quartz veins with which manganese oxides are associated were observed in some of the mines. Their trend is rather irregular and frequently obscure.

THE EAST CENTRAL GROUP

In this group belong some of the deepest and most highly concentrated ore bodies of the range. There are two reasons for such depth and concentration: the iron formation reaches its greatest thickness in this area, and in addition to a Lower Cherty division with a high primary iron content, the formation possesses an unusually thick and rich Lower Slaty division. (See Pl. II.)

The longer axes of most of the large ore bodies lie in the direction of major joints and are perpendicular to the strike of the Biwabik formation. The walls of the bodies are unusually steep and sharply defined. The transition from ore to rock is accordingly abrupt and at some places in the lower divisions magnetic oxides reach to within a few inches of the walls of the ore. The ore bodies are either of the trough or fissure type. Commonly the bodies are not confined to one of the four divisions of the formation but penetrate two or more. The Leonidas and Missabe Mountain deposits, for example, extend vertically through the whole iron-bearing formation.

The algal structures can be studied especially well in this area and are a great aid in the working out of the structure of the deposits. (See Pl. IX.) In a few of the smaller mines, such as the Ordean, the algal structures seem to form the bottom of the ore. Perhaps the very dense and lean algal bed acted as guiding plane to solutions. In the Alpena Mine the algal structures are exposed in the nearly vertical strata between two ore bodies (now mined out). This bed is sharply folded into a monocline (Fig. 4). Here, as in many other places on the range, there is a noteworthy amount of secondary quartz which cements joint cracks and bedding planes. Such cemented beds are especially massive and resistant to weathering.

More conspicuous than these joint fillings are large quartz veins in this area which were mentioned on page 27. They seem to have had some influence on the structure of the ore bodies. In the Eveleth district a vein beginning in the northwest wall of the Leonidas pit was traced for nearly half a mile into the Adams pit. (See Pl. IX.) It follows the major jointing N. 80° W. Especially noteworthy is the fact that it marks the limit of the slump of the ore body on the south side for some distance. The beds north of the vein show the general dip of the iron-bearing formation, while south of it there is a decided break and steep dip to the center of the ore body. Another outcrop, possibly a continuation of the vein just described, is exposed in the East Adams and Fault pits. Here it is in the north wall of the ore body.

A similar vein, 12 to 24 inches wide, and striking N. 20° W. may be seen in the east wall of the Commodore pit. As it appears now after removal of the ore, this vein formed the boundary between the ore and the taconite. There is also a quartz vein 4 feet thick in the underground workings of the Hobart Mine at Gilbert. This vein strikes N. 40° W. parallel to major jointing. It is reported that practically no ore occurs on the northeast side of the vein.

A vein or dike 15 feet wide is exposed in the Fayal pit. It is parallel to the axis of the body from the southwest to the northeast wall. Where the "vein" itself cannot be seen, its place is taken by a shattered zone in the iron ore very high in manganese and intermingled with small pieces of kaolin. Under the microscope the quartz of this vein looks like highly altered igneous rock in a few places. It is stated that this dike did not penetrate upward through the Intermediate Slate.

Large irregular quartz veins were observed also in the Biwabik and Mountain Iron pits.

THE WEST CENTRAL GROUP

The chief difference between the east central group and the west central group is the strike of the deposits. The trend of the large majority of the trough bodies in the west central group is either northwest or west, therefore neither perpendicular nor parallel to the strike of the Biwabik formation as a whole, but usually parallel to one of the major joint sets. The ore bodies are relatively not so deep as those east of Mountain Iron, but many are of great areal extent. Several parallel troughs may form one large body. The deposits are found in the lower as well as in the upper divisions. The algal structures make an excellent horizon marker as far west as Chisholm. Between this town and the Hull-Rust pit at Hibbing, they are only locally well developed.

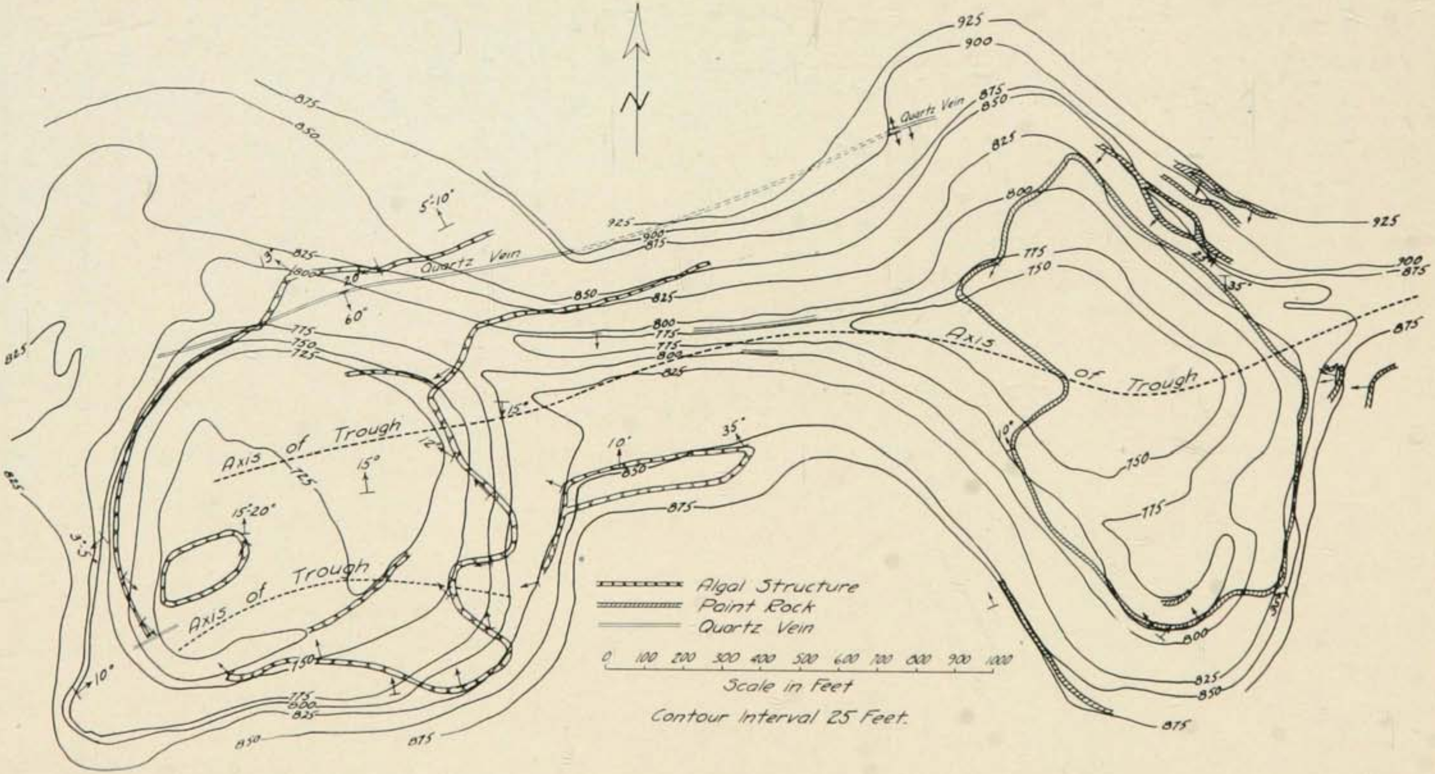
Unlike the group farther east, the transition from ore to wall rock is not quite so sharp in this group, with the result that the steep, sharply defined rock walls are not so common. Fissure bodies are not conspicuous. There is, however, plenty of evidence that leaching followed the jointing, though it was more extensive horizontally than vertically. Large quartz veins are found in some mines. Crystallized native copper was found in one of the large veins which cuts through the Dean and Wanless mines near Buhl.

Cretaceous conglomerate ore becomes important in some mines. It forms almost conformable layers with those of the iron-bearing formation and may reach a thickness of 30 and more feet, but usually is much thinner. The size of the pebbles of the conglomerate varies between that of coarse sand and boulders one foot in diameter. The smaller well-polished pebbles are limonite as a rule; the larger may be pieces of taconite. The conglomerates are generally little sorted, though there are exceptions. The cement between the pebbles is sandy or shaly material. Frequently it has a conspicuous scarlet or brick red color. Such conglomerate is high in phosphorus.

THE WESTERN GROUP

In this group belong most of the wash ore bodies that are mined at the present time. They are relatively shallow and usually belong to the class of flat lying bodies. Solutions probably advanced more along the bedding planes than along the joints in these deposits. Typical deep trough structures are rarely, if ever, developed, probably because the ore was leached only partially of silica and therefore has less pore space and shows less slumping. The transition from ore to wall rock is still more gradual than in the west central group. The trend of the ore bodies does not correspond to any particular set of joints. The deposits tend to be parallel to the strike of the formation. The Intermediate Slate which loses some of its usual distinctness is the only horizon marker.

PLATE IX



MAP OF ADAMS AND LEONIDAS PITS, SHOWING THE STRUCTURE OF THE TROUGH ORE BODIES AND THE POSITIONS OF THE INTERMEDIATE PAINT ROCK AND THE ALGAL STRUCTURES

Below it there occurs a characteristic lean, friable material which is too low grade in some places to make a wash ore. It is nearly white in many places and crumbles readily. Its thickness varies between a few inches and 30 feet.[5]

APPLICATION OF DETAILED STRATIGRAPHY IN THE EXPLORATION OF HEMATITE-LIMONITE ORES

It might appear that the exploration of the Mesabi Range has progressed to the stage at which the introduction of new horizon markers can be of little, if any, value. But even now, when most of the large ore bodies have been found, a careful study of the horizon markers in the drill cores and a plotting or replotting of them on the exploration sheets may reveal much new information. This study should also be extended to include the pits and underground workings of properties which have not yet been drilled thoroughly.

The value of the horizon markers is based on three considerations:

1. Originally before ore bodies existed the horizon markers which are now in the ore were at higher elevations; that is, they were in the same general planes and had the same general dip as their unleached continuations in the hard taconite which surrounds the ore bodies. Therefore, their slump practically always signifies the presence of ore beneath them. (See Pl. IX.)

2. As a rule, a given thickness of unleached taconite when changed to ore will yield a fairly constant thickness of ore on slumping. For example, 100 feet of taconite has slumped to yield 60 to 65 feet of ore in the larger deposits. In the wash ores about 70 to 75 feet of ore would represent an original taconite layer 100 feet thick. Therefore the amount of vertical slump of a horizon marker usually indicates the amount of ore beneath it.

3. The horizon markers like the Intermediate Slate, the algal structures, and the red basal taconite are practically always preserved even in ore highly concentrated and they are relatively easily recognized.

The mapping of the algal structures, for example, supplied knowledge of structure at one property. In examining shallow drill holes in the upper half of the somewhat weathered Biwabik formation it was found that they penetrated the algal bed. On plotting the algal bed a considerable sag or synclinal structure was noticed, which had escaped the attention of former explorers. Deeper drilling is justified in this area.

At many places it was possible by comparison of the height of a horizon marker in the walls of pits with the elevation of the same marker

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[5] Some of the wash ore contains a little magnetite mixed with martite grains, but the amount of magnetite found in testing six 40-pound samples is negligible.

in the ore to estimate the amount of ore underlying the marker. When these results were checked it was found that they were fairly accurate. There probably is no other iron-bearing district in which horizon markers would give more important and reliable information than on the Mesabi Range. But this knowledge of position and size of ore bodies is not the only information derived from detailed stratigraphy. The kind of ore to be expected at a certain depth is equally important and can be foretold by the study of the horizon markers. It was pointed out on page 34, and in Figure 11, that each phase of taconite on leaching produces a distinct type of ore. As the longitudinal section, Plate II, gives the phases of taconite and the thickness of each throughout the range, it also indicates the kind of ore and the possible maximum or minimum thickness that may be expected in a certain area.

CHAPTER VII

THE ORIGIN OF THE IRON FORMATION[1]

PREVIOUS VIEWS ON THE ORIGIN[2]

H. V. Winchell[3] in 1892 concluded that the iron formation consists of chemical and mechanical oceanic deposits. N. H. Winchell[4] in 1899 accepted Spurr's[5] hypothesis that the iron formation was a glauconite-like formation, but later he[6] proposed that the greenalite resulted from a volcanic sand. Leith[7] objects to Spurr's glauconite hypothesis and thinks that colloidal silica may have combined with ferrous iron to form greenalite. He concludes: ". . . that the greenalite granules may possibly have developed directly from the abstraction, through the agency of organisms of iron from solution in sea water, whence it was contributed from adjacent land areas. . . ."

Van Hise and Leith[8] in 1911 concluded that all the important Lake Superior iron-bearing formations are very similar in origin. They believe that a very large part of the iron and silica was contributed to the ocean directly, either by magmatic emanations from igneous rocks (probably poured out on the ocean floor), or by rapid decomposition of basic igneous rocks, due to their contact, while hot, with sea water. Van Hise and Leith, however, think that considerable portions of the iron and silica may have been derived from the land by processes of ordinary weathering.

Wolff[9] believes that the bulk of the iron oxides in the Biwabik formation are in the same "chemical state" now as that in which they were laid down, and that greenalite was relatively unimportant as original mineral. Grout and Broderick[10] in discussing the deposition of ferruginous cherts, are inclined to believe that deposition took place in shallow water, mainly by organic agencies.

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[1] This chapter is an abstract of a paper published in Econ. Geol., vol. 17, 1922, pp. 407-60. Descriptions of chemical experiments and references will be found there.

[2] For older literature see Leith, C. K., *op. cit.*, p. 31.

[3] *Op. cit.*, pp. 138-46.

[4] Winchell, N. H., The geology of Minnesota: Geol. Nat. Hist. Surv. Minn., Final Rept., vol. 4, 1899, p. 359.

[5] *Op. cit.*, p. 242.

[6] Winchell, N. H., Structural and petrographic geology of Minnesota: Geol. Nat. Hist. Surv. Minn., Final Rept., vol. 5, 1900, pp. 990, 997.

[7] *Op. cit.*, pp. 242, 254, 257.

[8] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior Region: U. S. Geol. Survey Mon. 52, 1911, p. 499.

[9] *Op. cit.*, pp. 233-35.

[10] *Op. cit.*, p. 46.

In a discussion of the iron formation it is necessary to consider (1) the solution of iron and silica in natural and artificial solvents, (2) the sources of the iron and silica for the formation of the Biwabik iron formation, and (3) the deposition of the iron and silica.

SOLUTION OF IRON AND SILICA

AMOUNTS OF IRON AND SILICA IN NATURAL WATERS

The average river water contains less than one part per million of iron.[11] Sea waters also are very low in iron. This suggests that such waters are an inadequate source for the deposition of a great iron-bearing formation. There are, however, some analyses showing more iron. The rivers of Brazil and other parts of South America carry from 2 to 7 parts of Fe_2O_3; this is a relatively large percentage of their total mineral content, which is usually low.[12]

Swamp waters commonly contain more iron than other surface water.[13] Moore[14] reports three waters with 47 to 61 parts of Fe_2O_3 per million, either from lakes in which iron ores are in the process of formation, or from creeks tributary to such lakes. Simpson[15] mentions a small stream which contains 17 parts per million of iron and much organic matter. It is noteworthy that organic matter seems to be always present in surface waters that contain much iron.

Spring waters often carry iron, but such waters are probably not the sources of the large iron-bearing formations, on account of their limited quantity. Silica is relatively abundant in many rivers and spring waters.

EXPERIMENTAL DATA ON THE SOLUTION OF IRON AND SILICA[16]

Experimental data show that iron minerals are soluble in weak acids but not in alkaline solutions. Carbonic acid (H_2CO_3) takes iron into solution as a bicarbonate of iron, but this bicarbonate is not stable in the presence of air which oxidizes the iron to the ferric form. Ferric iron is precipitated as limonite as a rule. It appears, therefore, that large amounts of iron cannot be carried by river waters as bicarbonate. Other acids, like sulphuric acid, which plays an important part in many geologic processes, do not enter into the transportation of iron over long distances.

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[11] Clarke, F. W., The data of geochemistry: U. S. Geol. Survey, Bull. 695, 1920.

[12] Clarke, F. W., *op. cit.*, pp. 90-92. See also analyses *B* and *E*, p. 77; *G*, p. 93; and *E*, p. 105, which contain unusual amounts of iron and organic matter.

[13] Endell, K., Der Säuregehalt des Moorwassers: Jour. prakt. Chem., vol. 82, pp. 414-22, 1910. See also Endell, K., Uber die chemische und mineralogische Veränderung basischer Eruptivegesteine bei der Zersetzung unter Mooren: Neues Jahrb. Min., Beilage Bd. 31, 1911, pp. 1-54.

[14] Moore, E. J., The occurrence and origin of some bog iron deposits in the district of Thunder Bay, Ontario: Econ. Geol., vol. 5, 1910, pp. 528-38.

[15] Simpson, E. S., Notes on laterites in western Australia: Geol. Mag., vol. 49, 1912, p. 405.

[16] For a full discussion see: Econ. Geol., vol. 17, 1922, pp. 422-46.

It was pointed out that organic matter seems always to be present in river water carrying appreciable amounts of iron in solution. Chemical experiments[17] show that waters containing organic matter (commonly called humic acid) are powerful solvents of iron. Still more important, however, is the fact that iron dissolved in such waters cannot be entirely precipitated by inorganic means to which we often attribute its deposition. Iron bacteria and other micro-organisms seem to be the only efficient natural agencies of precipitation of iron in waters containing organic matter.

Silica in silicates is dissolved by dilute acid as well as alkaline solutions.[18] Quartz and chalcedony, however, are less soluble than silicates. Organic solutions, as used in experiments in the solution of iron, are also strong solvents of silica. Silica may be transported long distances as a colloid in solution, especially if organic matter is present.

SOURCES OF IRON AND SILICA FOR THE IRON FORMATION

ORIGINAL EXTENT OF THE IRON FORMATION AND AMOUNT OF IRON INVOLVED

For the discussion of the sources of iron and silica deposited in the Biwabik and Gunflint formations it is necessary to make an estimate of the original extent of the formations. The total length of the Mesabi and Gunflint ranges from a point west of Pokegama Lake to North Lake, Canada, is about 175 miles. The widths of the ranges vary considerably. The Biwabik formation has been identified in a drill hole at a depth of 2200 to 2700 feet, about five miles south of the town of Biwabik. The area of the Biwabik formation not covered by the Virginia slate has been estimated as 135 square miles; that of the Gunflint formation does not exceed 10 square miles. Assuming much erosion and the gradual thinning out of the formations, the total area originally covered by the Biwabik and Gunflint formations may be conservatively estimated as 5000 to 10,000 square miles. If, as supposed by some, the iron formation extended across Lake Superior, then the area covered was much greater. Probably 550 feet would represent the average thickness of the exposed Biwabik formation. For a sheetlike sediment with an area of 5000 to 10,000 square miles, an average thickness of 330 feet may be a fair estimate. The explored portion of the iron-bearing formation contains an average of a little more than 25 per cent iron and has a specific gravity of 3.0 to 3.1. The total amount of iron in 10,000 square miles of formation 330 feet thick would be nearly 2,000,000 million metric tons.

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[17] Gruner, J. W., *op. cit.*, p. 422.

[18] See also Lovering, T. S., The leaching of iron protores: Econ. Geol., vol. 18, 1923, pp. 523-40.

POSSIBILITY OF DIRECT CONTRIBUTION OF SILICA AND IRON FROM MAGMA

Association of Lavas with Chert

Van Hise and Leith[19] based their argument, that probably the greater part of the silica and iron of the iron-bearing formations had been contributed directly from the magma or from hot lavas poured out on the ocean floor, on the frequent association of basic igneous flows with chert and jasper. Their best evidence seems to be the discovery, near Hudson Bay, of chert and jasper grading into basalts of Algonkian age. Leith[20] says that this jasper must have been deposited "under conditions differing radically" from those observed today.

In California, radiolarian cherts are associated with basalts, some of which are spheroidal and ellipsoidal.[21] Geikie[22] mentions a number of occurrences of pillow lavas and interstratified cherts. Of the cherts of the Lower Silurian (Arenig group) of Scotland he says:[23]

> It thus appears that during the volcanic activity there must have been intervals of such quiescence, and such slow, tranquil, sedimentation in clear, perhaps moderately deep water, that a true radiolarian ooze gathered over the seabottom. . . . Thus the great depth of strata which elsewhere constitute the Upper Arenig and Lower and Middle Llandeilo subdivisions is here represented by only some 60 or 70 feet of radiolarian cherts.

It has recently been pointed out by Davis[24] that pillow lavas are also intrusive, and not necessarily submarine flows. Davis presents many arguments in favor of, and against, the direct contribution theory of silica. Dewey and Flett[25] believe that pillow lavas are usually accompanied by radiolarian cherts, and that the silica of the cherts was derived directly from the magma.

Scrivenor,[26] on the other hand, thinks that this hypothesis is not applicable to many East Indian cherts which are probably algal cherts, but lays stress on the removal of silica by tropical weathering.

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[19] *Op. cit.*, p. 499.

[20] Leith, C. K., An Algonkian basin in Hudson Bay—a comparison with the Lake Superior basin: Econ. Geol., vol. 5, 1910, p. 242.

[21] Ransome, F. L., The eruptive rocks of Point Bonita: Bull. Dept. Geol. Univ. California, vol. 1, 1893, p. 109.

Lawson, A. C., Sketch of the geology of the San Francisco Peninsula: Fifteenth Ann. Rept. U. S. Geol. Surv., 1895, p. 420.

[22] Geikie, A., The ancient volcanoes of Great Britain: London, 1897, vols. 1 and 2.

[23] *Op. cit.*, vol. 1, p. 198.

[24] Davis, E. F., The radiolarian cherts of Franciscan group: Bull. Univ. Calif., vol. 11, 1918, p. 404.

[25] Dewey, H., and Flett, J. S., On some British pillow-lavas and the rocks associated with them: Geol. Mag., vol. 48, 1911, pp. 202-9, 241-48.

A recent paper by E. Sampson (The ferruginous chert formations of Notre Dame Bay, Newfoundland: Jour. Geol., vol. 31, 1923, pp. 571-98) favors the inorganic origin of cherts. Their association with lavas is pointed out.

[26] Scrivenor, J. B., Radiolaria-bearing rocks of the East Indies: Geol. Mag., vol. 49, 1912, p. 247.

Magmatic Springs or Submarine Lava Flows Possible Source of Silica

If direct contribution of silica from the magma is assumed, the present writer favors the hypothesis of the derivation of silica from hot submarine lava flows rather than from magmatic springs, for two reasons:

1. If we assume a siliceous water with 1000 parts of SiO_2 per million (a much more concentrated solution than those of geysers), over 524,000 cubic miles of solution would have been necessary to transport the silica of the Biwabik formation (of 10,000 square miles area and 330 feet thickness). Such a quantity would cover an area the size of the United States to a depth of 900 feet. The magma which could furnish so much aqueous solution would probably have to be 20 to 40 times 524,000 cubic miles in volume,[27] the equivalent of a cone with an altitude equal to the radius of the earth, and a base 10,000 square miles in area.

2. On the other hand, if we imagine hot lavas poured out on the ocean floor, there must have been tremendous chemical reaction and physical disintegration. Disintegration would not contribute colloidal silica directly to the water; but diatoms (and probably other organisms), as has been shown by Murray and Irvine,[28] can abstract silica from detrital material.

The chief objection to the theory of contribution of silica to the sea by hot lavas, in the case of the Biwabik and Gunflint formations, is that contemporaneous igneous rocks have not been found within a considerable distance. Van Hise and Leith[29] noted this, and thought that the remarkable uniform character of the Biwabik and Gunflint formations was possibly due to their distance from contemporaneous igneous activity. The iron-bearing formation of the Gogebic Range,[30] which was in or near the area of igneous activity, is much like that of the Biwabik. The iron-bearing formation of Hudson Bay[31] and the Belcher Islands,[32] in which basalts occur with the sediments, is also very similar to the Biwabik formation.

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[27] Gautier's figures for the amount of combined water in granite are about 2.5 to 3.0 per cent in "The genesis of thermal waters and their connection with volcanism," abstract by F. L. Ransome in Econ. Geol., vol. 1, 1906, p. 691.

[28] Murray, J., and Irvine, R., On silica and siliceous remains of organisms in modern seas: Proc. Roy. Soc. Edinburgh, vol. 18, 1891, p. 245.

[29] *Op. cit.*, p. 517.

[30] Hotchkiss, W. O., Geology of the Gogebic Range and its relation to recent mining developments: Eng. and Min. Jour., vol. 108, 1919, p. 501.

[31] Leith, C. K., An Algonkian basin in Hudson Bay: Econ. Geol., vol. 5, 1910, p. 227.

[32] Moore, E. S., The iron formation on Belcher Islands, etc.: Jour. Geol., vol. 24, 1918, pp. 412-38.

Contribution of Iron from Hot Springs

The evidence seems to show that iron and silica in the ratio found in the Biwabik formation cannot be carried in any but very weak solutions. Clarke[33] cites many analyses of spring waters high in silica and others high in iron, but no water high in both. As a matter of fact, these two elements seem to be mutually exclusive except in very weak solutions. In acid waters which are high in iron, aluminum seems to be equally or more abundant, but this element is only sparingly present in the iron formation. Silica is present to only a very minor degree in the more acid waters, as would be expected and as has been demonstrated by many experiments.[34] It is difficult to conceive of an acid ocean or even of an acid, large inland sea. The acidity would quickly be reduced by the presence of many base-forming elements in the rocks, and unless the acidity were reduced temporarily or periodically, no iron could be precipitated. Of course, we could imagine acidity around the submarine hot springs and neutralizing conditions at some distance, where deposition occurred. Even then the probable presence of much aluminum and other metals in the solutions and the small amounts of silica would probably preclude the precipitation of ferruginous chert.

Solutions charged with carbonic acid can carry iron and silica. Iron as bicarbonate could be present in such cold solutions to the extent of 100-150 parts per million,[35] if other salts were absent. Their presence as bicarbonates necessarily would repress the solubility of iron.[36] In hot solutions bicarbonates can exist only when pressure prevents the escape of carbon dioxide. It is obvious that this gas would have been expelled as soon as the solutions reached an open, probably shallow basin. Iron would have been precipitated immediately. Even if only a part of the carbon dioxide had escaped, from either hot or cold solutions, it would have resulted in the formation of normal carbonates like those of sodium[37] and magnesium. These are alkaline toward litmus, and precipitate iron from solution. It probably would have necessitated special currents in the sea to carry these precipitates a hundred or more miles.

Assuming that a bicarbonate solution with 100 parts of iron per million (which would require 300 parts of SiO_2 to be in the ratio of iron to silica in the cherts—more silica than probably can be held in such solution except under great pressure), we find that it would take about 630,000 cubic miles of solution to furnish as much iron as is assumed to

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[33] *Op. cit.*, pp. 174-95.

[34] Leuhner, V., and Merrill, H. B., The solubility of silica: Jour. Am. Chem. Soc., vol. 39, 1907, p. 2630.

[35] Smith, H. J., On the equilibrium in the system—Ferrous carbonate, carbon dioxide and water: Jour. Am. Chem. Soc., vol. 40, 1918, pp. 879-85.

[36] Repression of solubility by a common ion.

[37] Smith, Alex., General chemistry for colleges: New York, 1920, p. 462.

be in the Biwabik formation. An area the size of the United States could be covered with this volume to a depth of over 1000 feet. It does not appear probable that so much aqueous solution could come from a limited area.

Derivation of Iron from Hot Lavas

Van Hise and Leith[38] heated fresh basalt to 1200° C. and then plunged the mass into salt water. The violent reaction ensuing produced principally sodium silicate, but relatively little iron. They say that "the experiment does not seem to suggest an adequate source for the iron in this reaction." Igneous rocks in hot or cold water react alkaline,[39] for potassium and sodium silicates (water glass) are strongly alkaline. Therefore, it seems improbable that much iron will go into solution when hot lavas come into contact with sea water, even if some hydrochloric acid should be formed in the reaction of hot lava with sea water. A little iron may have been in the colloidal state, or adsorbed by the colloidal silica formed in such a reaction. It is probable that colloidal or adsorbed iron gives to jasper the red or brown color, but this coloring, if due to colloids, could also be formed in other ways.

Attention is called by Van Hise and Leith[40] to the association of basalts and ironstone in Great Britain. These clay-ironstone ores are usually associated with coal beds or vegetable remains.[41] Some of them show that molluscan life flourished on the spot at the time of formation. Geologists generally have not hesitated to connect the origin of these iron ores with the decomposition of rocks by weathering. It is probable, however, that porous, fresh basalts and tuffs on land furnished a considerable portion of the iron by their rapid decomposition, especially in the presence of abundant plant life. Chert does not occur to any extent with clay-ironstone and associated basalt.

Combination of Iron and Silica

A greenalite-like substance has been produced in the laboratory by Van Hise and Leith.[42] They state that silicic acid and a ferrous salt in the absence of air produce no precipitate, but that "ferrous sulphate reacts directly with solutions of silicates of the alkalies," forming a precipitate of silicate matter similar to greenalite.

When the solutions are very dilute silica probably does not exist as alkali silicate, but as colloidal silica. The colloid should not react with

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[38] *Op. cit.*, p. 516.

[39] Clarke, F. W., *op. cit.*, p. 475.

Cushman, A. S., The effect of water on rock powders, U. S. Dept. Agr., Bur. Chemistry, Bull. 92, 1905, p. 9.

[40] *Op. cit.*, pp. 508-9.

[41] Geikie, A., *op. cit.*, vol. 2, p. 204; vol. 1, p. 181.

[42] *Op. cit.*, p. 521.

ferrous salts in the absence of air to form a ferrous silicate. Soluble magnesium salts, which are plentiful in the ocean, should also be expected to form insoluble silicates with alkali silicates if iron salts did.[43] Yet only 3 to 5 per cent of magnesia are combined with the greenalite. It is probable, therefore, that in dilute solutions the reactions are more complicated than those of simple double decomposition, possibly similar to adsorption.

POSSIBILITY OF DERIVATION OF IRON AND SILICA BY WEATHERING

Leaching of Rocks

Under certain conditions, on weathering of igneous rocks, iron oxides remain in place as some of the most stable residual constituents. Under other conditions part of the iron is carried away, though this removal may not keep pace with the abstraction of the more soluble constituents of the rocks.[44] Van Hise[45] gives a table on rock decomposition in which the loss of Fe_2O_3 compared with Al_2O_3 as zero varies between 8.78 per cent and 88.84 per cent. In humid regions the loss of iron is much greater than in arid ones.

In tropical countries decomposition of rocks is rapid and extends to great depth, sometimes as deep as 200 to 300 feet.[46] Branner[47] states that in the forest covered portions of Brazil decay is greater than in the parts devoid of dense vegetation. Decomposition, however, is not limited to any particular region. Organic acids are important factors in the decomposition, according to Branner. In many places the laterites probably represent only a small part of the iron from the decomposed rocks. Many analyses show that, under the same conditions of laterization, titanium oxide and alumina are much more stable than iron oxide. These conditions have been described as follows:[48]

1. Alternating wet and dry seasons.[49]
2. Tropical heat with concomitant abundant vegetation.

As to the importance of abundant vegetation there has been some disagreement. Holmes[50] states that organic growth is usually absent where

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[43] Van Hise and Leith, *op. cit.*, p. 521.

[44] Merrill, G. P., Rocks, rock-weathering and soils: New York, 1913, pp. 197-211.

Leith, C. K., and Mead, W. F., Metamorphic geology: New York, 1915, pp. 1-24.

Lang, R., Geologisch-mineralogische Beobachtungen in Indien: Zentralblatt Min., 1914, pp. 257, 513, 545.

[45] Van Hise, C. R., A treatise on metamorphism: U. S. Geol. Surv. Mon., 1904, p. 515.

[46] Derby, O. A., Note on the decay of rocks in Brazil: Am. Jour. Sci., vol. 27, 1884, p. 138.

[47] Branner, J. C., Decomposition of rocks in Brazil: Bull. Geol. Soc. Am., vol. 7, 1896, pp. 255-314.

[48] Maclaren, M., On the origin of certain laterites: Geol. Mag., vol. 43, 1906, pp. 536-47.

Simpson, E. S., Notes on laterite in western Australia: Geol. Mag., vol. 49, 1912, p. 402.

[49] Campbell states that laterites also form in continually wet climate: Econ. Geol., vol. 18, 1923, p. 197.

[50] Holmes, A., The lateritic deposits of Mozambique: Geol. Mag., vol. 51, 1914, pp. 532-33.

[51] Campbell, J. M., Laterite, its origin, structure and minerals: Mining Mag., vol. 17, 1917, p. 178.

lateritic deposits occur, and implies that organic matter may be unfavorable to their formation. Campbell,[51] however, who probably expresses the opinion of the majority of the investigators, thinks that sterility of the soil sets in due to the formation of a hard crust of iron oxide at the surface when laterization is nearly completed. This oxide is deposited there from iron-bearing ground water reaching the surface. Changes in water table are also a factor. Simpson[52] remarks that "Primary laterite is a true efflorescence" brought to the surface by capillarity.

It seems to the present writer, then, that no hard iron oxide crust could form near the surface, if marked seasonal changes do not exist.[53] This seems to be borne out by the fact that only areas which are relatively small, compared with the great basins of many tropical rivers, are covered by laterite deposits. Most of the iron over the large basins must, therefore, be removed in some form or other by the surface and ground waters, probably with the aid of organic solutions.

Iron and Silica Carried by Waters Rich in Organic Matter

Attention was called to the large amount of silica and iron carried by rivers rich in organic matter (p. 46). The following analyses of the water of the Amazon River and its tributaries have been taken from Katzer[54] and recalculated to parts per million:

TABLE I

ANALYSES OF WATER FROM AMAZON RIVER AND TRIBUTARIES

(Parts per million)

	Amazon[a]	Amazon[b]	Paraná-mirim	Maecuru	Xingu	Tapajos	Itapacurú-mirim
SiO_2	9.4	12.2	8.8	19.2	9.6	9.2	9.0
$Al_2O_3 + Fe_2O_3$	3.6	6.2	9.5	6.6	3.9	2.8	6.8
Organic matter	5.7	8.9	6.3	5.8	11.8	12.2	11.6
Total solids at 110°	39.0	54.5	59.7	52.6	57.2	50.5	64.1
Suspended organic matter	37.2	61.4	100.8	96.7	56.3	62.8	103.2
Suspended inorganic matter	63.2	135.2	111.2	99.6	31.2	28.4	188.4

[a] Amazon River at Obidos at a depth of 26 m.
[b] Amazon River at Obidos at a depth of 0.5 m.

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[52] *Op. cit.*, p. 400.

[53] Lang, R., *op. cit.*, p. 257.

[54] Katzer, F., Grundzüge der Geologie des unteren Amazonasgebietes: Leipzig, 1903, p. 45.

Figures for CaO, MgO, K_2O, and Na_2O have been omitted. Lime is the only constituent which is abundant besides silica and iron. Al_2O_3 and Fe_2O_3 were not separated in the analyses, but there is little doubt that most of the "$Al_2O_3 + Fe_2O_3$" is iron oxide. This appears very probable when these analyses are compared with those of other South American and tropical streams in which iron is almost always greatly in excess over aluminum. These analyses seem to be in accord with experimental evidence of the writer, in which it was shown that iron up to 8.5 parts per million was exceedingly stable in organic solutions. A similar agreement is found between the amount of silica held by the tropical rivers, and that contained in the organic peat solutions of the laboratory.[55]

According to Katzer,[56] the Amazon River normally has a flow of 120,000 cubic meters per second, 200 miles from its mouth. During flood time this volume may increase several fold. If an average of three parts of iron per million is assumed for the water (which would be in keeping with the analyses), the Amazon River in 176,000 years could carry about 2,000,000 million metric tons of iron to the sea—the amount assumed for the Biwabik formation (p. 47). The amount of silica carried would be correspondingly large. If, however, the Biwabik formation extends to the Gogebic Range, as is postulated on a previous page, then it must be assumed that the period of its deposition required a longer time.

In a basin the size of that of the Amazon River, the iron from rock of a thickness of only a few feet would be needed to furnish the stated amount. We may postulate conditions assumed by others[57]—many fresh basalt flows and tuffs on land, possibly with much pyrite like that in the greenstone of the Lake Superior region. Under such conditions enough iron could be dissolved from a much smaller area than the Amazon Basin without there being a decomposition to a greater depth than is common.

Reasons for Favoring Weathering Hypothesis in Case of the Biwabik Formation

The following additional reasons favor the hypothesis that iron and silica were derived from land and transported by rivers rich in organic matter:

1. A steady supply of material over a long period would be assured by such a source.

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[55] Gruner, J. W., Econ. Geol., vol. 17, 1922, pp. 423-46.

[56] *Op. cit.*, p. 38.

[57] Van Hise and Leith, *op. cit.*, pp. 512, 514.

2. No abnormally acid or basic solutions would have been necessary to carry the salts of iron and silica to their places of deposition without suffering premature precipitation.

3. Carbon dioxide, derived from the oxidation of organic matter on the sea floor, could prevent the deposition of calcium and magnesium carbonate to a certain extent by the formation of soluble bicarbonates.

4. The average sedimentary rock contains less magnesia and more lime than the igneous rock from which it is derived.[58] The Biwabik formation contains more magnesia than lime. Experiments dealing with adsorption by organic and inorganic matter seem to show that magnesia is adsorbed more rapidly than, and probably in preference to, lime. Moreover, the fact that iron and magnesium show more tendency to associate, both in sedimentary and igneous rocks, than iron and calcium is shown by the abundance of ferromagnesian minerals especially in old rocks.

5. If we consider rivers rich in organic matter as the transporting agency, it does not seem necessary to account for anything except the lack of lime in the iron formation. There is no reason why calcium and the larger part of magnesium carried to the sea by such rivers could not have been deposited in a different, probably a deeper, part of the ocean. The occurrence of almost pure limestone certainly proves that there has been separation of the constituents of river waters. Moreover, there exists a gradation between iron-bearing formation and calcareous rocks on the Gunflint Range and the east end of the Gogebic Range.[59]

6. The Biwabik and Gunflint formations show no signs of volcanic disturbance, either sudden uplift or sinking of the sea floor during sedimentation. A slow, steady subsidence probably took place. If great volcanic activity had occurred within a hundred miles, some indications might be expected in the structure of the sediments.

7. Lavas were extruded during Keewatin time in greater quantities than during any succeeding period, yet the greatest development of iron-bearing formations occurred during the Upper Huronian. This suggests, at least, that these lavas were the source of iron-bearing sediments not so much during the time of their extrusion, as during their exposure to weathering much later.

8. There exist large iron-bearing formations which are not associated with larger masses of contemporaneous basic igneous rocks. The pre-Cambrian (?) Itabira formation of Minas Geraes, Brazil, is such a primary sediment.[60]

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[58] Leith and Mead, *op. cit.*, p. 84.

[59] Van Hise and Leith, *op. cit.*, p. 515.

[60] Leith, C. K., and Harder, E. C., The hematite ores of Brazil and a comparison with the hematite ores of Lake Superior: Econ. Geol., vol. 6, 1911, p. 670.

DEPOSITION OF IRON AND SILICA

ORIGIN OF OÖLITES AND SIMILAR GRANULES

As much of the iron and silica of the Biwabik iron formation is found in the shape of granules of the size of oölites, their origin becomes one of the chief problems in a study of the deposition of the formation.

Link's[61] experimental work has shown that calcium carbonate, when precipitated as finest mud, will form oölites. Essentially the same thing is reported by Vaughan.[62] Brown[63] comes to the conclusion that oölites are produced either by algae or similar organisms, or chemically by precipitation. The tendency now is to favor more the organic origin of deposits in cases in which it may be either inorganic or organic, since bacterial action and other micro-organic action are now recognized.[64] It is also possible that inorganic and organic formation of oölites can go on side by side, or that organisms cause precipitation of colloids, while the actual shaping of oölites from these colloids is due to the "tendency of the droplets forming during the separation of the dispersed phase of an emulsoid to coalesce," as expressed by Bucher.[65]

The cause of the formation of concentric layers in oölites has been studied by Schade,[66] who comes to the conclusion that in a deposit consisting mostly of colloidal material (gel), the tendency for the formation of concentric rings is less than in a mixture of crystalloids and colloids. Bucher[67] thinks that the rate of formation of the spherulites is important, those forming rapidly being more or less without definite structure. He also says that "the amount of other substance thrown out simultaneously with, and mechanically enmeshed in, the growing structure" has some effect on the structure.

In the Biwabik formation are three kinds of granules:

1. Typical oölites made up of concentric layers. They consist of red jaspery or black graphitic (?) material with a center of the same material or of fine-grained chert. They do not make up one per cent of all the granules. Spurr[68] and Leith[69] have mentioned them.

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[61] Link, G., Die Bildung der Oolithe und Rogensteine: Neues Jahrb., Beilage Bd. 16, 1903, pp. 495-513.

[62] Vaughan, T. W., Remarks on the geology of the Bahama Islands and on the formation of the Floridian and Bahaman oölites: Jour. Wash. Acad. Sci., vol. 3, 1914, pp. 302-4.

[63] Brown, T. C., Origin of oölites and the oölitic texture in rocks: Bull. Geol. Soc. Am., vol. 25, 1914, p. 772.

[64] See, for example: Drew, G. H., Papers from the Tortugas Laboratory, Carnegie Institution, Washington, vol. 5, 1914, p. 44.

Wethered, E. B., The formation of oölite: Quart. Jour. Geol. Soc., vol. 51, 1895, p. 205.

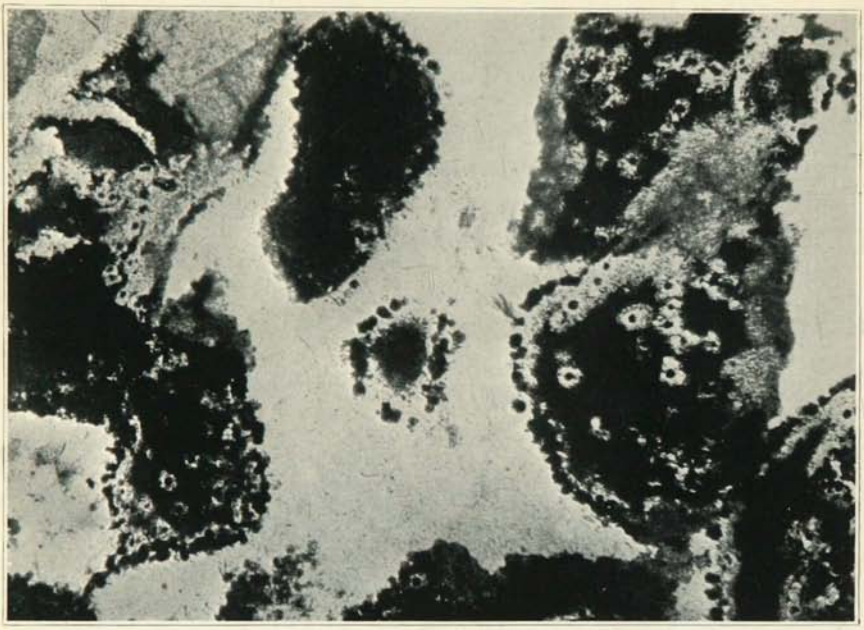
[65] Bucher, W. H., On oölites and spherulites: Jour. Geol., vol. 26, 1918, p. 594.

[66] Schade, H., Zur Enstehung der Harnsteine und ähnlicher konzentrisch geschichteter Steine organischen und anorganischen Ursprungs: Zeitschr. Chem. u. Ind. d. Kolloide, vol. 4, 1909, pp. 175-80, 261-66.

[67] *Op. cit.*, p. 594.

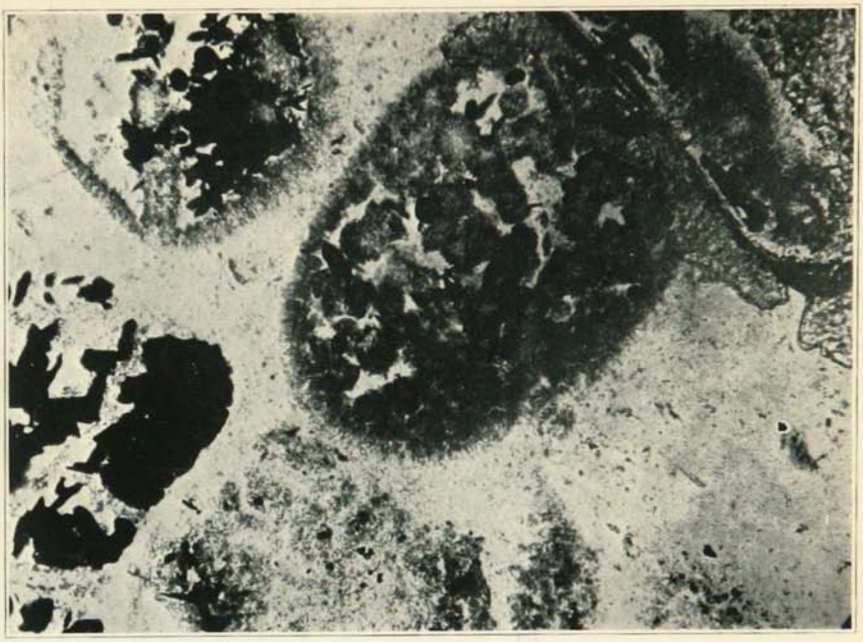
[68] *Op. cit.*, Pl. VII, Fig. 2.

[69] Op. cit., Pl. XIII.



A. GROUPS AND CHAINS OF MINUTE CONCENTRIC RINGS OF CHERT IN GRANULES OF GREENALITE. MATRIX OF LARGE GRANULES IS CHERT. NUCLEI IN SMALL RINGS AND SURROUNDING MATRIX OF GREENALITE-LIKE SUBSTANCE. SOME RING STRUCTURES NOT VISIBLE. x 88

B. STRUCTURES SIMILAR TO A. CHERT RINGS SURROUNDED BY "DUSTY" BLACK RINGS. NUCLEI OF SAME MATERIAL. SOME ROUND DUSTY BLACK AREAS WITHOUT RINGS. COMPARE WITH PLATE XI, B. x 88



C. LARGE GRANULES (IN MATRIX OF CHERT) WITH SMALL CONCENTRIC STRUCTURES OF HEMATITE "DUST" AND CHERT. HEAVY BLACK AREAS ARE MAGNETITE AND HEMATITE. NEEDLES OF SPECULAR HEMATITE CUT THE CONCENTRIC STRUCTURES. COMPARE WITH PLATE XI, B. x 165

D. PART OF STRUCTURE IN FIGURE 16. FROM "ALGAL STRUCTURE" HORIZON OF GUNFLINT RANGE. DARK AREAS IN PICTURE ARE LIGHT GREEN. X 220

2. Typical greenalite granules and their alteration products. No internal structure is visible in these "oölites." Their alteration products are many times more abundant than the unaltered granules, and at many places cannot be distinguished from the alteration product of the kind of structure described under (3).

3. Bodies which have the size and outlines of greenalite granules, but which possess a visible internal structure. They appear to be made up of groups of chains of minute concentric rings which are commonly of chert but may be of a dark graphitic (?) dust or exceedingly minute specks of hematite. Their centers and the matrix in which these rings are embedded are practically always of the same material, but different from the rings themselves. For example, Plate X, A shows chert rings with greenalite centers and matrix. Black centers (probably not magnetite) with a white chert ring and another "dusty" black one around it may be seen in Plate X, B. A somewhat similar structure is that of Plate X, C. In it the dark centers are missing. Spurr[70] noticed these structures and has an excellent illustration of the greenalite phase of them in his report. He thought that they represented a decomposition phase of "glauconite." Leith[71] also illustrates them and says that they suggest organic structures. In the Clinton ores in which similar structures occur, they are "clearly due to the replacement of a shell with regular structure," according to Leith. Wethered[72] shows some similar structures in oölitic limestone, and attributes them to organisms.

Moore[73] also observed similar structures in the granules of the iron formation of the Belcher Islands. These are of remarkably uniform size (0.03-0.04 mm.). Due to the difference in degree of alteration, they may be composed of different minerals as in the larger greenalite structures. The fact that they are preserved only in fine-grained or almost amorphous material, and not in the more crystallized granules, indicates the primary origin of these structures. It is usual to find them penetrated by magnetite, hematite, or amphibole crystals. In places they may form rings around apparently massive greenalite. When such greenalite granules were examined carefully with strong artificial light, it was sometimes noticed that the apparently homogeneous mass showed faint outlines of these minute structures.

About 200 thin sections from the Biwabik and Gunflint ranges were examined; in many of the less altered ones these structures were seen.

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[70] *Op. cit.*, Pl. VI, Figs. 1, 2.

[71] Mon. 43, p. 117 and Pl. XIV, A, B.

[72] *Op. cit.*, Figs. 5, 7.

[73] Moore, E. S., The iron formation on Belcher Islands, Hudson Bay, etc.: Jour. Geol., vol. 24, 1918, pp. 412-38.

In most of them (except those from the East Mesabi) at least traces of the structures were preserved. In the light of the other evidence presented on page 57, they are attributed to the work of micro-organisms, and may be called cell structures. Unless all of the greenalite granules are made up of cell structures or some other form of organism, we may conclude that the following conditions probably would be favorable for the formation of granules without internal structure:

1. Relatively rapid deposition of colloidal precipitates.
2. Lack of strong tendency to crystallize, on account of the colloidal character of silica and ferrous and ferric organic compounds and hydroxides.
3. Absence of fragmental grains which could have formed the nuclei of oölites.

STRUCTURES RELATED TO GREENALITE GRANULES

Many iron ore formations show granular structures similar to greenalite, but most of them differ in one respect—that the majority of their granules are true oölites with concentric ring structures. In most of the formations, however, there occur a relatively small number of granules which have not concentric structures, and therefore resemble typical greenalite structures.

In the Wabana oölites[74] other features also are noteworthy. Boring algae have been found in the oölites, and Hayes thinks it possible that they were active in the production of hematite.

In the Biwabik formation we find hematite- and greenalite-like minerals together. Hematite is commonly taken to be an alteration product of the greenalite. In the Wabana oölites hematite and chamosite occur in alternating concentric rings. It seems fairly certain that such hematite is not an alteration product of chamosite. It would be difficult to believe that one concentric layer could have remained in one state of oxidation while adjacent ones were changed to some other state, unless there was a conspicuous original difference. Ferrous silicate and ferric oxide (hydroxide), both primary according to Smith,[75] also occur in the Clinton ores. There is no reason, then, why a *ferric* oxide, where associated with greenalite, could not have been an important primary mineral in the Biwabik formation.

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[74] Hayes, A. C., Wabana iron ore of Newfoundland: Canada Geol. Surv. Memoir 78, 1915.

[75] Smith, C. H., Jr., On the genetic significance of ferrous silicate associated with the Clinton iron ores: University of State of New York, Albany, 1919, p. 190.

The similarity in shape of the greenalite and Clinton granules has been emphasized by Leith.[76] McCallie[77] describes Clinton ore granules with a nucleus of a greenish mineral which he thinks is similar to greenalite.

Glauconite resembles greenalite closely in shape and internal structure. Spurr[78] thought that greenalite is a potassium-poor variety of glauconite. Leith objected[79] to this, because aluminum is also absent from the greenalite, and because detrital mud, always associated with glauconite, is not found with greenalite. It is probable, however, that greenalite granules form by processes similar to those active in the making of glauconite. According to Clarke,[80] this process may be adsorption. So far, however, no generally accepted theory has been advanced for the formation of glauconite.[81]

MICRO-ORGANISMS IN AND NEAR THE BIWABIK FORMATION

Lower organisms seem to have been widespread as early as Archean time.[82] Their presence in pebbles at the base of the Pokegama quartzite and in chert which fills cracks in the conglomerate has been described on page 6. Fossiliferous chert of the same kind also fills joint cracks and irregular areas in the underlying graywacke and greenstone. It is thought that this chert filling the joint cracks and areas is at least as old as the bottom beds of the Biwabik formation.[83]

The majority of the thin sections of the chert show structures which resemble organic structures. These structures, however, may often be only faintly outlined. Plates XI and XII show iron bacteria, blue-green algae, and bacilli. Plate XIII pictures similar algae. Figures 14 and 15 are other organic structures. All of them are found in the same kind of chert though in different specimens and places. They show that life was abundant in the sea in which the cherts were deposited.

In studying the algae of Plate XI, B and C, and the organisms shown in Plates III and IV and in Figures 14 and 15, and comparing them

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[76] Mon. 43, p. 251.

[77] McCallie, S. W., Report on the fossil iron ores of Georgia: Geol. Surv. Georgia, Bull. 17, 1908, p. 174.

[78] *Op. cit.*, p. 242.

Hummel, K., Die Entstehung eisenreicher Gesteine durch Halmyrolyse: Geol. Rundschau, vol. 13, 1922, pp. 49-77; Review in Econ. Geol., vol. 18, 1923, p. 612.

[79] *Op. cit.*, pp. 242, 254.

[80] *Op. cit.*, pp. 513-14.

[81] Murray J., and Renard, A. F., Voyage of the challenger; deep sea deposits: 1891, p. 389.

Murray, J., and Hjort, J., Depths of the ocean: London, 1912, p. 189.

Collet, L. W., and Lee, G. W., Recherches sur la galuconie: Proc. Roy. Soc. Edinburgh, vol. 26, 1906, pp. 259-62.

Andree, K., Uber Sedimentbildung am Meeresboden: Geol. Rundschau, vol. 8, 1917, pp. 59-61.

[82] Gruner, J. W., Algae, believed to be Archean: Jour. Geol., vol. 31, 1923, p. 146.

[83] Gruner, J. W., Econ. Geol., vol. 17, p. 418.

with the peculiar structures of Plate V, which show a faint resemblance in places to some irregular greenalite granules, it is observed that there seems to exist a gradation from the perfect algae of Plate XI (which form a network) to groups which seem to consist only of concentric rings, or round spots (like some in Plate XI, B) without any connecting portions or sheaths between them. These simpler rings or spots usually seem to be a little larger than the cross sections of the algae in Plate XI, C. They resemble the rings in the greenalite structures (Pl. X, A, B, and C) very much, and strongly suggest a relation in origin.

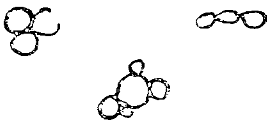


FIGURE 14. SKETCH OF ORGANIC STRUCTURES REPLACED BY SILICA OR LIMONITE. X 100. SLIDE M 932

New organisms were also found in the cherts of the algal structure horizon of the Gunflint and Biwabik formations. Bacilli (there is little doubt that they are such) of the same kind as those shown in Plate XII, B were found in two specimens from the algal structures of the Upper Cherty division near Hibbing. They are of the same shape and size as those in Plate XII, B, but are less numerous.

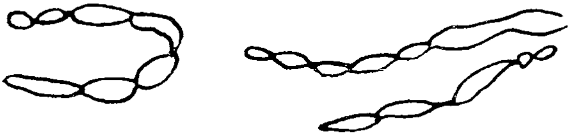
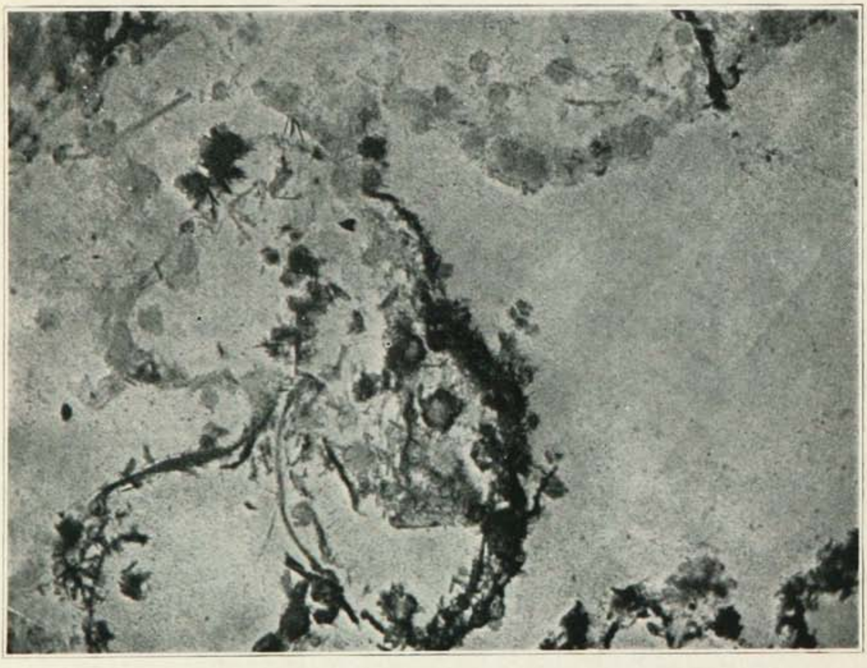


FIGURE 15. SKETCH OF RING AND CHAIN STRUCTURES OF BROWNISH OR GREENISH MATERIAL. X 150. SLIDES M 943 a, M 944 b, M 947 a

In this connection may be mentioned rods of silica (about 10 to 12 microns long) which were observed by Bleicher[84] in oölites of the Minette ores of France. These rods are said to resemble bacteria. In a specimen from the algal structure horizon of the Upper Cherty division on the Gunflint Range, the algae shown in Figure 16 and in Plate X, D were

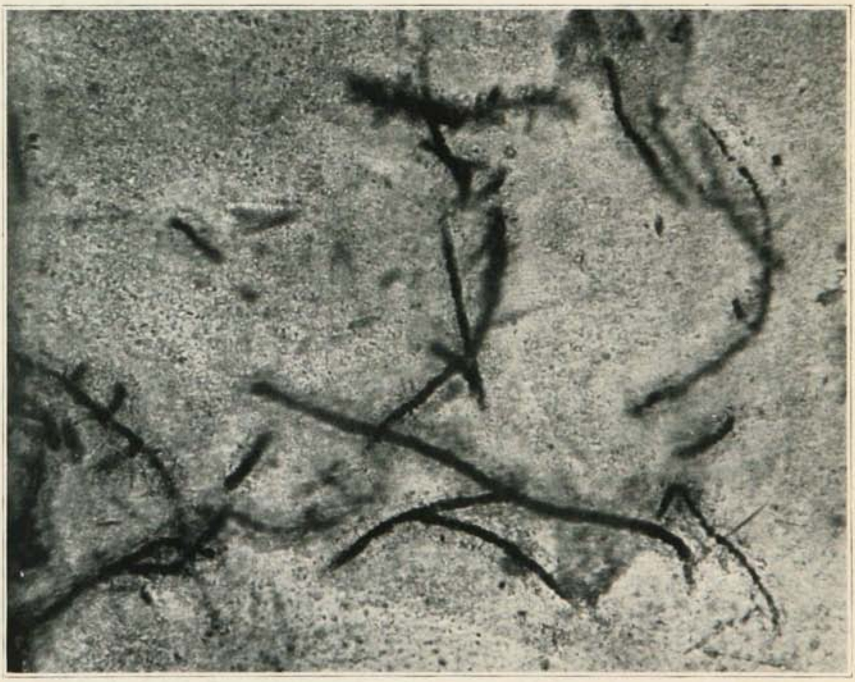
[84] Quoted by Van Werweke, L., Bemerkungen über die Zusammensetzung und die Enstehung der lothringisch-luxemburgischen oolithischen Eisenerze: Zeitschr. prak. Geol., vol. 9, 1901, p. 396.

A. IRON BACTERIA AND ALGAE IN CHERT. MOST BACTERIA OUTLINED BY HEAVY SHEATHS OF BROWN COLOR. X 77



B. ANOTHER VIEW OF A. ALGAE ARE PROMINENT. NOTE RESEMBLANCE OF ROUND STRUCTURES TO THOSE IN GREENALITE STRUCTURES. PLATE X DARK COLORED STRUCTURES ARE BROWN. X 88

C. ALGAE RESEMBLING MICROCOLEUS (PROF. JOSEPHINE TILDEN) IN CHERT. SAME SLIDE AS A. CHERT AND ALGAE ARE PRACTICALLY OF THE SAME COLOR. x 340



D. IRON BACTERIA RESEMBLING CHLAMYDOTHRIX FROM SAME SPECIMEN AS ALGAE IN C. x 340

found. There still exists some doubt as to whether these plants belong to a higher class than algae.[85]

CHEMICAL AND ORGANIC PRECIPITATION

It was pointed out on page 46 that iron can be taken into solution in several ways, but that it is precipitated too rapidly to be transported long distances. However, in solutions containing small amounts of organic matter, iron is not precipitated completely by inorganic agencies. Silica is also very stable in solutions containing organic matter and it seems that it cannot be precipitated completely by ordinary inorganic means from such solutions.

The existence of iron bacteria and algae at the time of deposition of, and in, the Biwabik formation makes considerable organic precipitation highly probable. Drew[86] has shown the importance of bacilli in organic precipitation of limestone. Algae, radiolaria, and diatoms cause the deposition of silica. Iron bacteria, as shown by Harder, are some of the most efficient precipitating agents of iron. According to him[87] and to Ellis,[88] all traces of iron bacteria may easily become altered beyond recognition. Mumford[89] believes that a certain type of bacillus can precipitate iron under anaerobic conditions, when some of the precipitate will become partially reduced to the ferrous state (not sulphide). If this is the case, it might offer an explanation for the occurrence of a part of the ferrous iron. Though iron bacteria of the higher type have not been found in sea water, this does not preclude their existence there. Neither are we sure that the Biwabik formation was deposited in sea water.

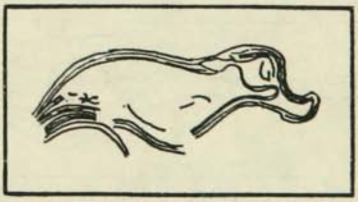


FIGURE 16. TRACING OF AN ORGANIC STRUCTURE FROM THE ALGAL STRUCTURES OF THE UPPER CHERTY IN THE GUNFLINT FORMATION. X 80. SLIDE M 561
A PORTION OF THIS ORGANISM IS SHOWN IN PLATE X, D

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[85] The writer wishes to express his thanks to Dr. C. D. Walcott and to Dr. Albert Mann, of the Smithsonian Institute, for examining one of the sections containing fungi-like plants, to Professor Josephine Tilden, Professor C. O. Rosendahl, and Professor F. K. Butters, of the Department of Botany of the University of Minnesota, for the identification of algae and similar structures, and to Professor A. T. Henrici, of the Department of Bacteriology, for identification of the bacteria. Professor Charles Schuchert, of Yale University, also had the kindness to examine the photographs.

[86] *Op. cit.*

[87] *Op. cit.*, p. 80.

[88] Ellis, D., Iron bacteria: London, 1919, p. 169.

[89] Mumford, E. M., A new iron bacterium: Chem. Soc. Jour., vol. 103, 1913, p. 650.

Bacterial action, however, does not mean that inorganic processes did not take part in the precipitation of iron and silica. Temporary conditions may be imagined under which algae and bacteria could not thrive.

Special conditions are required for the separation of mechanical sediments from chemically dissolved or colloidal matter. This separation must depend on physiographic conditions similar to those for the formation of glauconite of which Murray and Renard[90] say that it is found "most characteristically on the continental slopes of high and bold coasts where currents from different sources alternate with the season."

ALTERATIONS OF ORIGINAL SEDIMENT

Grout and Broderick[91] have emphasized certain changes of oxidation, re-solution, and mechanical action which probably took place during deposition. This is illustrated by Figure 17, where a hard slaty layer has buckled and broken in several places. Such breaking may have given rise to intraformational conglomerate. Figure 2 seems to prove that solution went on at the surface of carbonate precipitates, producing the stylolitic surface upon which slate was laid down. Probably most of the organic matter in the precipitates, while still at, or near, the surface, was oxidized to carbon dioxide. This could have caused local re-solution of iron which was then redeposited under different conditions. Such a process may have led to the formation of irregular bands of iron oxides and carbonate, which do not seem at all related to original sedimentation. Many other reactions probably occurred at that time, and some concretions developed.

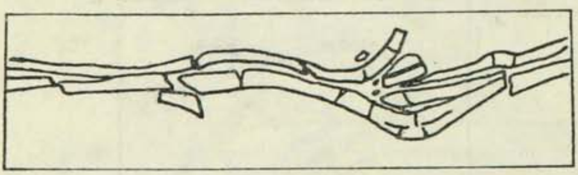

FIGURE 17. SKETCH SHOWING DEFORMATION AND BREAKING OF A DENSE SLATELIKE LAYER

Amphiboles and magnetite were formed, on deep burial of the formation. The ferruginous cherts are the result of this metamorphism. Lately the statement has been made that magnetite in minute dust particles may form as a colloid on the sea bottom.[92] If this actually happens, it probably is on such a small scale that it would not enter seriously into any discussion of the origin of the magnetites of the Mesabi Range.

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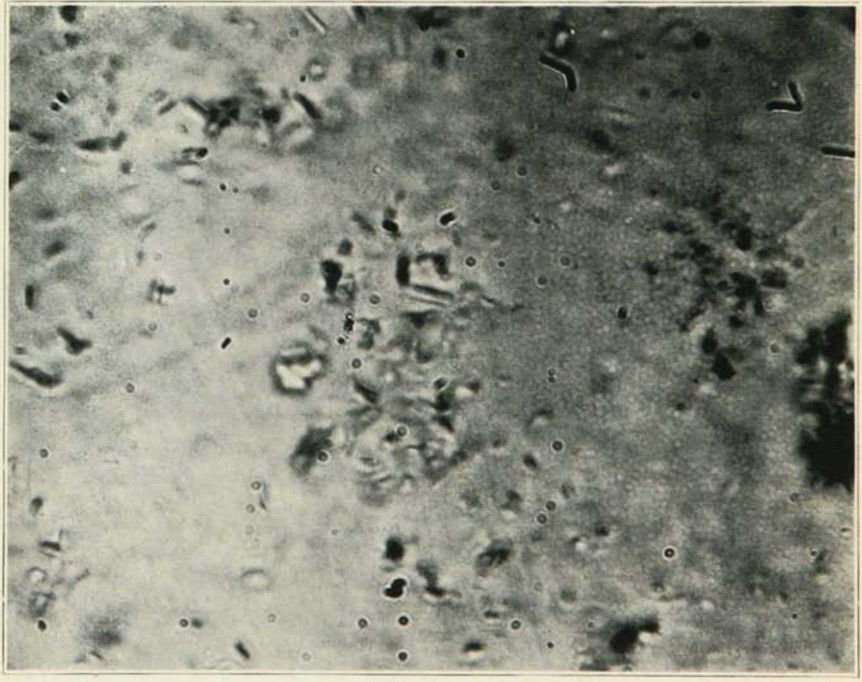
[90] *Op. cit.*, p. 234.

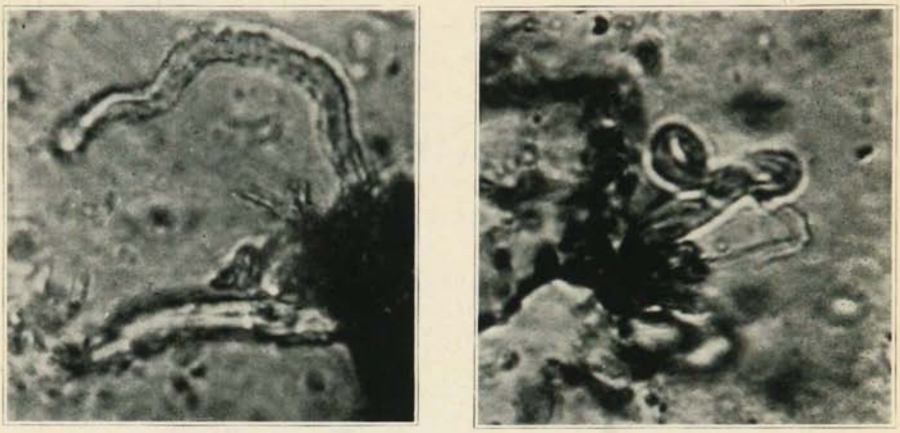
[91] *Op. cit.*, Bull. 17, p. 42.

[92] Berz, K. C., Ueber Magneteisen in Marinen Ablagerungen: Centralbl. Min., 1922, pp. 569-77.

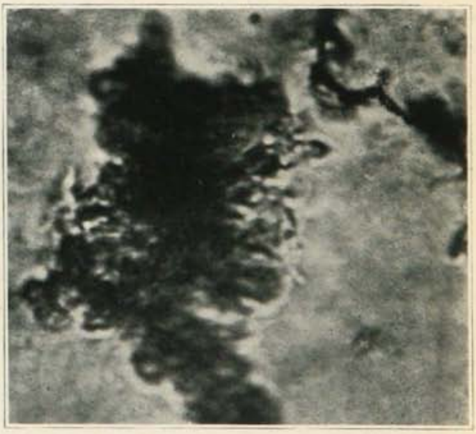
A. IRON BACTERIA FROM SAME SPECIMEN AS PLATE XI. NOTE SHEATH AND CROSS SECTION OF SHEATH IN UPPER RIGHT CORNER. BLACK AREAS BROWN IN SPECIMEN. X 1540



B. BACILLI FROM THE SAME SPECIMEN AS A. MINUTE RODS ROUNDED AT THE ENDS; SOME ARE BENT; UNIFORM IN SIZE AND NUMBERS. ONLY A FEW CAN BE GOT INTO FOCUS AT ONE TIME. THEY ARE WHITE LIKE THE CHERT. X 1540



A, B, AND C SHOW SEVERAL TRICHOMES GROWING FROM A COMMON CENTER



D. IN THIS PHOTOGRAPH THE TRICHOMES ARE
SO NUMEROUS THAT THEY APPEAR
TO BE ONE MASS

BLUE-GREEN ALGAE RESEMBLING INACTIS AND MICROLEUS IN CHERT. THE TRICHOMES (THREADS) REPRESENT THE REAL PLANTS WHICH LIVE IN THE SECRETED SHEATHS SIMILAR TO THOSE SHOWN IN PLATE XI C. x 2200. SLIDE M 931 b

CONCLUSIONS

From the foregoing discussions, the following conclusions may be reached: During Upper Huronian time there existed large land areas in North America which were covered largely with greenstone and basalts. It is probable that fresh extrusive rocks and volcanic tuff and ash were deposited on parts of the land as well as in the sea basins then existing. The climate of the continent was humid. Vegetation of a low form was abundant, and aided in the rapid decay of the rocks. Under these conditions iron, which usually is one of the most stable elements in weathering, went into solution to a large extent, but only in waters with organic colloids was it stable for any length of time in the zone of oxidation. Silica was also dissolved on a large scale. Both iron and silica were carried to the sea by rivers rich in organic matter.

Whether this was a large inland sea or the ocean is a matter of speculation. There is little to indicate that the iron-bearing cherts could not have been precipitated in fresh water. The suspended material carried by the rivers was deposited probably in deltas, while the stable colloids of iron and silica were carried by currents to places of shallow and clear water. Only under exceptional conditions did mechanically suspended material reach these places and become deposited as slate. Such exceptional conditions may have been unusually large floods, and temporary changes in the coast lines.

The precipitation of silica, iron, and part of the organic colloids was caused chiefly by algae and bacteria, which used the organic matter for their life-processes and the inorganic silica or iron for the building of their cells or sheaths. It is also probable that inorganic reactions caused much colloidal silica, iron, and organic matter to be precipitated. By adsorption some of these colloids partly united to form indefinite amorphous iron silicates. These may have been ferrous silicates from the beginning, or may have been ferric at first. Iron hydroxides and silica probably did not form silicates at many places. One reason may have been that the iron was not of the proper valence or in condition to make a silicate.

A large part of the colloidal precipitates assumed the shapes of oölites, differing, however, from typical ones in their internal structure. In many places the granules thus formed seem to be made up of groups of cells; this suggests algae or similar plants. It is thought improbable that all of the granules showing oölitic shape were deposited originally as ferrous silicate. A large portion of them probably consisted of iron oxides, cherts, or carbonates.

A part of the silica contained in the taconite may have been contributed to the sea directly by magmatic springs or hot submarine lava flows. We do not believe, however, that much iron had this origin.

Before a freshly precipitated layer of iron-bearing formation could be buried to any depth, there was considerable alteration of the amorphous material. Re-solution and diffusion in one place and redeposition in another were accompanied by reduction and oxidation of portions of the iron. Most of the organic matter was oxidized to carbon dioxide at this time. On deeper burial, ferruginous chert (taconite) originated by the formation of magnetite, amphiboles, and coarse-grained carbonates from the amorphous minerals and substances.

CHAPTER VIII

THE ORIGIN OF THE HEMATITE-LIMONITE ORE BODIES

The problem of the origin of the ore bodies has been discussed at length by Winchell, Spurr, Van Hise, Leith, and Wolff. In the present report nothing essentially new on this subject is offered. However, some known factors which have a bearing on the origin of the ores may be summarized here.

1. *Structural factors.*—In the previous literature concentration of ore at its present places is supposed to be due chiefly to structural features of the iron formation.

Wolff,[1] who probably expresses the opinion of most geologists, says:

> . . . in every case where the exploration data is complete enough, it has been found that the ore bodies occur where the whole formation has been warped. In the eastern part of the district (Virginia and eastward) the ore bodies are on the crests of gentle anticlines or on axes of combined anticline and syncline. . . . In the central part of the range great broad flexures rather than merely localized ones seem to have determined the locations of the ore bodies. The formation was generally cracked up and the broad structural basins directed the flow of underground waters.

In the present investigation attempts were made to relate ore bodies to original structures of the Biwabik formation. Contour maps and cross sections of the top of the Pokegama quartzite were made to locate any synclines or anticlines. In a few cases the contours seem to show that ore bodies are on anticlines, but about as many are on synclines or even on the limbs of the anticlines.

Field work in the open pits and outcrops is inconclusive on account of the usual slump of the taconite toward the ore bodies. This makes the original structures appear synclinal. There are, however, at least two known examples, the Alpena and Biwabik mines, in which the ore bodies are related to special major structures, a monocline and a normal fault respectively.

Stress has been laid on the importance of impervious layers of the iron-bearing formation in guiding the course of solutions which leached the silica. There is no doubt that this factor is important. An impervious layer, the Intermediate Slate, extends throughout the formation. Great deposits of ore are found above and below it. Along the dip this layer must have been of great importance in the guiding of the leaching solutions. Along the strike, however, it is not so evident that this layer determined the position of ore bodies. The same is true of the Pokegama

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[1] *Op. cit.*, pp. 247-49.

quartzite which acted as an impervious layer even more than the Intermediate Slate. It was just pointed out, however, that the ore bodies do not seem to be situated upon any particular anticlines or synclines of the Pokegama quartzite.

How extensive the fissuring and jointing of the taconite was in the places now occupied by the ore bodies is a matter of speculation. It has been thought that the taconite was more fractured in these places than in the rest of the formation. Observations on the natural outcrops of the whole Biwabik and Gunflint formations show that the taconite is extensively fractured throughout, sufficiently so that solutions could have circulated in it with ease almost anywhere.

2. *Textural factors.*—In the description of the various phases of the taconite, page 10, the difference in their textures and the manner of their alteration to ore was given. On account of this difference some beds were undoubtedly much more susceptible to weathering than others. In the cherty phases of taconite a fine grained sandy material forms at first in the process of decomposition. It is due to the disintegration to such sandy material that washing of the ore on the West Mesabi Range is so successful. The formation of this sandy, friable phase seems to be always an intermediate step in the alteration of taconite to completely leached ore, though not so conspicuous in the central and eastern parts of the range because here it exists usually only at the margins of the ore bodies. It has been removed from the bulk of the ore.

The matrix which originally cemented the sandy alteration phase was probably silica, but there is a possibility that there was more carbonate in the matrix of the taconite now weathered than in that which remained unattacked. Considerable attention was paid to such a possibility, but, due to the nature of the problem, no conclusive results were obtained. It was observed, however, that originally very fine grained, dense phases of slaty taconite containing considerable amounts of carbonate weather to a fine grained, porous product not unlike the ore from the cherty phases except in size of grain.

It is a well-known fact that chalcedony dissolves more easily than quartz. Chert,[2] on the other hand, seems to be attacked more easily than chalcedony by weathering. Observations in the field showed that chert pebbles and chert cementing the conglomerate of the Pokegama quartzite were attacked commonly much more than chalcedony pebbles in the same conglomerate. The chert most "worm-eaten," or decomposed, invariably seemed to be that which most closely resembled the chert in which fossil organisms were found. How rapid this decomposition can be is shown

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[2] In this paper chert may be defined as silica precipitated by organic or inorganic agencies in open bodies of water. The term chalcedony is used for silica deposited in veins and cavities by ground water.

by the finding of porous, cellular chert on glaciated surfaces where decomposition probably occurred after the retreat of the continental glaciers. The writer therefore believes that organic chert breaks down more easily than silica precipitated by inorganic agents, provided recrystallization has not advanced very far. The reason for more rapid recrystallization of some cherts than of others is not apparent. That it has taken place at different rates can, however, be observed in many localities.

3. *Chemical factors.*—The nature of the chemical factors which caused the formation of ore bodies in some places and not in others is not known, but since structural factors and textural ones alone do not seem to account entirely for the positions of the ore bodies, chemical causes must be taken into consideration. It is not probable, however, that the taconite, altered to ore, was very different in chemical composition from the remaining taconite. It may have contained a little more carbonate and possibly a little more organic matter than the unweathered taconite, but as a whole there cannot have been much difference between the phases of taconite. This is shown by the martite[3] in the ore which is about as abundant as magnetite in the taconite.

It has been assumed by most of the previous investigators that alkaline carbonate waters and oxygen brought about the weathering of taconite to ore. This is probably true. Acid waters would not have attacked the silica more than the iron. Meteoric alkaline waters are abundant, but there is no other instance known in which weathering as complete as that of the taconite to ore has been carried to such depths except in other pre-Cambrian formations. Ordinary laterization rarely is complete at a depth of more than 40 feet, though in this process silicate rocks much more easily attacked are weathered. Conditions of weathering, therefore, must be assumed to have been somewhat different from those known to us today. If the climate had been humid it seems that oxidation would hardly have reached to such depth below the ground water level. The change from magnetite to martite must be extremely slow for microscopic examination of taconite from glaciated outcrops in the Virginia Horn has shown that the magnetite in it has not been changed noticeably by weathering, not even to the depth of a fraction of one millimeter. The taconite of these outcrops has probably been exposed without a cover of glacial drift or soil for centuries.

It seems, then, that the problem of the enrichment of the ore deposits is only partially solved. Conditions and factors in the iron formations of the Lake Superior region, even in one single formation, are so varied that it is difficult to place the emphasis on any particular set of conditions and factors without being in serious disagreement with other investigations.

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[3] Gruner, J. W., *op. cit.*, Econ. Geol., vol. 17, 1922, p. 1.

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