The University of Minnesota

MINNESOTA GEOLOGICAL SURVEY
William H. Emmons, Director

BULLETIN NO. 17

THE MAGNETITE DEPOSITS OF THE EASTERN MESABI RANGE MINNESOTA

BY
FRANK F. GROUT
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THE MAGNETITE DEPOSITS OF THE EASTERN MESABI RANGE, MINNESOTA

CHAPTER I

INTRODUCTION

LOCATION

The Mesabi range is a belt of iron-bearing formation about 100 miles long, located about 80 miles north of Duluth, which is situated at the west end of Lake Superior. The trend of the belt is east-northeast. (See Figure 1.) The iron-bearing formation, commonly called taconite, is largely drift covered throughout the main range and has few of the topographic features of a "range." It is called a range because iron-bearing formations in other districts form ranges; and at the east end of the Mesabi district there are some rocky hills rising 200 to 400 feet above the general level.

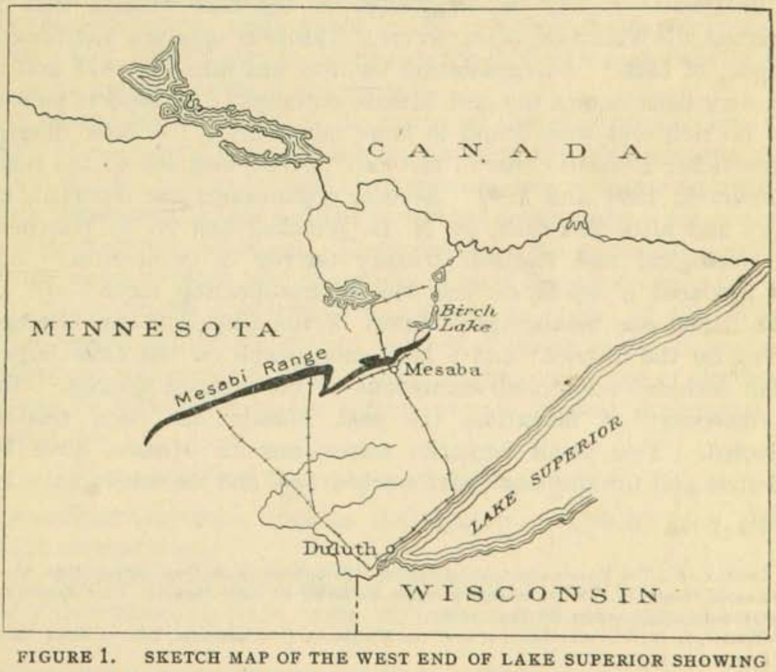

FIGURE 1. SKETCH MAP OF THE WEST END OF LAKE SUPERIOR SHOWING THE LOCATION OF THE EAST MESABI, ON THE MESABI RANGE

This report is a discussion of the eastern end of the range—that part which lies between the town of Mesaba and Birch Lake, a distance of about 20 miles. This portion of the range is commonly called the "east Mesabi." It is distinguished from the rest of the range by several features, besides the topography above mentioned. In this area, outcrops are numerous; most of the iron is in magnetic form; recrystallization has increased the size of grain and reduced the porosity; there has been very little leaching or enrichment; and in places the beds are more highly tilted. These several peculiarities make the east Mesabi a logical unit for separate study.

The field work was done in the summer of 1917, by Frank F. Grout and T. M. Broderick. The Mesabi Syndicate (D. C. Jackling, and Hayden-Stone and Company) were at that time actively exploring certain parts of the area and Mr. W. G. Swart, in charge at the Duluth office, made the work much more effective by rendering many drill records accessible to the Survey. A large number of samples have been assayed in their laboratories.

HISTORY

Leith[1] has summarized the literature of the Mesabi range as a whole up to 1903. It was the magnetite of the east Mesabi that first attracted the attention of explorers. The iron ores are mentioned in a report of 1866.[2] An exploration for iron was made in 1875 and covered very little except the east Mesabi outcrops.[3] All reports indicated that no rich ores were found in large quantities. The later discovery of the richer hematite ores in test pits farther west led to the rush of explorers in 1891 and 1892. Several explorations are reported, both before and after this rush, by N. H. Winchell and H. V. Winchell of the Geological and Natural History Survey of Minnesota.[4] Spurr also prepared a report on the Mesabi iron-bearing rocks.[5] In 1903 Leith issued the monographic report of the United States Geological Survey on the district,[6] and a later monograph on the Lake Superior region includes additional discussions of the Mesabi district.[7] Since the discovery of hematites the east Mesabi has been relatively neglected. Two small hematite mines east of Mesaba have been exploited and for the most part worked out, and no others have been found.

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

[2] Eames, Henry H., The metalliferous region bordering on Lake Superior: First Report of the State Geologist of Minnesota, St. Paul, 1866.

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

[4] See for example, Iron ores of Minnesota: Geol. and Nat. Hist. Survey of Minn. Bull. No. 6 by N. H. Winchell and H. V. Winchell, 1891.

[5] Spurr, J. E., The iron-bearing rocks of the Mesabi range in Minnesota: Geol. and Nat. Hist. Survey of Minn. Bull. 10, 1894.

[6] *Op. cit.*

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

PRESENT EXPLORATION

In the logical continuation of the work of Leith on the Mesabi range published in Monograph 43 and part of Monograph 52 of the United States Geological Survey, it is to be expected that the detailed petrography of the several parts of the iron formation will be the basis of a more detailed stratigraphy. The beginnings of this subdivision of the iron-bearing formation have been made by Leith himself in notes on certain persistent horizons and in maps showing a persistent slate bed. More in detail are the sections worked out by the engineers of the Oliver Iron Mining Company—Kingston, Wolff, Cronk, and others—working under J. U. Sebenius. The sections published by Wolff[8] show numerous persistent beds with recognizable peculiarities.

The east Mesabi is particularly suitable for a study of detailed stratigraphy, because outcrops are vastly more numerous than in other parts of the range, and there are also many drill cores available. The season of 1917 was especially favorable for mapping on account of the recent forest fires and lack of vegetation. It is now thought that the less developed eastern end of the range reveals several recognizable horizons which will aid one to determine the structure and some of the ore reserves in other parts of the range.

The immediate incentive to the study of the east Mesabi was the certainty of magnetite bodies of a large size, and the prospect that they were of a quality and so located as to warrant magnetic concentration. This is a commercial affair and the continued success of such a venture is a matter of close calculation. The costs of several processes involved have been much reduced, and the prices of good low-phosphorus ore are such as to encourage an attempt to mine these ores. In any event, with the reduction of the hematite reserves, interest in the leaner concentrating ore will increase. The details of the occurrence of the magnetite will be of interest in the future, even if present exploration is not continued.

SUMMARY OF THE ORIGIN OF THE MAGNETITE

In a sedimentary rock, such as the taconite, magnetite may accumulate in several ways:

1. By mechanical concentration of magnetite in sand.
2. By deposition as ferric oxide and subsequent alteration to magnetite.
3. By deposition as ferruginous chert in a leaner condition and enrichment to ferric oxide, as ores are now being enriched; and later by alteration to magnetite.

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[8] Wolff, J. F., Recent geologic developments on the Mesabi iron range: Amer. Inst. Min. Eng. Trans., vol. 56, p. 148, 1917.

4. By deposition as magnetite from solutions emanating from gabbro or granite near the contact.

The determination of the actual origin, then, involves a determination of the original mineral and textural character; the time the iron oxide accumulated; whether it was enriched, and if so, when; what processes altered the ferric oxides to magnetite; and what igneous rocks contributed to it or altered it. The first drilling that was done ignored the question of origin and only attempted to determine that the known outcrops of ore were connected by similar material under cover, and the depth to which the ore extended. When the matter of origin was considered, a small amount of drilling soon confirmed the observations of outcrops, indicating that (1) the concentration was primary, (2) the original oxides, probably mostly limonite, were altered by general metamorphism to magnetite, (3) none of the igneous rocks have essentially modified the iron content of the taconite, (4) most of the beds showing a concentration of iron are characterized by a conglomerate texture.

PLATE II

Section of rocks in S.E. ¼ section 6, T. 59N., R. 13 W., as determined from diamond drill cores

Group	Formation name	Symbol	Columnar section	Approximate thickness in feet	Character of formation	Estimated average percentage of iron in magnetite
UPPER HURONIAN	Virginia slate	Auvs			Gray slate with no secondary cleavage.	
	Biwabik formation (iron bearing)	Aub.		10	Cherty limestone with coarse silicates.	
				45	Thin bedded cherty taconite somewhat calcareous. Coarse amphiboles common. Beds wavy and lenticular.	15±
		Aub.		30	Thin bedded taconite with thin seams of magnetite becoming abundant toward bottom.	15
				40	Similar to the beds directly above. Presence of septaria, drag folds, brecciated bedding, and the slightly greater magnetite contents. Garnet developed commonly toward bottom.	18±
		Aub,		10	Magnetite rich horizon characterized by conglomerate.	32±
				10	Ferruginous chert, characterized by conglomerate and "algal" structures.	15
				17	Thick beds of chert and magnetite. Characterized by conglomerate.	32±
				105	Thick beds of chert and magnetite with conglomerate texture alternate with beds of magnetite. The matrix of the conglomerate pebbles is granular quartz, magnetite and amphibole; with magnetite decreasing toward the bottom.	18±
		Aub,		65	Siliceous amphibolite with fine cherty to slaty texture.	10±
		Aub,		25	Black slate, easily broken into thin slabs	0-5
		Aub,		10	Chert with large structures resembling those ascribed to algae. In places ferruginous and conglomeratic.	0
				42	Magnetite rich zone with some granules and conglomerate, but in many places a later brecciation. In places has basal conglomerate at bottom.	33±
	Pokegama quartzite	Aup		32	Fine grained pink quartzite with graywacke and slaty phases. Shows cross bedding. Basal conglomerate at bottom with boulders and pebbles, many of which are from the underlying granite.	0
Lower middle Huronian	Giants Range granite	Alg			Pink, porphyritic, moderately quartzose hornblende granite.	0

COLUMNAR SECTION OF THE IRON FORMATION IN THE EAST MESABI, SHOWING THE SUBDIVISIONS RECOGNIZED IN THE FIELD.

CHAPTER II

GENERAL GEOLOGY OF THE EAST MESABI RANGE

THE FORMATIONS

All the formations of the east Mesabi, as shown in the following table, are in the Algonkian system except the thin Pleistocene deposits. For detailed descriptions of the several formations, reference should be made to the monographs of the United States Geological Survey concerning the region as a whole.[1] Brief notes are given below, but some details are added in the case of the iron formation. The map (in pocket) shows their areal distribution.

Quaternary system	
Pleistocene series	Deposits of late Wisconsin age
Unconformity	
Algonkian system	
Keweenawan series	Duluth gabbro and diabase dikes and sills
Unconformity (only intrusive contacts in this area)	
Huronian series	
Upper Huronian	Virginia slate Biwabik formation (iron-bearing) Pokegama quartzite
Unconformity	
Lower-Middle Huronian	Giants Range granite Slate and schist formation

THE LOWER-MIDDLE HURONIAN SERIES

The slate and schist formation.—These slates and schists are light green rocks of variable grain. Most of them show a nearly vertical cleavage and bedding which strike a little north of east. They include several phases, not very extensive, which apparently represent old intrusions and beds of different character. They extend from the railroad at Mesaba to a point east of the Spring mine in R. 14 W.

The Giants Range granite.—The granite is in general pink, porphyritic, moderately quartzose, hornblende granite. It was intruded north of the present outcrops of green schist and forms the main ridge behind them. The contacts show the intrusive nature of the granite. In much of the east Mesabi the schists were eroded before Upper Huronian time and the iron formation rests on the granite. These contacts do not show any intrusions of granite into the sediments. The granite had evidently been weathered before the sediments were

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

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

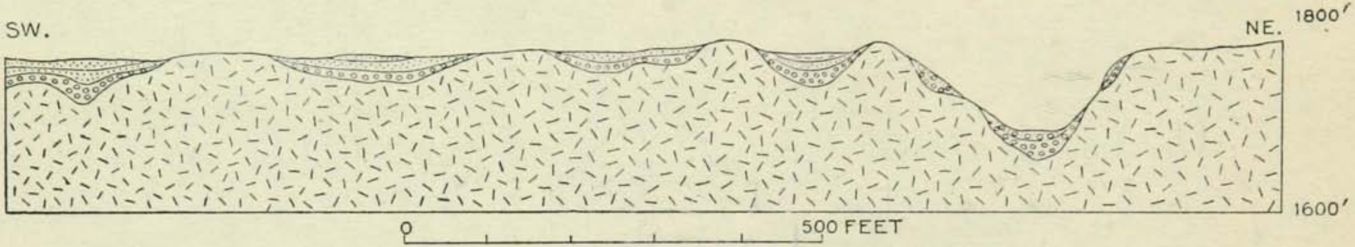
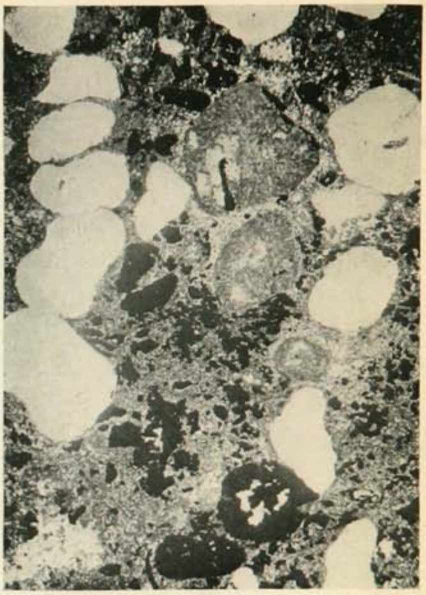
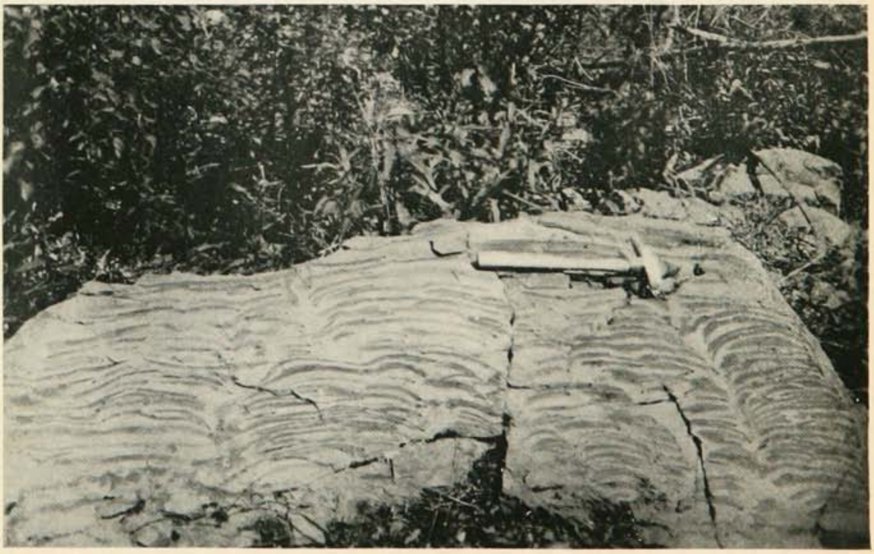


FIGURE 2. A SECTION ALONG THE STRIKE AT THE BASE OF THE IRON FORMATION IN SEC. 17, T. 60 N., R. 12 W., SHOWING THE UNCONFORMITY, AND THE STEEP SLOPES OF THE GRANITE FLOOR

A. THE BASAL CONGLOMERATE OF THE BIWABIK IRON FORMATION, RESTING ON THE GRANITE. THE GRANITE MASS AND BOULDERS SHOW DARK CHLORITIC BORDERS



C. GRANULES OF QUARTZ, MAGNETITE, AND AMPHIBOLE, SIDE BY SIDE IN THE LOWER CHERTY BEDS. MAGNIFIED x 15



B. THE LOWER CHERTY BEDS SHOWING A STRUCTURE LIKE PILES OF INVERTED BOWLS. THIS IS PROBABLY DUE TO ORGANISMS, SUCH AS ALGAE

deposited, for it now shows an upper zone (and a zone around many pebbles in the conglomerate) altered to a quartz-chlorite-garnet rock.

Unconformity.—The erosion preceding the deposition of the Upper Huronian seems to have cut deeply into the slates and granite, and although the general trend of the contact with the over-lying beds is regular, there are minor irregularities indicating a relief of 50 to 100 feet in many valleys in the pre-Animikie surface. Since the sediments are more easily eroded than the basement complex, the present valleys tend to follow, in many cases, the older valleys. (See Figure 2.)

THE UPPER HURONIAN SERIES (Animikie group)

The Pokegama quartzite.—The Upper Huronian (Animikie) formations lie on the older beds with a conspicuous unconformity in most places. The boulders of slate or granite in many places show the derivation from the slate or granite below. Above the coarse conglomerate, and in some cases directly upon the older rock, are finer sediments of several kinds. Where the sediment is quartzite it is given the name of Pokegama as a formation. Where it is cherty and ferruginous it is the Biwabik formation. In many places there is a mixture of clastic grains and a good deal of magnetite, leaving some doubt as to its classification.

The Pokegama quartzite is a hard, pink quartzite in lenses with a maximum thickness of 30 feet in the eastern district. Where it is prominently developed several exposures show a conglomeratic phase at the top. The conglomerate pebbles in most cases are not fragments of the Pokegama, such as would indicate its erosion; but they are chert fragments, probably indicating a breaking up of newly formed sediments above the sand.

The Biwabik iron-bearing formation.—The conglomerate, which is above the granite and schists in most places along the east Mesabi, grades into a series of ferruginous cherty rocks of unusual and variable character. These make a formation 350 to 500 feet thick. Its mineralogy, petrography, and structure are described in detail in later chapters.

The Virginia slate.—The Virginia slate lies with apparent conformity upon the Biwabik iron formation, but the change in material is somewhat abrupt. The cherty ferruginous iron formation may be thin bedded (slaty in texture) in certain parts, but the Virginia slate is slaty in both texture and composition. The contact of the formations is marked by a layer of limey carbonate, rather than a gradation from chert to slate.

The total thickness of the slate can not be measured in the eastern district, for its upper part is everywhere intruded by the Duluth gabbro. The gabbro lies above several hundred feet of slate near Mesaba, but cuts down gradually across the slate into the iron formation near Dunka River, in R. 12 W.

The sills and dikes (*of uncertain age*).—Intruded into the iron formation and the lower part of the Virginia slate are several sills 10 to 20 feet thick. They are much harder than the slate and form conspicuous ridges. Drilling has revealed also several dikes of similar material. The diabase of the sills is characterized by an abundance of coarse white feldspar phenocrysts in most exposures. Each good outcrop shows that the phenocrysts have concentrated in the upper half of the sill. While the sills are mostly fine grained, at many places the phenocrysts are as much as 2 inches in diameter.

The diabase of the sills and dikes would naturally be correlated with the gabbro which is of similar chemical composition, especially since most of the exposures occur at the east end, very close to the great gabbro area. It would be logical to consider them apophyses of the gabbro, except that detailed study shows that they are metamorphosed by contact action of the gabbro. Hence, although they are later than the slate and earlier than the gabbro, it is uncertain whether they were intruded in Upper Huronian or early Keweenawan time. Igneous action was more characteristic of Keweenawan time and in the table of formations given above the intrusions are placed in this division.

KEWEENAWAN SERIES

The Duluth gabbro.—Along the eastern Mesabi practically all of the gabbro is a coarse olivine gabbro with a somewhat variable composition, in alternating bands. The bands dip eastward at a steep, but variable angle. The texture is coarse up to the contact, though in some places the contact is determined only by close study.

CONTACT METAMORPHISM

The intrusions of diabase and gabbro have produced alterations in the earlier rocks. The effects of the diabase are not conspicuous except where it is in contact with slates, which are crumpled and recrystallized in a thin zone. The rock is greatly hardened, and spots of cordierite and amphibole appear. A chilled border phase of the diabase is also spotted, containing spherulites, and may be confused with the cordierite rock in the field.

The granite of this area has been described by Leith[2] as intrusive, into the upper Huronian, but it has produced no visible contact effect, and is now believed to be older than the sediments, as it was mapped by Winchell.[3]

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

[3] Winchell, N. H., Geol. and Nat. Hist. Survey of Minnesota Final Report, vol. 4, plate 67, 1899.

A. THE "INTERMEDIATE" SLATE OF THE BIWABIK FORMATION

B. THE SPOTTED FAYALITE ROCK IN THE SLATY BEDS ABOVE THE INTERMEDIATE SLATE

The gabbro is the largest mass of igneous rock in the region and one of the largest intrusions in the world. The contact effects extend in some places several hundred feet. Probably the most important effect is a very complete recrystallization of practically all the adjacent formations, into a sugary textured hornfels. The weathered surface of the contact rock is at places much like brown sugar in appearance. For this reason, it was referred to as "muscovadite" by Winchell.[4] The uniformity in appearance of the hornfels, whether from slate, diabase, or even from some iron-bearing formation, leads naturally to the conclusion that contributions from the gabbro have considerably changed the composition as well as the texture of the contact rocks. This, however, has not been proved, and the beds are so recrystallized that it is difficult to correlate altered and unaltered beds, if it was desired to make a comparison.

The iron-bearing formation contains bands of quartz and magnetite, which have resisted the apparently general tendency to become hornfels. Recrystallization develops coarse quartz grains up to half an inch thick from chert, amphiboles several inches long from the cherty carbonates, and magnetite in large crystals from pebbles and dust of iron-bearing minerals. It might be expected that iron oxide in the layers would react, during metamorphism, with quartz layers, producing silicates, but there is little evidence of such action. On the other hand, white quartz bands are much more conspicuous than the original gray chert bands alternating with iron oxides, and it is possible that during recrystallization some disseminated magnetite in chert has been more or less segregated into bands. One thin section made from pyroxenite, formed by contact action of the gabbro on the taconite, shows clear evidence of replacement by iron oxide along the borders and cracks. The temperature during recrystallization may have reached 575° C. or more,[5] near the gabbro.

In places, where the gabbro is close to the several horizons of iron formation, pegmatitic stringers are visible in great numbers. The feldspars are coarse and there is a great deal of graphic intergrowth with quartz. Farther away similar patches appear but are less definitely pegmatitic—feldspar is not so prominent, but quartz stringers with vugs are found in similar positions. These stringers are not connected by visible dikes or cracks, but suggest a pervasive emanation from the gabbro. No sign of so much feldspathic material is visible in the less altered iron formation. To check the matter, however, samples were taken from the same horizon near the gabbro and farther away.

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[4] Winchell, Alexander, Geol. and Nat. Hist. Survey of Minn. Fifteenth Ann. Rept., p. 183, 1886. "Muscovado" was the early settlers' name for brown sugar.

[5] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 549.

The alkalies were .78 per cent near the gabbro and .38 per cent at a distance. The difference, equivalent to about 3 per cent feldspar, may possibly give a fair idea of the additions of alkalies that took place.

REGIONAL METAMORPHISM

The long time and many events recorded in the geologic history of these formations make it difficult to determine how much of the rock alteration is due to contact action and how much to regional metamorphism. The progressive increase in coarseness of grain toward the gabbro indicates that this coarseness is largely a contact effect. However, the burial of the iron formation under a great thickness of slate favored some general metamorphism. This is shown by the induration and partial recrystallization of the slate itself, and by the drag folds in the less competent beds of the iron formation.

Some of the mineralogical changes in the iron formation seem to vary with the amount of recrystallization and the proximity of the gabbro; others are apparently independent of position and may be attributed to regional metamorphism. For example, it seems unlikely that the original deposit contained iron in a magnetic form, but at present the central beds of the iron formation, where unaffected by weathering, contain about 30 per cent of magnetically separable iron oxides, all the way from the gabbro at the east end of the range, to Coleraine, 60 miles from any gabbro exposures. This may result from a reduction of primary ferric oxides, either by simple heat, by ferrous compounds, or by organic material which is now represented by graphitic beds. There are, in many specimens, intimate mixtures of oxides, which give a red streak but are attracted by an ordinary magnet.

STRUCTURE

The general structure is simple, the beds dipping south and southeast at angles of about 5 degrees, on the side of the great Lake Superior basin. Locally, disturbances such as the gabbro intrusion produced steeper dips. The drag folds, a few feet in extent (Plate XI A) in the thin bedded formation are so placed that they may be related to this larger structure. However, there are folds of intermediate size, one hundred to several hundred feet across. Most of the irregularities shown on the map in the boundaries of the several formations, are due to the valleys crossing gently dipping beds. However, the folds like that at the Spring mine, or south of Iron Lake, are more likely related to some set of forces other than those which produced the major structure, possibly to igneous intrusions or some local modification of the larger stresses by the bed rocks below. The intrusion of the gabbro is very likely responsible for the sharp turn northeast of Dunka River. A few small domes in the lower cherty beds are probably due to the irregularity of the floor on which the beds were deposited.

No faults were noted in the iron formation. If present they are probably of very local significance.

GLACIATION

Throughout a large portion of northeastern Minnesota, glacial ice has scoured off the products of weathering and left relatively thin deposits of gravel. This seems to be true of the east Mesabi range, but on the main part of the range soft hematites have not been entirely removed, and a deeper deposit of drift covers them. The east end of the range stands at a level perhaps 200 feet above the west end, and it is a question whether the absence of soft ores at the east end is due to the fact that they never were formed, or to their formation at a higher level more exposed to glacial scouring, or to a difference in their relation to the lobe of ice that moved across them. Van Hise suggests that some of the range occupies an interlobate position.[6] Many of the rock surfaces are polished and scratched as if considerably glaciated; but in the rock of these high lands there are some gorges cut about 100 feet deep, which have not been obliterated by the glaciation, and it does not seem likely they were formed since glaciation. Possibly the soft ores are absent for the same reason that the rocks stand higher than those farther west; not because of glaciation, but because the rocks were recrystallized, hard, and resistant to weathering.

WEATHERING

The effects of weathering on the iron formation are very slight in the east part of the Mesabi range. The cherts stand out as ridges on the slope below the main granite ridge. The Virginia slate forms a lowland between the gabbro on the south and the granite and iron formation on the north. The slaty layer below the middle of the iron formation is also marked in many places by a valley. These topographic effects are probably due to the more rapid weathering of the slate.

In exposed places the cherty iron ore has stood under the weather probably for centuries without apparent attack. On the other hand, ground waters of different kinds produce some effects. The leaching of silica at the hematite mines has probably resulted from alkaline solutions which might originate near the granite. Contrasted with this, the swamp waters are acid and any taconite in the water loses its iron minerals; magnetite and fayalite dissolve rapidly, amphiboles next, and quartz remains. Most of the springs issuing from the iron formation and the waters reached in drilling, are almost free from iron. In swampy areas there are some limonite deposits. A spring carrying considerable iron issues in sec. 27, T. 60 N., R. 13 W.

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[6] Van Hise, C. R., Iron-ore deposits of the Lake Superior region: U. S. Geol. Survey Twenty-first Ann. Rept., pt. 3, pp. 411-12.

CHAPTER III

THE MATERIAL OF THE IRON-BEARING FORMATION

MINERALS OF THE IRON-BEARING FORMATION

The following minerals have been noted in the iron formation of the east Mesabi.

Quartz is the most abundant mineral in the recrystallized taconite. It occurs also in fragmental grains and a few small veins and septaria cracks. Chert and jasper make up some large primary beds, two of which show structures indicating organic (probably algal) origin. Some of the cherts and jasper layers were broken into fragments and pebbles.

Amphibole is the second mineral in abundance in the main taconite beds. It was probably formed by metamorphism of the greenalite and other silicates, that may have been present in the primary deposit. It is now intergrown with the quartz and magnetite. Rounded markings, consisting of amphibole in quartz, are seen in some thin sections—apparently the only remaining sign of an original granule texture. Some conspicuous grains, poikilitically enclosing quartz, etc., have grown to be 6 inches or more in length. Dark amphiboles are conspicuous also in pegmatitic stringers near Dunka River. Most of the amphibole is light green, and may be classed as actinolite, but other specimens vary from yellow to black. Grünerite and cummingtonite have been reported. The darker silicate in many specimens is probably grünerite.

Magnetite forms variable layers almost pure, up to 6 inches or more thick, alternating with the more common intergrowth of quartz, amphibole, and magnetite. Magnetite occurs also as pebbles, small rounded granules, crystals, and most commonly intergrown with quartz and amphibole, making up small rounded granules, and the matrix of the granules. There is a slight concentration of magnetite in a zone at the border of many granules. Recrystallization is so complete that little trace of granules is visible except these rings of fine grained magnetite. No attempt has been made to distinguish magnetite from other magnetic iron oxides. Ordinarily it is probably correct to call a magnetic oxide with a black streak, magnetite. In some parts of the Mesabi range there may be other magnetic oxides.

Hematite and *limonite* were rarely seen in the east half of the area except as a slight film of weathered mineral. At several places in the western part the leaching and oxidation have produced considerable bodies of these ores. In much of the western belt, the fresh black magnetic ores also show in places a red streak. The hematite and magnetite are intimately mixed, and magnetic concentration separates most of the iron oxides from the silicates.

Garnet is developed at several horizons in the iron formation. In the chloritic alteration product of the weathered granite and conglomerate at the base of the formation are many small, well formed red crystals. A more massive brown garnet forms layers and spots with the amphiboles, etc., near the slaty beds of the formation. While garnets may be found at a number of horizons, the only other prominent occurrence is above the main conglomerate beds; here also it is brown and in irregular spots.

Fayalite is conspicuous in crystals up to an inch in diameter. Most of them are about the size of peas. The fayalite is yellow when fresh, and brown when weathered. Thin sections show that most grains have thousands of microscopic inclusions of quartz and amphibole. Some have also magnetite. Fayalite was seen in greatest abundance in the slaty taconite above the main slate of the iron formation, and was best developed in R. 12 W.

Pyroxenes include augite, diopside, and hypersthene. The augite forms metacrysts resembling fayalite, in the recrystallized cherty taconite. Hypersthene was seen only in pegmatitic stringers near Dunka River. Babingtonite has been reported.

Mica occurs as microscopic grains in the altered slaty horizons. A larger specimen was seen in a drill core from the taconite near Sulphur.

Feldspars are not seen in the main outcrops, but both orthoclase and plagioclase occur in the pebbles of granite in the basal conglomerate; also in the pegmatitic stringers near the gabbro.

Carbonates are to be found in small amounts in the ore horizons intergrown with quartz, amphibole, and magnetite. A layer rich in calcium and possibly other carbonates is more or less continuous at the upper contact of the iron formation, and some carbonate appears in the lean taconite, just below this layer,—Aub_6. The magnetite-rich bed below the intermediate slate also contains carbonate. Secondary carbonates have been deposited in openings in the leached zones, where there has been enrichment, and in pseudomorphs after some of the granular greenalite.

Greenalite has been found mostly in the more western parts of the area. Nearer the gabbro, recrystallization has altered it to several other minerals, and more or less modified the texture of the rock, so that little greenalite is left. We have checked the low alkali content of greenalite rock by several analyses. The granules of amphibole may form from greenalite with little change in material.

Graphite.—Many black layers and flint concretions and pebbles in the midst of magnetite-quartz masses prove to contain little or no iron. The solution of the silica and iron by successive treatments with hydrofluoric and hydrochloric acids leaves a soft black residue, apparently graphite.

Apatite is not visible in most thin sections, but has been detected in the coarser recrystallized ore at the east end of the Mesabi range.

Chlorite is characteristic of the basal conglomerate where the feldspars were weathered before metamorphism. Some is believed to occur also in the aluminous beds higher in the formation.

Pyrite occurs as numerous scattered small bunches below the slate member of the iron formation, and is scattered in small amounts at other horizons.

Pyrrhotite, *chalcopyrite*, and *arsenopyrite* have been noted in drill cores.

Epidote and *tourmaline* are visible in the contact zone near the gabbro.

Kaolin may be present in some of the slates.

Malachite is derived from chalcopyrite near the surface.

ROCKS OF THE IRON-BEARING FORMATION

It has become the custom on the Mesabi range to refer to practically any phase of iron formation (except hematite ore and paint rock) as taconite. Most of the rocks are derived from an original sediment containing granules that may have been greenalite, but the greenalite is so altered in most specimens that the name greenalite-rock is applicable to very few. There are, of course, small amounts of some ordinary sediments, conglomerates, quartzite, and slate, with the usual range of impurities, but these make up a very small proportion of the whole. From the prominence of fine quartz, the rocks may properly be classed as cherts, with various qualifications to distinguish the minerals intergrown with the quartz; thus there are ferruginous cherts, amphibolitic cherts, calcareous cherts, and sideritic cherts. These so-called cherts, however, differ considerably in origin from the concretionary and precipitated cherts of limestones and common sediments. They are derived by alteration from the rocks with granules like those of greenalite. Furthermore, in certain places, there are, in the iron formation, chert concretions of a more normal sort, and it is somewhat confusing to make no distinction. For the rocks of the east Mesabi there are several reasons why the name *chert* is not very satisfactory. The granules, analogous to the greenalite structures farther west, vary in size up to pebbles 6 inches in diameter. Recrystallization has enlarged the grains so that many specimens no longer have any resemblance to common chert. For these reasons we use the local name, taconite, in its broader sense for any part of the iron formation. Certain phases may be easily classified as chert, amphibolite, pyroxenite, quartzite, amphibole-magnetite rock, or magnetite; others have so many rare minerals or such unusual proportions of minerals that no name has been given and a descriptive name becomes very cumbersome. Added to this, it may be necessary to use a textural qualification. There are, for example, some cherty amphibolites with fayalite metacrysts; and some conglomeratic augite-amphibole-quartz-magnetite rocks. Probably no elaborate additions to the nomenclature are desirable, and the general term taconite may be understood to cover these recrystallized rocks.

CHAPTER IV

SUBDIVISIONS OF THE IRON-BEARING FORMATION

The several divisions of the iron-bearing formation here tabulated (Plate III) are based to a large extent on the appearance of outcrops. Wolff[1] has emphasized the fact that the several grades of Mesabi ore are more or less related to the beds from which they were formed; and this relation is even more pronounced in the magnetite than in the hematite ore. The divisions previously made by Wolff are indicated

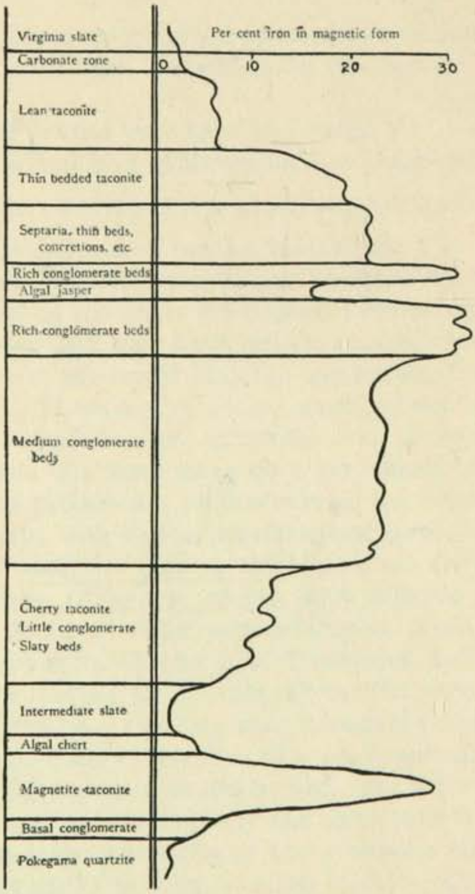

FIGURE 3. CURVE SHOWING THE VARIATION IN MAGNETIC IRON CONTENT IN THE SEVERAL HORIZONS OF THE IRON FORMATION ON THE EAST MESABI

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[1] Wolff, J. F., *op. cit.*

in the diagrammatic sections (Figure 4), and were useful in the structural studies on the east Mesabi: but the thickness of the main divisions is very different in this part of the range from those plotted by Wolff. Some of the divisions are given detailed descriptions on pages 19 to 26.

Tabular Section of the Biwabik Formation Where Prospected for Iron on the Eastern Mesabi

Top	VIRGINIA SLATE	
	UPPER SLATY BEDS	
Aub$_6$	Limy carbonate layers. Less than 5 per cent magnetite	5 to 10 feet
	Banded amphibole and white quartz in thin layers up to 6 inches thick. Less than 5 per cent magnetite	40 to 50
Aub$_5$	Taconite in thin beds mostly less than 1/8 inch thick. About 20 per cent iron in magnetite, decreasing at the top	25 to 35
	Taconite in thin beds, like above, but alternating with thicker gray beds and concretions with a granule texture, and white quartz septaria. The thin beds are drag folded and even brecciated. A zone of garnets occurs near the bottom. About 20 per cent iron in magnetite	40 to 45
	UPPER CHERTY BEDS	
Aub$_4$	Dark heavy taconite, with some conglomerate texture, and granules, alternating in thick beds with thick magnetite layers. About 30 per cent iron in magnetite	10
	Jasper and chert with algal structure and conglomerate. About 15 per cent iron in magnetite	1 to 10
	Dark heavy taconite like the bed above the jasper. About 30 per cent iron in magnetite	20 to 30
	Gray taconite with conglomerate and granule texture and many thinner lenticular beds of magnetite. About 20 per cent iron in magnetite	80 to 110
	LOWER SLATY BEDS	
Aub$_3$	Fine massive to slaty quartz amphibolite with only obscure granule structure, and few magnetite beds. Fayalite crystals in places. About 10 per cent iron in magnetite	65
Aub$_2$	Black thin bedded slate, more or less recrystallized. About 5 per cent iron in magnetite	25
	LOWER CHERTY BEDS	
Aub$_1$	White to gray chert with coarse algal structures. Less than 5 per cent iron in magnetite	10 to 15
	Variable taconite with some cherts, breccias, fragmental sands, garnets, etc. From 25 to 35 per cent iron in magnetite	2 to 52
	Basal beds; conglomerate in many places, and (in absence of Pokegama quartzite) some green shales. Less than 5 per cent iron in magnetite	0 to 15
		350 to 470
Base	GIANTS RANGE GRANITE; OR LOWER-MIDDLE HURONIAN SLATE; OR POKEGAMA QUARTZITE.	

LOWER CHERTY BEDS

The bottom of the lower cherty beds, Aub_1, is for the most part a conglomerate of irregular thickness, which fills in some of the erosion valleys in the older surface. It is not separately shown on the map. Where it rests on granite, as it does in most of the east Mesabi, some of the boulders are clearly of the same granite. Evidently the weathering of the boulders and the granite below left an aggregate which under later metamorphism developed chlorite and garnet, between the original quartz grains that seem to remain unaffected (Plate III A). Between the pebbles and in thin beds overlying them are greenish shaly beds, probably derived from the same weathered granite. Where the iron formation rests upon the older slates or the Pokegama quartzite, this basal bed consists mainly of quartz and chert pebbles.

Above these basal beds is the lowest of the magnetite beds. It is not recognized at the east end of the area, but is found a few feet thick in R. 13 W., and over 50 feet thick near Mesaba. It contains magnetite layers more or less mixed with sand and cherts. (See Plate III C.) There are phases that resemble the conglomerate of the upper cherty beds, but more that seem to be brecciated after deposition.

The increase in thickness toward Mesaba and the high per cent of iron make this bed of interest as a prospective ore horizon farther west. It is no doubt the bed which Wolff describes as producing "hard blue ore" in the "brown cherty taconite."[2] Toward the east where it is thin it was missed in so many places that it has not been mapped as a continuous belt.

At the top of the lower cherty beds, a hard chert crops out in many places, indicating a continuous formation over the length of the range. Most of the rock is of fine grain and has a peculiar structure, emphasized in gray and white or jaspery bands. (See Plate III B.) The bed is not so lenticular and irregular as the concretionary beds, such as occur above the slate, but is characterized by a more regular waviness, probably due to organic action. It closely resembles several forms from the pre-Cambrian ascribed to algal growth. Similar forms were recently described and illustrated by Moore from the iron formations near Hudson's Bay.[3] These forms on the Mesabi are almost wholly chert, while the others are characteristically calcareous. Nevertheless they are considered of organic origin, for it is likely that many early forms of chert are analogous to later calcareous forms.[4] The concentric masses are 6 to 18 inches across. (See also the description of smaller

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[2] *Op. cit.*, p. 154.

[3] Moore, E. S., The iron formation on Belcher Islands: Jour. of Geology, vol. 26, pp. 425-26, 1918.

[4] See Clarke, F. W., Geochemical evidence as to early forms of life: Jour. Wash. Acad. Sci., vol. 6, p. 603, 1916.

algal forms in the upper cherty beds, page 22.) The gray color of some bands may be due to their magnetite content, but only a few thin layers in the cherts have a high per cent of iron. In some outcrops the banded cherts include fragments of iron oxide, so that the rock greatly resembles the conglomerate beds of the higher divisions of the formation. The thickness of these lean beds below the slate is about 15 feet and is fairly constant in the eastern area.

LOWER SLATY BEDS

The lower part of the lower slaty beds, Aub_2, is the most notably slaty in structure of any part of the iron formation. It is known through the main range as the "intermediate slate." (See Plate IV A.) In contrast with the lower beds it is very constant in thickness and bedding through the whole range. It is probable that the lower beds had filled up the irregularities in the bed rock surface before the time of deposition of the slate. It is so much more like an ordinary shale that it is natural to attribute the material to normal mechanical deposition and, in contrast, to attribute the ferruginous cherts to precipitation. Well-developed ripple marks are seen in places. None of these slaty beds contains much magnetite. Extensive recrystallization at the east end does not prevent the weathering to thin slabs along the bedding, at most outcrops. An analysis of the slate by George Steiger is reported by Van Hise and Leith.[5]

This bed grades into overlying rock of a very different general character, with no sharp break. The slates, about 25 feet above the bottom of the bed, become more granular in texture and show less regular bedding. Higher up the rocks are hard and fine grained, with conchoidal fracture. They are more massive in structure as compared with the thin beds below. Thin sections show a mat of very fine amphibole needles in chert, with a very obscure granule structure. In a few places small areas of conglomeratic texture appear, with small magnetite pebbles, but abundant magnetite is found in few beds, and as a whole, in very small amounts. In the area near Sulphur the rocks of this division show fayalite in many outcrops. Plate IV B shows the spots that develop as the fayalite weathers brown. As a division of the formation it will be called the siliceous bed above the intermediate slate.

UPPER CHERTY BEDS

The lower part of the upper cherty beds is the lowest bed with a thickness as much as 50 feet that contains a large per cent of magnetite. The line between this bed and the more siliceous beds below is not sharp, but the formation in a few feet becomes granular, magnetite

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[5] *Op. cit.*, p. 191.

pebbles grow more numerous, and layers of pure magnetite become thicker and more abundant. The whole mass is characterized by the occurrence of the pebbles. No exposure 5 feet thick lacks pebbles. Any drill core from these beds that is 5 feet long will show cross sections of pebbles.

A vertical section of the bedding shows it to be very irregular. Most of the beds, whether of magnetite, conglomerate, or amphibole, pinch out in irregular lenses. Such a bedding is illustrated in Plate V A. It is not regular enough for ripple marks; neither is it evidently related to folding; both ripples and folding are observed in the beds independently of this structure. There are no signs of cross bedding. Three processes are suggested below (in discussing the origin of the magnetite deposits), which may have made the beds irregular: (1) the shrinkage of a colloidal precipitate; (2) the solution of deposited layers; and (3) concretionary rearrangement.

Many of the pebbles of the conglomerate are of magnetite, many are of material resembling the beds just below, and many show a core of siliceous granular rock with a zone of magnetite around the border. Plate V B indicates the variety of pebbles in a fair sample. The shapes are mostly somewhat flattened and fairly well rounded, but a considerable number are angular, and plate-like. Some vertical sections of the beds indicate that magnetite layers, which can be traced some distance, may be broken up into flat, vertical-sided blocks at one end. (See Plate V A and Plate VI A.)

The matrix between the pebbles in the lower part of this bed is much the same as the main portion of the bed under it; but in the middle and upper parts, it is of sandy or granule texture, containing much more magnetite, and showing under the microscope structures that have been attributed to greenalite. In the altered grains of these rocks, there seems to be no difference in the nature of the material in the granules and in the coarser pebbles. Grains of the same general character range in size from $\frac{1}{16}$ inch up to 6 inches. There is no break in the series. (See Plate IX.)

The magnetite content of these beds is fairly constant if taken in large masses. However, it is possible to select five-foot drill cores, or five-foot exposures, a few feet apart along the beds, which will vary as much as 50 per cent of the total. This is exceptional and the average magnetic iron[6] content is probably well above 20 per cent. Total iron is about 37.5 per cent.

The next division of the upper cherty beds is not essentially different from the main conglomerate, except that the magnetite layers

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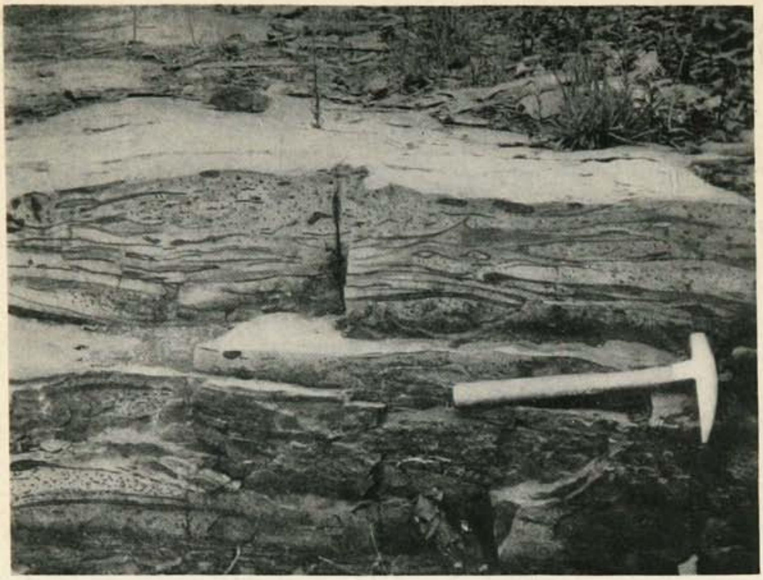
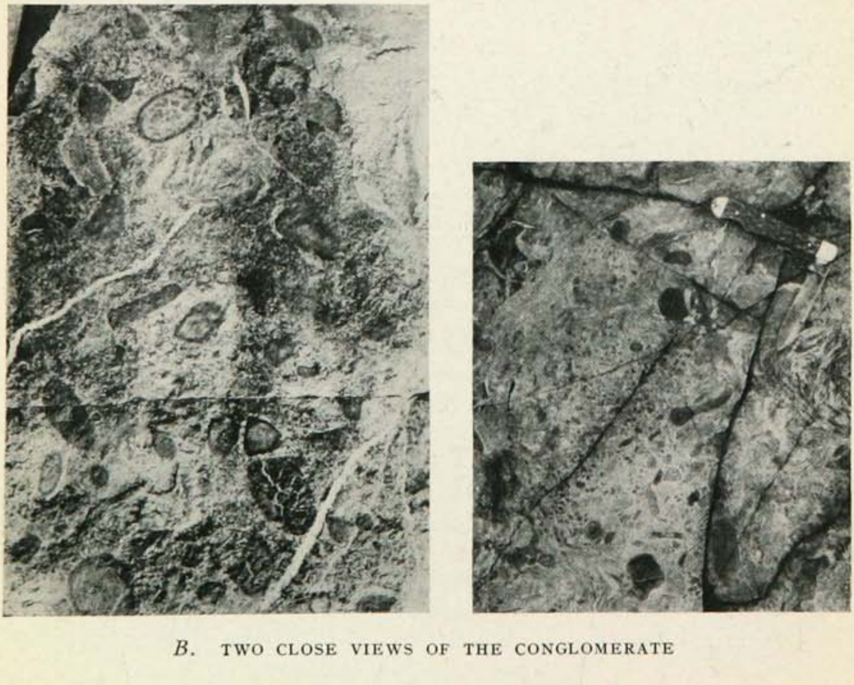
[6] The term "magnetic iron" is used in this report to designate the iron contained in minerals which are attracted by an ordinary hand magnet.

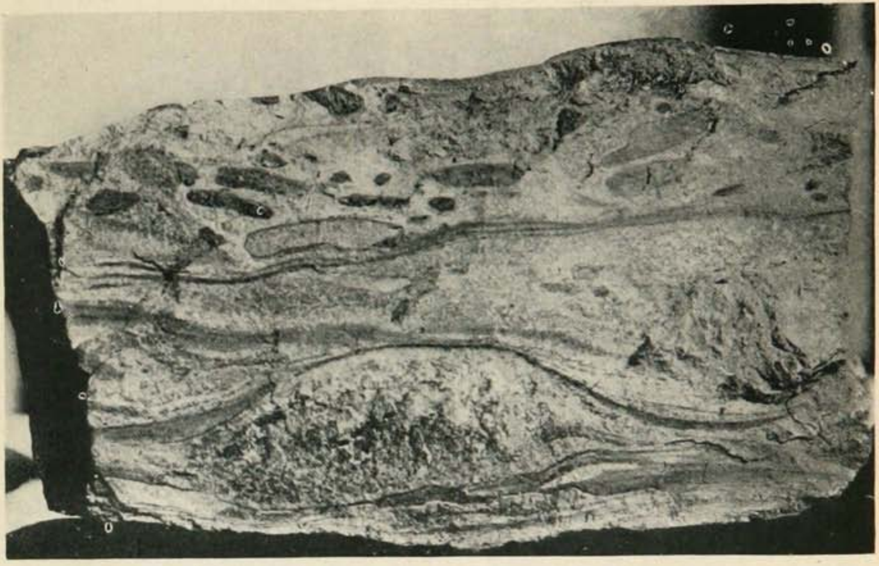
PLATE V



A. THE CHERTY TACONITE OF THE MAIN MAGNETITE BEDS ON THE EAST MESABI, SHOWING THE LENTICULAR BEDS, WITH SOME INDICATIONS THAT THE BEDS BREAK UP INTO CONGLOMERATE PEBBLES



B. TWO CLOSE VIEWS OF THE CONGLOMERATE



A. CHERTY TACONITE SPECIMEN SHOWING THE IRREGULAR BEDDING AND THE PARALLELISM OF THE FLAT PEBBLES OF THE CONGLOMERATE

B. THE UPPER SLATY BEDS, SHOWING SOME NODULES OF COARSER CHERTY MATERIAL, GRADING INTO LENTICULAR BEDS OF SIMILAR MATERIAL

are thicker and more numerous. This seems to be the best magnetite deposit as much as 20 feet in thickness. To the west of this area the richer beds show a red streak indicating considerable hematite, though magnetic concentration separates most of the iron.

Above the best magnetite deposit is a thin bed of cherty or jaspery material with the characteristic algal structure mentioned in the description of the upper part of the lower cherty beds. This bed is very hard, and so placed in the midst of hard beds that it outcrops in many places. However, it is too thin to show on the map. The color varies from gray to red, with variation in composition, but the cause of the variation is undetermined. The magnetite content of the algal bodies is slight (see Plate VII), but between the finger-like masses are some pebbles of magnetite and granular material much like the conglomerates in adjacent beds.

The bodies whose origin is here attributed to algal growth resemble little piles of thimbles or inverted bowls. They are half an inch to three fourths of an inch in diameter, piled in irregular columns about six to twelve inches high. The lower parts, like the sides and upper parts, seem to merge into the granular fragmental material of the conglomerate. Along the east Mesabi the curving lines of the structure do not seem to include any fragmental grains or granule markings except along the margins. However, some drill cores from taconite near Eveleth show a more confused mixture of banded jasper and pebbles, indicating that the growth could occur simultaneously with fragmental deposition and even concentrically around the grains. Horizontal sections of these masses show the concentric rings of a concretion, but the vertical sections are not easily explained as concretionary, or even as results of diffusion. It seems more likely that the finger-like masses grew, convex surfaces upward, all over the bottom of the water. Plate VII shows the characteristic forms. It is noteworthy that these small growths, forming a layer a few inches thick, are so widespread that the structure serves as a horizon marker in the drill cores examined from places all along the range. The outcrops indicate a continuous bed 15 miles long and the curving bands are so small that they are easily recognized in drill cores far to the west of the outcrops.

Specimens of the algal material were examined by Dr. Charles D. Walcott, who writes; "I am still at a loss to explain the origin of such structure without the influence of some organic agency acting in conjunction with diffusion and concretionary phenomena. The structure is very much like that which occurs in the siliceous limestones of the pre-Cambrian in the Grand Canyon, Arizona, and somewhat like those found in the pre-Cambrian Belt series of Montana. The Grand

Canyon forms are referred to Collenia."[7] No cell structures have been detected in the thin sections of this rock, but recrystallization has been so complete that it probably destroyed all trace of algal cells, which are less than .01 mm. across. The forms may safely be attributed to probable algae.

The top of the upper cherty beds is in nearly every respect a continuation of the best magnetite bed, below the chert layer. It seems that the algal growth occurred at one stage in the accumulation of the conglomeratic ore. Possibly the accumulation never ceased, for the spaces between the algal "fingers" are filled with similar pebbly material.

All this rock that has as much as 25 per cent magnetic iron can be concentrated to a product over 60 per cent iron, without grinding finer than about 100 mesh. The thin sections show a large proportion of the magnetite to be recrystallized grains of large size, and easily separated from the silica.

Summarizing, it may be said that the upper cherty beds, with the exception of the algal chert near the top, constitute a unit in which the subdivisions are more or less arbitrary. The total thickness is between 120 and 160 feet with a little richer material near the top. The conglomerate is most conspicuous in R. 12 W. and is a distinguishing feature throughout the entire thickness of the upper cherty beds. While the thickness of these beds with relatively high magnetite content apparently remains about constant throughout the entire Mesabi range, the conspicuously conglomeratic phases, containing within them the best concentrations of magnetite, may be thinner toward the west.

UPPER SLATY BEDS

The lowest of the upper slaty beds marks the end of most of the coarse conglomerate. There is no abrupt change, however. The granule texture is seen in lenses in the slaty beds and there are even a few pebbles. Two features distinguish these beds from the preceding: first, the magnetite layers instead of being lenticular and compact, are straight thin layers of very fine grain, a set of thin magnetite beds alternating with the lenticular beds of granule texture; second, the coarser beds contain and may consist of nodules, or concretions distinct from the matrix. Plate VI B shows these two features and indicates clearly the characteristic nodules.

The development of nodules has probably played a more or less prominent part in the history of the formation. The nodules are not recognizable in drill cores, but they are very clear in the exposures and grade into the lenticular bedding, so as to suggest

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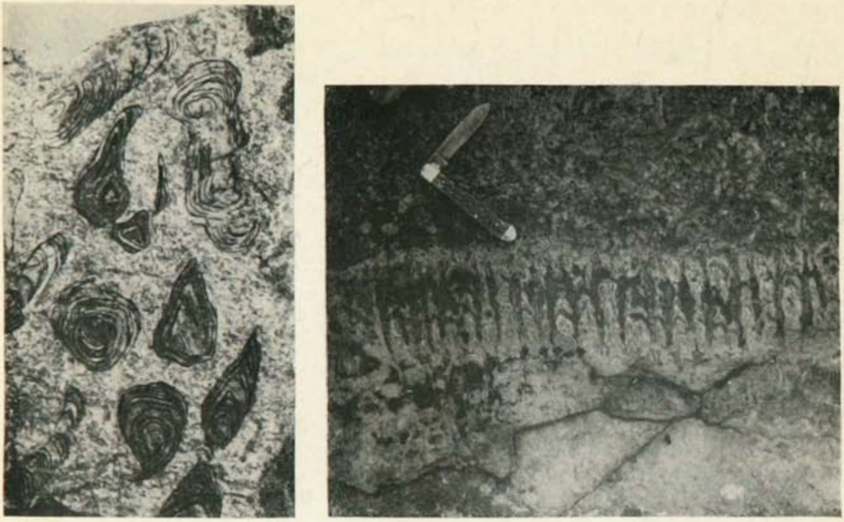
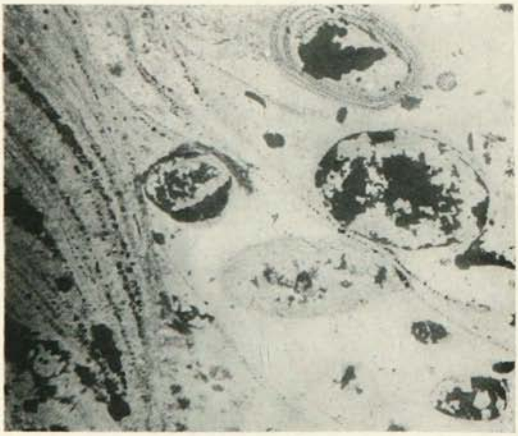
[7] Walcott, Chas. D., Pre-Cambrian Algonkian algal flora: Smithsonian Miscellaneous Collections, vol. 64, no. 2, p. 111, 1914.

PLATE VII



A. CROSS SECTION ONE HALF NATURAL SIZE

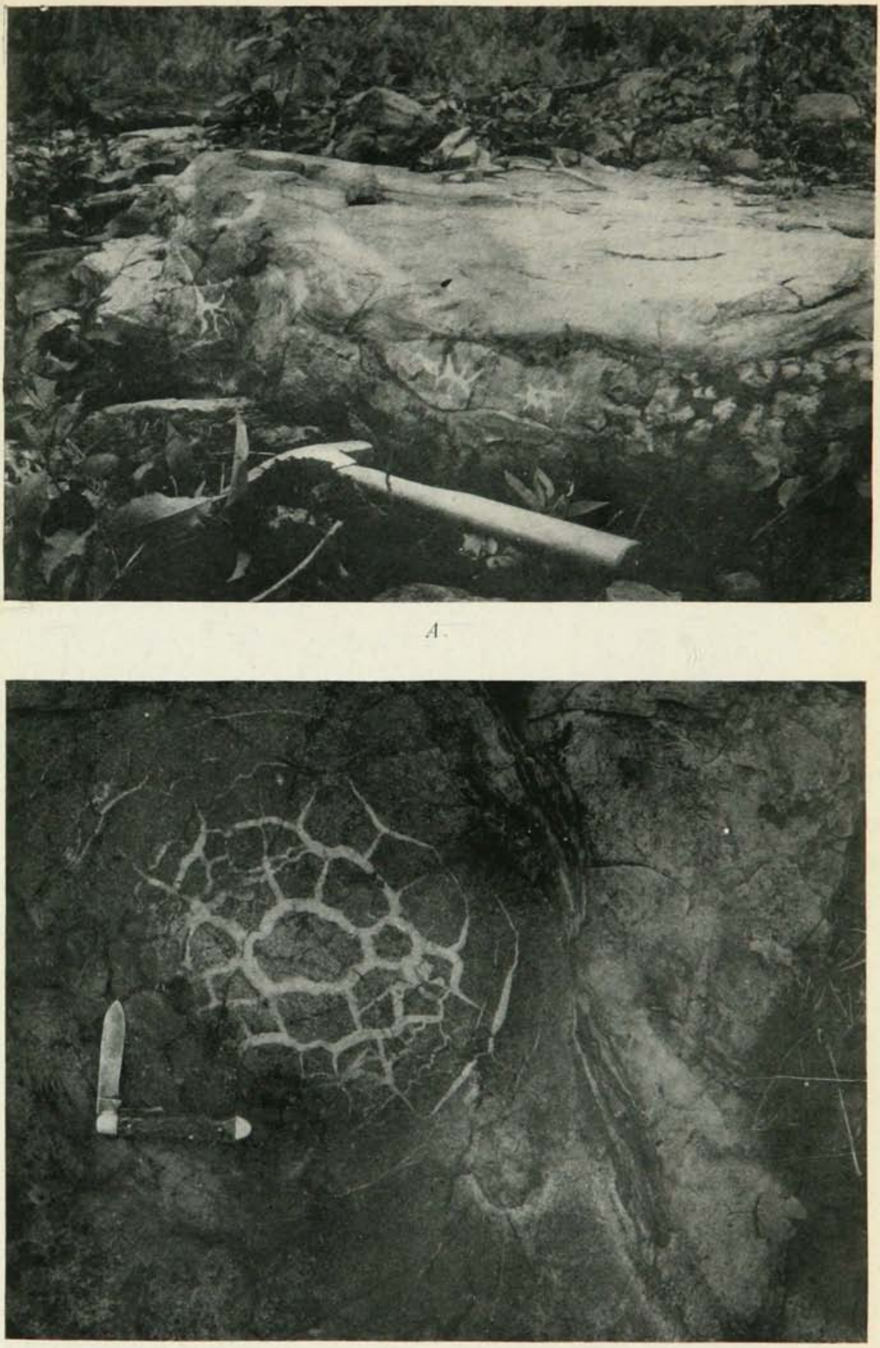
B. VERTICAL SECTION



C. THIN SECTION, X 40. NOTE THE ZONES OF DEPOSITION EXTEND AMONG AND IN SOME CASES AROUND THE PEBBLES. THE IRON OXIDE IS IN LAYERS ALTERNATING WITH SILICA AND SEEMS CLEARLY A PRIMARY PRECIPITATE

THE CHERTS WITH STRUCTURES PROBABLY DUE TO ALGAE

PLATE VIII



A.

B.

THE SEPTARIA CRACKS IN COARSE CHERTY NODULES OF UPPER SLATY BEDS

that the very lenticular beds, even in the conglomerate, may have developed by concretionary action. It is noteworthy also that the nodules and matrix have the granules and even pebbles in them; so that the growth of a nodule apparently does not mean a replacement of all the material by a uniform precipitate from solution; rather it must have been more like a special cementation of a certain part of the beds.

One of the most striking features noted in the outcrops of taconite on the east Mesabi is the septaria cracks in these beds. Septaria seem to have been described chiefly in carbonate concretions; and there may have been more or less carbonate in the iron formation—some still is to be found. The concretions now, however, are mainly quartz and magnetite, while the cracks are filled with white quartz. Plate VIII shows the appearance of the septaria. They are very useful in determining the horizon of an outcrop.

Several of the magnetite beds of this division have been crumpled or drag folded between more competent layers of chert, and more or less irregularly thickened (Plate XI A).

There are abundant brown spots of garnet near the bottom of this bed, as compared with other parts of the magnetite rocks, but the garnet zone is too thin to be separately mapped.

The abundance of thin magnetite beds makes the average of this bed worthy of consideration, though its concretions have only a small amount, and the finer grain requires finer grinding for good concentration. The magnetite bands, under the microscope, show swarms of minute quartz and amphibole inclusions and intergrowths, and Mr. E. W. Davis of the Mesabi Syndicate found that grinding must be carried to about 300 mesh to get a concentrate over 60 per cent iron.

On the basis of the thin beds of fine grain, we have correlated these beds with Wolff's "upper slaty" beds, since he states that his terms are textural only and do not refer to composition. This report refers to them as "septaria beds."

The beds above the septaria beds are similar in most respects, but septaria cracks have not been noted. They have less of the concretionary forms and granule structure, but the thin beds with a fair per cent of magnetite persist, growing a little leaner at the top. This upper part is not separated from the septaria bed in the general map. It has a relatively small number of magnetite layers, and grades into the beds above, (Aub_6).

Taken together, the beds mapped as Aub_5, are about 75 feet thick, except east of the Dunka River where they seem to be thinner. The outcrops show very little slaty character, except that the magnetite layers are very thin. Near Spring mine there is an outcrop at this

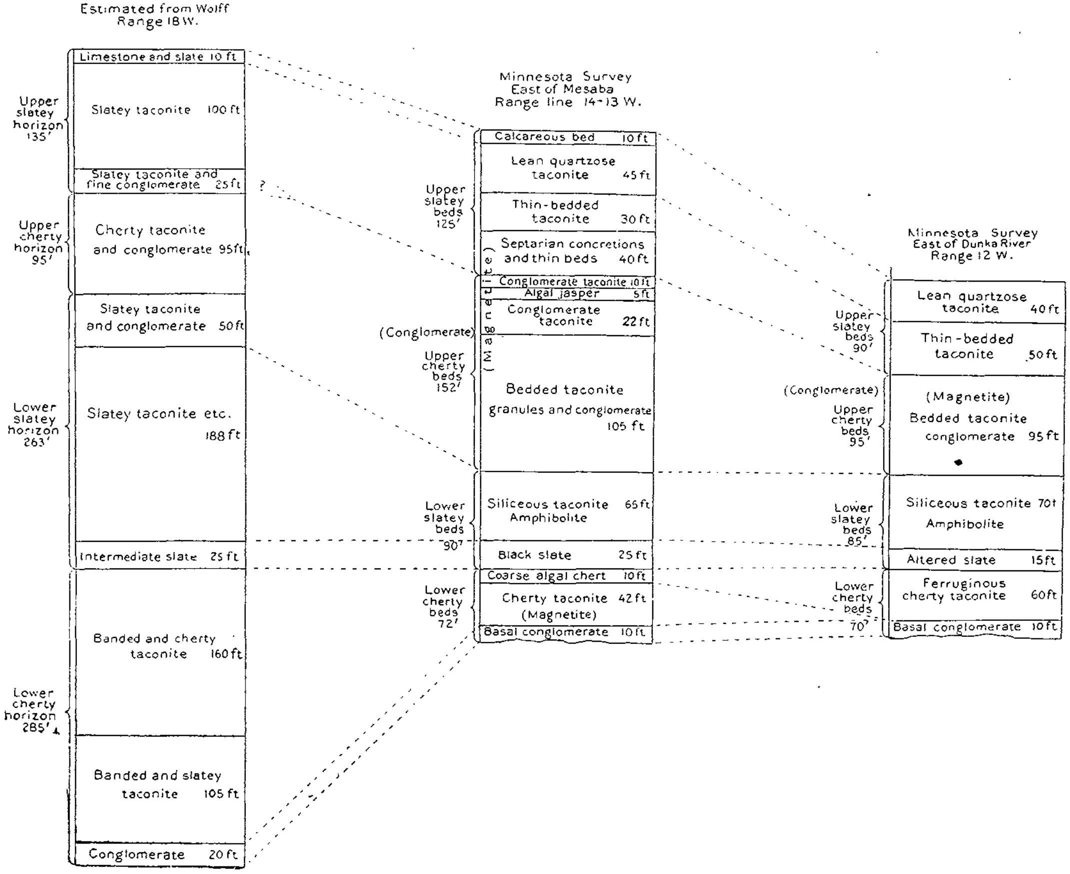
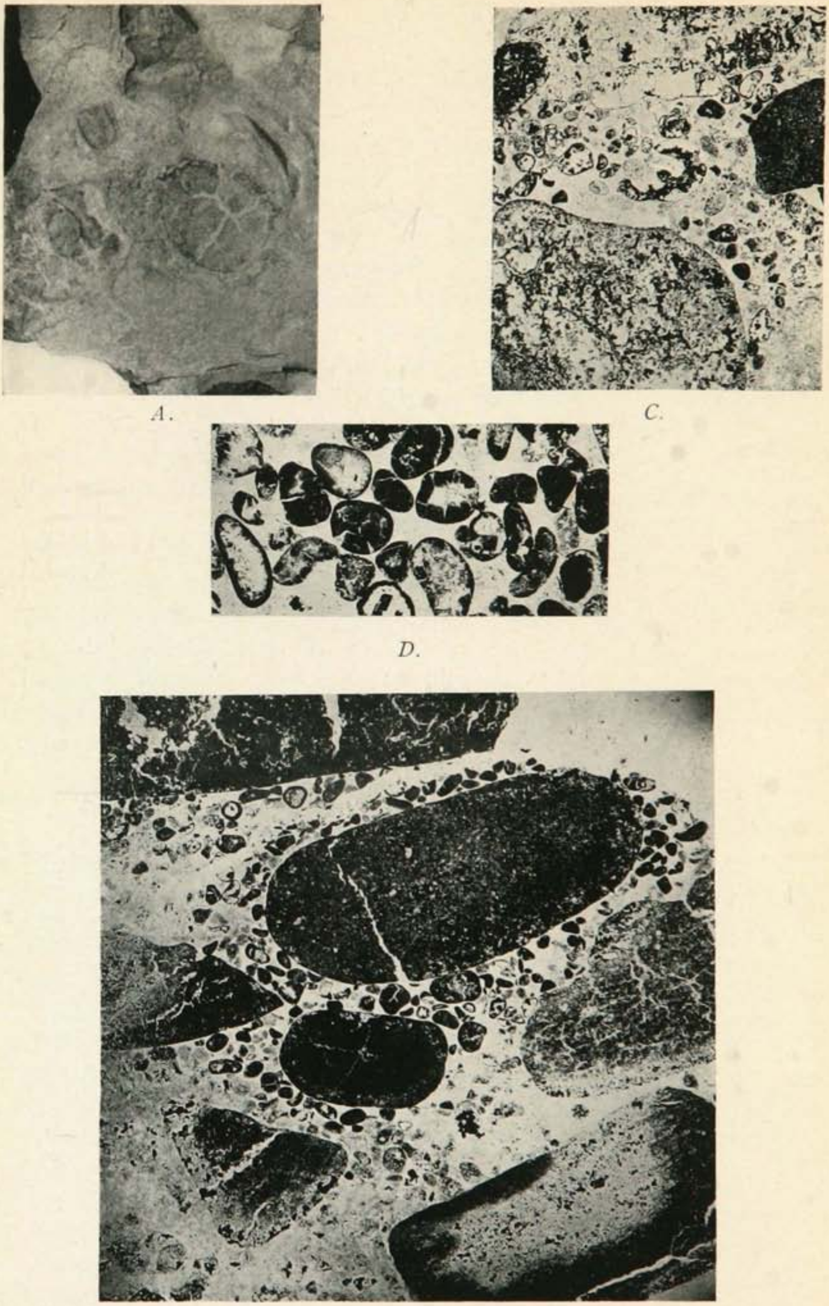


FIGURE 4. CORRELATION CHART OF THE BIWABIK IRON FORMATION FROM CENTER TO THE EAST OF THE MESABI RANGE

PLATE IX



A, *B*, *C*, AND *D*. A SERIES OF GRAINS FROM 0.1 MM. TO 30 MM. SHOWING SIMILAR FORMS, COMPOSITION, AND DETAILED STRUCTURES. *A*. PEBBLE AN INCH IN DIAMETER. *B*. MAGNIFICATION x 8 ½, GRAINS FROM .1 MM. TO 10 MM. *C*. THE SAME. *D*. COMMON GRANULES ABOUT 1 MM. OR LESS.

horizon that weathers into thin slabs and breaks up much more readily than most of the taconite.

The upper member of the formation lies on the slaty beds just described, with a rather sharp change in character. The magnetite is almost entirely lacking and the thin beds and granule texture have not been noted. Beds of white quartz and green silicates, from half an inch to 6 inches in thickness alternate to make a conspicuously banded light colored rock. Scattered grains of carbonate are more abundant than in the lower beds. There is little reason for describing this division as slaty, but it lies between slaty taconite and Virginia slate, and is not given a separate group name. It is everywhere about 50 feet thick.

The topmost bed of iron formation does not outcrop at many places and is too thin to show on the map. It is a calcareous bed about 10 feet thick. Nearly every drill core that passes from Virginia slate to iron formation reaches such a bed just below the slate. This is not a pure limestone, but is more calcareous than any other beds of the iron formation. It is generally assumed that this marks the top of the iron formation. In contrast with the varying character of the iron formation, the slate above is very uniform, so that this last change in material is a good horizon to select as the upper limit of the formation.

CORRELATION OF SEDIMENTS OF EAST AND WEST MESABI

The section given differs in some details from the sections given by Wolff, but there seem to be sufficient data for the correlation given in Figure 4. The persistent and characteristic "intermediate" slate is so well identified that it may be at once correlated with the slate in the eastern area. From this correlation it follows that the beds below the slate are much thinner at the east than on the main part of the range. Wolff shows the lower cherty beds about 280 feet thick; at Mesaba they are about 70 feet and in R. 12 W., about 30 feet thick. Accompanying this change, and agreeing well with it, the Pokegama quartzite disappears to the east. It is clear that active sedimentation began somewhat later in the east Mesabi than farther west.

The persistence of the layer of calcium carbonate at the top of a series of four recognizable divisions of the iron formation is taken as a very strong indication that all the iron formation is represented in this eastern section. Van Hise and Leith[8] refer to the "known irregular alternation of iron-bearing formation and slate, both across and along the beds," as a cause of the varying width of the iron-bearing formation. However, where the exposures are best and drill cores most numerous, there is no alternation that causes any doubt as to the loca-

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[8] *Op. cit.*, p. 174.

tion of the limiting zone of carbonate. The reduction in thickness and width of outcrop is not explained by a lateral gradation of the upper beds into slate. Wolff, in calling attention to the variation in thickness in neighboring drill holes, suggests an erosion after the deposition of the iron formation was completed, but the persistence of the upper beds makes this less likely than the variation in thickness of the lower beds.

Thus the reduction in the total thickness of the iron formation from 800 feet, as a large average, to 400 feet at the east, is largely attributable to the thinness or absence of the lower beds. The granite surface on which the iron formation was deposited, in R. 12 W., shows valleys about 80 feet deep. The upper beds, however, decrease somewhat in thickness.

The value of such correlation has been emphasized by Wolff in his work on the hematite ores.[9] In summary it is found that the character of the hematite, whether blue and hard, or brownish-yellow and soft, is largely determined by the original horizon. Leith has noted a very constant relation also between the amount of phosphorus and the horizon;[10] the finer grained rocks, slate and paint rock, and the ores near them have high phosphorus. It is noted by both Leith and Wolff that the detail of differences in beds, and the correlation of beds, can be used to determine structures in the iron formation; and the slumping and folding so determined are guides to the occurrence of leached and enriched ore.

Wolff observes further that the lower cherty and upper cherty horizons seem to be the most susceptible to enrichment into ores. Emphasis should be placed on this fact here, for it is not an accidental or arbitrary condition. The original taconite was richer in these horizons. It is evidently more likely that ore will be enriched to 55 per cent iron, if the original contained 30 per cent, than if it had less than 10 per cent iron. On the east Mesabi, interest centers in the quality of the original, unenriched taconite, and since the several beds are characteristically rich or lean this determination may guide the exploration farther west along the favorable horizons.

Plate X shows that the several horizons are recognizable in drill cores and can thus be traced across the range.

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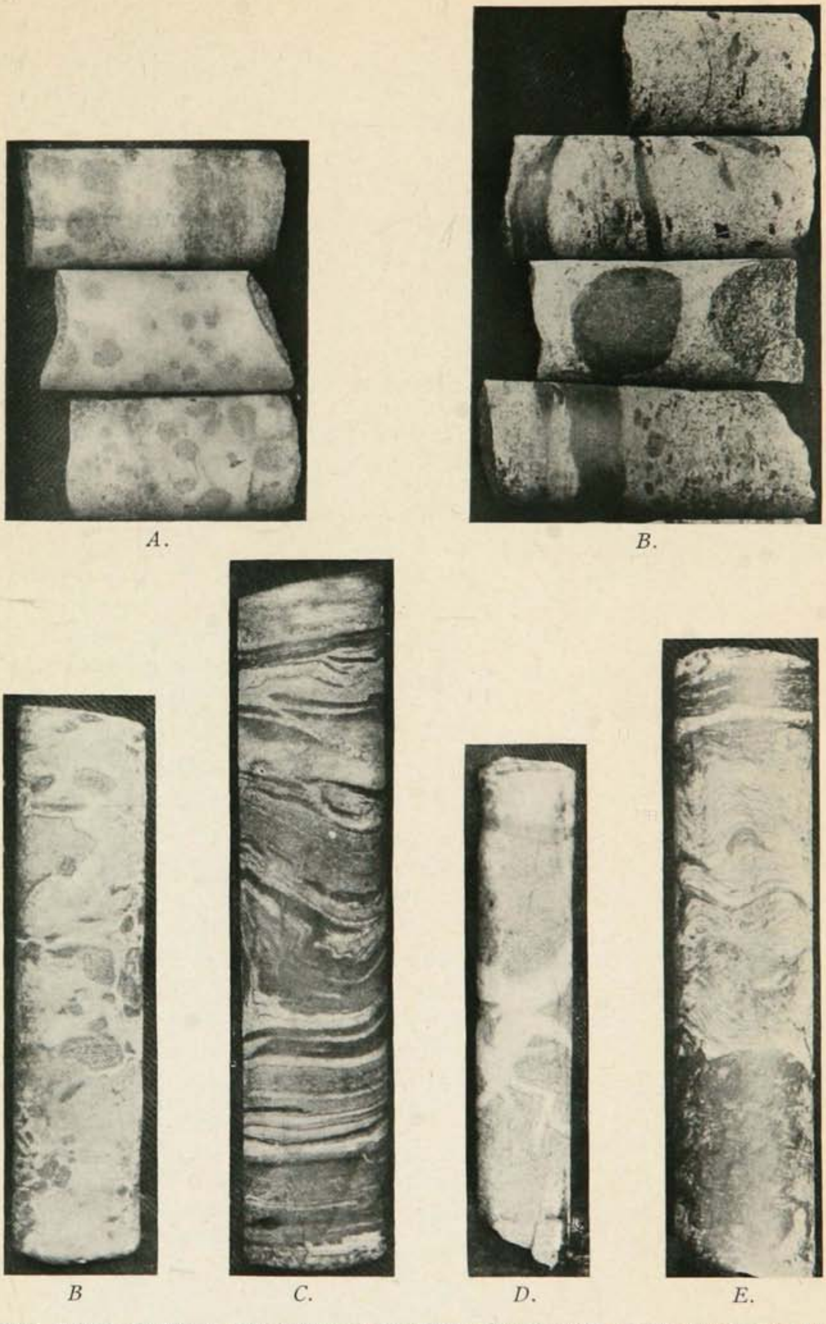
[9] *Op. cit.*, p. 154.

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

PLATE X



DRILL CORES SHOWING THE SEVERAL HORIZONS RECOGNIZED AS CLEARLY AS IN THE OUTCROPS. *A.* LOWER SLATY BEDS WITH FAYALITE. *B.* CONGLOMERATE. *C.* UPPER SLATY BEDS DRAG FOLDED. *D.* SEPTARIA CRACKS. *E.* ALGAL CHERT

CHAPTER V

THE HEMATITE ORE DEPOSITS

The Graham pits at Mesaba.—The two Graham open pits at Mesaba are near the main line of the Duluth and Iron Range Railway. They were until recently worked for hematite. The magnetite which may be assumed to have been the chief primary iron mineral is almost wholly oxidized in the workable ore. Very little attention is given in this paper to the process of enrichment of such ores. It is noteworthy, however, that the horizon of the ore bodies is shown to be that of the primary magnetite beds (Aub_4 and Aub_5). Septarian flint concretions occur near the tops of the pits.

The Mayas mine.—The enriched hematite of the Mayas mine was apparently about worked out to the depth of the pit. Some ore is left in the bottom, as shown by recent drilling. The hematite concentration at this point occurred near the horizon of the lower zone of magnetite concentration below the intermediate slate. Recently the demand for manganese has led to renewed exploration of the pit and several layers with 6 to 30 per cent manganese have been uncovered and mined. These are to be attributed to secondary concentration.

The Spring mine.—The ore of the Spring mine, like that at the Mayas mine, was concentrated at the horizon of the lower magnetite bed, below the slate. Oxidation has not been complete in all parts of the ore, as the remnants left in the pit contain considerable magnetite. The ore formerly mined, probably all of the best grade, may have been mostly oxidized.

Hematite prospects.—Prospects and drill holes show hematite at several places east of the Spring mine, but all show a mixture of hematite with magnetite. None seem to have been rich enough to warrant development. Most of the prospect holes are in the lower magnetite zone, below the slate. An area in the N.W.¼ sec. 28, T. 59 N., R. 14 W., received special attention.

The enrichment of hematite ores.—The leaching, oxidation, and enrichment of these ores was no doubt accomplished by the processes affecting the ores farther west, and studied in detail by Leith[1] and Wolff,[2] both of whom recognize a relation of the enrichment to folds and jointing. The eastern hematite deposits have not been examined in detail, but it is noteworthy that the Spring mine, the most easterly mine worked, is in a rather sharp fold. It may also be noted that the lower ore horizon is near the granite, and likely to receive alkaline

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

[2] Wolff, J. F., *op. cit.*

solutions that would leach out silica; while the upper ore horizon along much of the belt is nearer to a swampy tract where the acid water would dissolve out iron rather than leave the ore enriched in iron.

It is commonly supposed that the enrichment of the soft hematites of the Mesabi occurs without much effect on the state of oxidation of the iron. However, it is clear that at these eastern mines the iron of the fresh taconite was mostly in magnetic form. Outcrops on both sides of the hematite body contain magnetite. Since this magnetite has been altered to the ferric iron producing the secondary hematite ore bodies, it is possible that magnetite may have been the chief primary oxide all along the range. This is indicated by some preliminary tests on drill cores from the central and western parts of the range.

CHAPTER VI

THE MAGNETITE DEPOSITS—GENERAL

The minerals of the deposits.—Practically all the minerals mentioned as occurring in the iron formation, are found in the magnetite bodies. Probably over 95 per cent of the beds Aub$_4$ and Aub$_5$ consists of amphibole, quartz, and magnetite. To the west, some hematite is intergrown with the magnetic iron oxide.

The magnetite is rarely pure, but the impurities are the intergrown quartz and amphibole. There are very small amounts of pyrite, and analyses show that the phosphorus is low in the beds containing the most magnetite. Titanium has not been found even in the deposits close to the Duluth gabbro, which contains much titaniferous magnetite.

Chemical composition of the magnetite rock.—Van Hise and Leith[1] give the following analysis of the average rock of the east Mesabi (apparently the samples are actually from the Gunflint Lake region) which is tabulated, for comparison, beside the average taconite of the west Mesabi.

Average Composition of Amphibole-Magnetite Rock and Taconite of the Mesabi District

	AMPHIBOLE-MAGNETITE	TACONITE
SiO_2	60.51	58.71
Al_2O_3	1.20	.54
Fe	25.22	25.71
MgO	.52	.....
CaO	.67	.....
H_2O	Small	(Ignition) 1.96
P_2O_5	.05	(P) .021
S	.59	
MnO_2	.92	
TiO_2	None	

As compared with these analyses, which represent the average of the whole formation, the following results were obtained by J. H. McCarthy, at the Minnesota School of Mines experiment station, on an average sample taken from the upper cherty beds, where magnetite is more abundant than in the average of the whole formation.

Analysis of an Average Sample of Cherty Beds of Magnetite Rock near Sulphur

SiO_2	45.17
Al_2O_3	0.67
Total Fe	33.80
CaO	3.02
MgO	2.39
CO_2	0.58
TiO_2	Trace
Mn	0.61
Soluble Fe	29.20
P	0.049

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[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 181, 185, 204.

Textures.—The textures of the magnetite and its matrix are probably indicative of their origin. The most conspicuous features are the abundance of conglomerate in the upper cherty beds and the concretionary beds above the conglomerate. (Plates V B and VI B.)

The granule texture of the taconite in layers alternating with magnetite has been studied in detail by Leith, who ascribes most of it to the occurrence of greenalite in the fresh original rocks. In the altered rocks of the main eastern area, greenalite is entirely recrystallized. Some granules of amphibole may represent original greenalite, but there are many rocks in which the texture gives an impression of a series of fragmental grains of varying size. The small grains are less than .05 inch, but they seem to have similar characters in all sizes up to 6 inches. Most of the grains are magnetite in large part, though the magnetite may be intergrown with or intimately related to the quartz and amphibole. Many of the pebbles are cherts or other siliceous material. Many of the siliceous pebbles have a richer magnetite rim or border. A few are zoned in alternating bands of magnetite and siliceous matter, as if altered by diffusion. Many are fractured in an irregular network of cracks resembling septaria, with white quartz filling. These remarks apply to the microscopic grains as well as to the larger pebbles. (See Plate IX.) Some of the larger pebbles consist of conglomerate made of granules and smaller pebbles.

Some of the black pebbles show a dull appearance resembling graphitic rather than ferruginous minerals. Many of these have adjacent to them in the granular matrix a zone of lighter color than the average matrix. Some of the pebbles, themselves composed of granular material, are hardly distinguished from their granular matrix.

The magnetite layers alternating with the conglomerate and granular taconite are compact and contain more or less quartz and amphibole intimately mixed. Many of them, however, seem fairly pure.

The concretions, bearing septaria of white quartz, have been described above as guides to horizons near the center of the magnetite deposits.

All these textures tend to become obliterated by recrystallization, northeast of Dunka River. The conglomerate, however, is recognizable almost to Birch Lake, while the chert becomes an aggregate of quartz with grains up to half an inch in diameter. The coarser grain has an economic significance, because in the magnetic separation the grains of impurities must be separated by the grinding, and the coarser ores require less grinding to give a clean concentrate. It is probable also that the reduction in porosity during crystallization, from 5 per cent to less than 1 per cent,[2] is responsible for the lack of much weathering in the eastern areas.

Stratigraphy of the magnetite.—It has been found that the amounts of magnetite in the several beds of the iron formation here distinguished are fairly constant over a wide range of territory. The preliminary estimates made on field observations have been checked by a number of assays, and notwithstanding considerable local variation in any given bed, the concentrations of iron prove to be at fairly uniform horizons. Figure 3 gives a generalized estimate of the horizons of magnetite concentration. It may be assumed at once that any large area of the conglomerate bed and probably the lower member of the upper slaty beds will bear about 20 per cent of iron in magnetically separable form wherever they are located east of Mesaba, except in the rare case of weathering to hematite. In detail, however, these beds in large areas probably vary from 12 to 28 per cent in magnetic iron. Drilling has already shown some variations, and there are concealed areas as large as a square mile. Furthermore it may be assumed that the smaller beds just above and below the cherty beds with algal structure, will be considerably richer than 20 per cent iron in magnetite. In the magnetite beds, the iron in minerals other than magnetite increases the total iron content to about 35 per cent, but this is not considered available, so long as the recovery of iron depends on magnetic concentration. The smaller magnetite layer below the intermediate slate is perhaps less uniform, and certainly not exposed in so many places, but it is similar in grade to the thicker upper zone.

The importance of the detailed stratigraphy reported in Chapter IV becomes apparent as soon as the deposits of magnetite of this grade prove to have commercial value. Outcrops along the range are about as numerous in one horizon as another, and the identification of any one horizon will be a definite guide to the location of the magnetite deposits. The persistence of certain features such as the algal structure and septaria cracks, or even the intruded diabase sills, makes it possible to determine the limits of the magnetite zone with unusual accuracy even without drilling. A small amount of drilling confirms the field estimates in most cases. The drill cores furnish still other horizon markers. Mr. Fred Jordan, one of the engineers conducting the explorations near Sulphur, has found that correlation is possible on the basis of the per cent of soluble iron in the tailings from magnetic concentration. This iron may be in the form of fayalite or siderite, or possibly hematite. The fayalite was most often noted in the field.

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[2] Van Hise, C. R., and Leith, C. K., *op. cit.*, p. 554.

It is to be expected from the greater thickness of the iron formation farther west, that there will be some variation in the thickness of magnetite zones. The irregularities of the bedding, on a small scale, might suggest that the deposit would be erratic. Nevertheless it may again be emphasized that in spite of local variation the average magnetite content of certain beds is high enough to be of interest. The thickness of the main zone carrying conglomerate or septaria is 200 feet, and as this increases to the west, there may be included lean beds. A certain amount of drilling is necessary to determine the favorable locations. Outcrops and drill records, however, in R. 12 W., show a conglomerate zone 100 feet thick near the center of the iron formation. Wolff shows a similar section with conglomerates through a zone of 100 feet in R. 18 W., and 95 feet in R. 20 W., 35 miles west of the eastern Mesabi area. These records make correlation fairly safe.

Distribution of the magnetite deposits.—The magnetites east of Mesaba were known before the deposits of the Mesabi range west of Mesaba were developed. The changes from hematite ore bodies under drift, farther west, to harder magnetite in good exposures farther east, are conspicuous. Certainly the proportion of hematite in the formation grows rapidly lower to the east of Mesaba. Nevertheless when attention is directed to the leaner, unaltered taconite containing magnetite, and the secondary concentrations are ignored, the amount of ferruginous material that can be concentrated magnetically from fresh taconite is only slightly less near Mesaba than farther east. West of Mesaba fresh taconite, mostly from drill cores, is available from Aurora, Gilbert, Virginia, Eveleth, Hibbing, and Coleraine. Concentration tests on these samples indicate about as much magnetic iron in these cores as there is in the area between Mesaba and Birch Lake. The data at hand indicate that the horizons of primary iron concentration (now magnetic) are probably just as thick as they are east of Mesaba. The western areas are more interrupted by secondary leached zones of hematite, and are much more deeply covered with drift, but there can be no doubt that large bodies of lean taconite in the western areas carry over 20 per cent iron in form for magnetic concentration. Furthermore, there are in the western, as in the eastern area, two main horizons, one above and one below the "intermediate slate." Through the central part of the range each of these magnetite zones is over 100 feet thick.

As an illustration of the masses which have been drilled without recognition of magnetite, Figure 5 is presented. It is sketched from a reëxamination of cores from drilling, in which a fair body of hematite was discovered—perhaps two or three million tons. Two magnetite bodies are outlined, one about two million and the other ten million tons. These are an average of 55 feet thick, under a drift cover of 65 feet,—less favorably situated than the deposits east of Mesaba, but still worthy of note. The samples of these cores were ground to 100 mesh and concentrated magnetically, 2.83 parts of ore giving 1 part concentrates with an iron content of over 64 per cent.

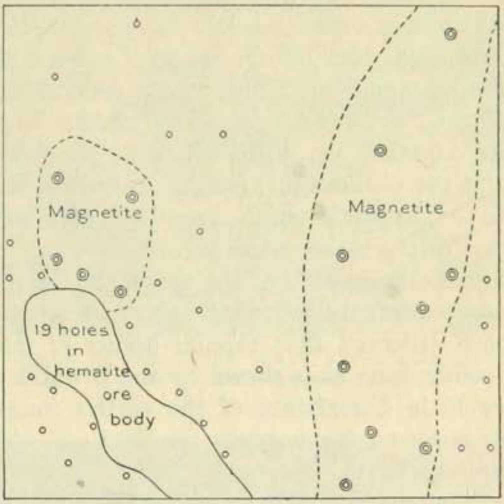

FIGURE 5. SKETCH MAP OF A QUARTER SECTION ABOUT 20 MILES WEST OF MESABA, IN WHICH DRILLING HAS DEVELOPED A BODY OF HEMATITE. THE CORES SHOW TWO BODIES OF MAGNETITE WHICH HAVE BEEN IGNORED, BUT WHICH ARE ABOUT 5 TIMES AS LARGE AS THE HEMATITE BODY.

This discovery that magnetite is a prominent constituent in the fresh taconite of the west Mesabi was unexpected, because of previous reports of the dominance of hematite west of Mesaba.[3] It was also supposed that magnetite is relatively stable under leaching and would not ordinarily alter to a soft hematite. It is very evident, however, that ferric oxide has formed east of Mesaba, by alteration of magnetite. The occurrences of abundant magnetite in the west part of the range in the fresh unweathered iron formation suggest that the protore there also contained more magnetite than hematite.

Magnetic mapping.—The persistence of magnetite across the range and its localization in certain beds of the iron formation might indicate the probability of a successful magnetic search for these horizons. Leith, however, recorded observations along the range indicating much more magnetic effect in the east Mesabi than on the main range and

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[3] Magnetite has recently been noted by J. F. Wolff, Recent geologic developments on the Mesabi iron range: Lake Superior Min. Inst., Proc., vol. 21, pp. 229-57, 1917.

concluded that there is much more magnetite east than west; he also noted that no special horizons were detected by the needle unless it was the zone just above the Pokegama. He found high readings in places near the contact of hematite and fresh taconite.

Detailed dip needle and dial compass readings have been taken on lines one quarter of a mile apart, all along the east end of the range, and while the deflections show the boundaries of the iron formation as a whole, it has not been found possible to relate them very definitely to the several horizons. No line of readings crossed the iron formation without finding some high dip needle deflections, and the dial compass was affected somewhat erratically, mostly in the belt of the better magnetite deposits, but it has not been possible to make much use of the data in the detailed mapping or in the search for the richest magnetite. (See the description of the Iron Lake area, pages 52 and 53).

In explanation of the rather weak attraction which is shown by the iron formation of the main part of the range for the magnetic needles used in exploratory work, the following points are mentioned:

1. It has been observed that tabular bodies of magnetite with a low dip to the south, such as is shown by the Biwabik iron formation, may cause very little disturbance of the earth's magnetic field, and hence have little effect on the magnetic needles.[4]
2. The oxidation of the magnetite to ferric oxides to a depth of several hundred feet in many places makes the attraction at the surface weaker.
3. The burial of the iron formation beneath a great thickness of glacial drift has the same effect.

Method of estimating reserves.—With a little more drilling it seems likely that the continuity of the zones of iron concentration through the range may be very definitely established. If it is agreed that the primary magnetite concentrations occur as strata, drill holes spaced several hundred yards apart will give a good check on the location of ore and the amount of drift cover. The estimation of reserves becomes a problem of stratigraphy rather than one of drilling. Detailed drilling will be entirely unnecessary unless it is found to be the best method for the study of the thickness of drift, and two or three variable features which interrupt the formation locally, viz., dikes, faults, and secondary alteration to hematite. With due allowance for these factors, the volume of ore can be calculated with very little drilling.

The quality of the ore also may be estimated in the case of such primary beds with much less drilling than in the case of enriched ores. While there are variations in the quality of beds, the changes are much less abrupt than in the case of enriched ores, and a few holes should give a fair indication of the average ore.

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[4] Broderick, T. M., Some features of magnetic surveys of the magnetite deposits of the Duluth gabbro: Econ. Geology, vol. 13, no. 1, pp. 35-49, 1918.

A. DRAG FOLDS IN THE UPPER SLATY BEDS, ALTERNATING WITH MORE COMPETENT LAYERS

B. THE CLOSELY SPACED JOINTS OF THE CONGLOMERATE PHASE OF MAGNETITE DEPOSITS

CHAPTER VII

THE MAGNETITE DEPOSITS—ECONOMIC CONSIDERATIONS

Commercial situation.—It is, of course, a commercial matter to decide whether or not any particular deposit of magnetite is to be classed as ore. Up to this time reports on the Mesabi magnetite have been unfavorable; but the economic features of these deposits indicate that as the reserves of richer hematite ores are depleted they will be worthy of more and more consideration.

The commercial situation naturally varies from day to day. The world war started an increase in the demand for iron, and the statistics issued by the United States Geological Survey show that the production in the Lake Superior district increased greatly in 1915 and 1916.

Iron Ore Produced in Lake Superior District, in Gross Tons

1914	33,540,403
1915	46,944,254
1916	63,735,088

Prices have advanced as the demand continued, and in spite of labor and transportation difficulties new reserves have been discovered and new mines opened. Some old abandoned mines have been reopened, and it has been said that if an iron mine can not be made to pay under such favorable circumstances there seems to be little hope for its immediate future.[1] It seems likely that a well equipped plant might have made a profit under these conditions, if it had been already established on the east Mesabi, but the time was not as favorable for building new plants as for stimulating production from those already built. Two small quarries and the experimental mill at Duluth have been operating recently.

Per cent of iron and volume of material.—The grade and amount of ore must be considered together. Specimens a few inches in diameter may show over 70 per cent iron, but no large volume of such ore is to be expected. Van Hise and Leith[2] dismiss the magnetites with the statement that they are a few inches to a few feet thick in layers with other rocks less rich in magnetite. It is true that beds with 30 per cent or more of iron in a form for magnetic concentration are relatively thin, but the beds with 20 per cent of iron (including some smaller beds with over 30 per cent) make up an immense tonnage. The tonnage and quality of material necessary to constitute workable ore must be determined by mining and milling costs and prices of ore.

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[1] Burchard, E. F., Our mineral supplies, iron: U. S. Geol. Survey Bull. 666, V, p. 3.

[2] Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, p. 185.

This report gives simply an indication of the general situation as to grades and quantities.

The upper cherty beds, Aub_4, contain near the top two layers of ore with about 30 per cent magnetic iron, and even more in some places. The lower of these is in places 20 to 30 feet thick and the upper about 10 feet thick. They are separated by a few feet of leaner cherty or jaspery material with a conspicuous algal structure, so that they are easily recognized. If this leaner bed is quarried with the rest, to get a working face 40 to 50 feet high, the grade might be reduced to a little below 30 per cent. The lean bed is easily distinguished, however, and could be cobbed out. The volume of such a bed several miles long and 50 feet thick must be very great, but since it dips at an angle of about 5° there is a relatively narrow belt in which the ore can be worked, with a high quarry face, without stripping off the overlying formation.

The beds mapped as Aub_4 and Aub_5, taken all together with rich and lean beds, and rich and lean areas, may contain as much as 20 per cent of iron available for magnetic concentration. Lean beds, especially near the top, will be partly balanced by the richer beds near the algal chert. Since the drilling shows some areas much richer than others along the belt, it must be remembered that drilling may be needed to select a favorable area. The outcrops shown on the map extend along a belt about 20 miles long and the average width is about 2,000 feet. With a dip of 5° it may be assumed that the northern edge is too thin to be considered for a distance of 400 to 500 feet from the border. South of that, the magnetite beds cover the area mapped to a depth of from 50 to 200 feet, with only a small amount of drift cover at most places. A rough calculation indicates that the east Mesabi range from Birch Lake to Mesaba contains about 1,500,000,000 tons of this magnetite formation within 100 feet of the present rock surface, without any bed rock cover. If such a reserve is to be considered as "available at present," it will more than double the present reserves of the range. The reserves of similar grade farther west are less accessible since they are covered more deeply with drift, but they are very large.

Van Hise and Leith[3] estimated in 1911 that the total present available reserves on the Mesabi were nearly 1,500,000,000 besides the "wash ores." If the lean bodies of "wash ore" of the west Mesabi are to be included, these magnetic ores of the east Mesabi may well be added also. They have certain advantages over other lean ores. For example, Van Hise and Leith[4] include in the reserves available for the distant future, ores that have 35 to 40 per cent iron, regardless

[3] *Op. cit.*, p. 489.
[4] *Op. cit.*, p. 491.

of whether or not they are concentrating ores, but add that very little of this ore will be used for a long time, except by mixing with high-grade ores. The advantage of the magnetites lies in the fact that they can be concentrated to a very high grade. This gives a supply of high-grade concentrate which will make it possible to continue mixing in the low-grade ores, long after the naturally high-grade ore is exhausted. Much of the magnetite bed here considered now contains about 35 to 40 per cent total iron, but only part of this iron occurs in the mineral magnetite.

Topographic situation.—Most of the outcrops of magnetite are on the south slope of the Giants Range and extend with minor undulations down the slope, descending about 100 feet in half a mile. Some of the exposures on the lower southern side are near the level of the swamps or valleys in the slate and not favorably situated for mining, but a large part of the formation stands at high levels and can be mined in open cuts with surface drainage.

Structures.—The beds dip gently and it will not be very difficult to follow the valuable beds down the dip. The bedding planes, though very irregular, furnish surfaces of easy parting.

The joint system in the conglomerate beds is especially favorable to shattering the rock with heavy blasts "against resistance" of previously broken material. The joints are nearly vertical and run prominently about north and south in most places, spaced 1 to 6 inches apart. They are crossed by another set about at right angles. Other sets of joints have been locally noted. Plate XI B shows the prominence of the joints where weathered, but traces of the same structure make the rock break well even at considerable depth.

Magnetism.—The fact that the ores are of magnetic oxides has led to experiments with magnetic milling methods which are so promising that ores of much lower grade than heretofore become of interest. Throughout the east Mesabi the beds designated as magnetite deposits have their iron largely in a form that can be magnetically concentrated. Nevertheless the ore of some of the deposits shows under the hammer a red powder and contains some hematite.

The chemical tests of the several divisions of the iron formation have not been carried far enough to determine why some beds consist largely of iron silicate—fayalite—while others with similar amounts of iron consist of magnetite and quartz. The fayalite is most commonly developed in a quartz-amphibole matrix, but some of the samples have magnetite also, and may be as rich as the rest of the deposit. The matter of combination may be determined by the state of oxidation or by the presence of other elements. Whatever it is, the results are clear;

some beds have considerable iron in magnetic form, and these are the beds distinguished in mapping.

Size of grain.—The grain varies in different beds as well as in different areas, with more or less relation to the distance from the gabbro. The coarser grain is favorable, requiring less fine grinding for the magnetic separation of a rich concentrate. The finer grains remain attached to quartz and silicates which then get into the concentrate and reduce its grade.

The coarse-grained beds, favorable to concentration without the expense of grinding finer than 100 mesh, are the conglomerate beds, Aub_4, and all those that have magnetite east of Dunka River.

The impurities that may be retained in the concentrates, if not ground fine, consist not only of silica, but of phosphorus, which is even more deleterious. The concentrates normally bring a premium because of their low phosphorus. Apparently some parts of the deposits can be made to yield, without special treatment, concentrates so low in phosphorus that the premium is high. Sulphur is normally removed without extra care.

Hardness.—The taconite is one of the toughest, hardest rocks that is quarried. It will always be hard to drill, but the jointing is a great aid in breaking up the rock after blasting.

Milling.—The Mesabi Syndicate have had the benefit of the work of men widely experienced in magnetic concentration, and have built a mill at Duluth in which they have conducted tests of their ore as well as several new devices for milling, and various materials for sintering. The mill has been operating to capacity, producing low-phosphorus concentrates.

Grade of product.—The fineness of grinding and other variable processes in milling permit the operators to determine in advance about what quality of concentrate will be produced. By manipulation of the process, then, the mill can produce any grade of concentrate for which there may be a demand, even those which draw a premium for unusually low phosphorus, and high iron, contents.

In the fall of 1918, a trial cargo of low-phosphorus sinter made from east Mesabi ore was shipped from Duluth to the Midvale Steel and Ordnance Company's blast furnace at Coatesville, Pa. The cargo analysis shows an iron content of 63 per cent, with .008 per cent of phosphorus. It is expected that the concentrates made from these ores to supply the normal demand will run over 60 per cent iron and from .020 to .025 per cent phosphorus.

Transportation.—The distance from market is about equal to that of other Mesabi ores. The Duluth and Iron Range Railroad now has a temporary line along most of the magnetite belt.

Cost of exploration.—It has already been suggested that when enough drilling has been done to satisfy the explorers that the ore beds are continuous, a very few drill holes will give all the data needed as to the quality. It should be much cheaper to explore a property of this regular bedded type, than the irregularly leached deposits of soft ore of the Mesabi.

Scale of operations.—There is plenty of magnetite so that mining operations can be undertaken on as large a scale as at any mine in the world.

Suggestions for conservation.—1. Sampling. Since 1891 when the rush came to the rich ores of the Mesabi range, it has become a fairly established custom to sample drill cores for analysis wherever there was an appearance of enrichment, even if the ore seemed to be lean. On the other hand, hard unaltered looking taconite was of no interest and any lump of core might be thrown in a box as a fair sample for the 5 or 10 feet of core from which it came. In the magnetite bodies all the core looks fresh and unaltered. Nevertheless it is important to have a fair sample. Many of the old cores which have been examined in this work indicate large bodies of magnetic material, but the accuracy of the samples is very uncertain.

2. Magnetic tests. Before a mining property is wholly abandoned for lack of ore, the cores with magnetite should be tested by magnetic concentration to see if any very large body of 20 to 30 per cent magnetite is in favorable position for development.

3. Location of dumps. It has often happened on the Mesabi range that the dump piles from stripping operations and the waste of mining were placed where they had to be moved later, to get some good ore that was unknown at the time. We suggest therefore, that even now before the magnetites are worked, dumps should not cover the better magnetite bodies. It is uncertain how long it may be before the magnetite will be wanted, but when the time comes, the ore should not be inaccessible because of our carelessness in locating dumps. (See Figure 5, illustrating a neglected magnetite body which might be carelessly buried under so much waste that it would not pay to remove it, to get the magnetite.)

CHAPTER VIII

THE ORIGIN OF THE MAGNETITE DEPOSITS

Introduction.—The bedded and banded character of the iron formation taken in conjunction with its mineral composition indicates clearly the sedimentary origin of the material.

Agent of transportation.—Cherts and the several primary sediments of iron, on the Mesabi, are materials known to be precipitated from water solution, and it is generally agreed that in those parts of the formation where clastic grains are lacking, it may be assumed that the iron-bearing sediments were deposited from water solution. No mechanical sediment is known which closely resembles them. The solution of silica may have been facilitated by the presence of alkalies; that of iron would be more likely in the presence of acids. If carbonate minerals were more abundant (as in some other ranges) an alkaline bi-carbonate solution might be suggested as the most probable combined solvent. This kind of solution is known to have had an igneous origin in some places. Incidentally some alkali may have been derived from the granite near by.

Source of the iron.—The source of the iron in the water solutions is naturally a matter of great interest. This question is discussed at length by Van Hise and Leith.[1] They conclude that for the iron of unique, thick, extensive iron formations like this, it is necessary to appeal to contemporaneous basic igneous rocks. Some of the iron may have been derived from the action of water on the rock, either hot or cold, but large parts of it may have been carried in solution by direct magmatic emanations. There is less contemporaneous igneous rock near the Mesabi than in most iron districts, but there was a large amount of igneous activity from the Cuyuna range in Minnesota, to the Marquette district in Michigan, and probably elsewhere.

Deposition.—1. Precipitation.—From any assumed solution, it is easy to suggest reactions that will precipitate silica and iron.[2] The direct evidences of the actual form of the precipitate and the nature of the precipitating agent are very slight. There are the supposed algal forms in the cherts and jaspers indicating organic action. There are also the graphitic cherts and slates indicating organic material. Steiger[3] reports organic matter in some greenalite rock. Since it seems that organisms could live at that time and organisms are known to precipitate iron at the present time, it may be assumed that they

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[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, pp. 506-18.

[2] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 519-27.

[3] Steiger, George, See analysis in U. S. Geol. Survey Mon. 52, p. 167.

played a part also in the deposition of the iron of this formation. This is not certain, because the deposits seem to have been more or less modified since their first deposition, and their original form is in doubt. Leith has shown that material of similar composition and character can be produced by inorganic action in the laboratory, so that the action of organisms is not essential to precipitation. Current studies however seem to indicate that if a reaction may occur both organically and chemically, it occurs more rapidly and completely by the action of organisms. It is therefore believed that organisms precipitated not only cherts, but at times, highly ferruginous cherts. Harder and Johnston refer to the possible precipitation of ferric oxide and silica, as the primary deposits of the iron formations, associated with more or less organic matter.[4] The iron of the Biwabik formation was probably in a combination of a ferrous silicate and carbonate, and a ferric oxide, in proportions varying according to varying conditions.

2. Conditions of deposition. The extent of the magnetite deposits and the associated sediments indicates deposition on a broad sea bottom. The beds lie above a sand and below a clay, as a part of a series of sediments, probably formed in shallow water. Van Hise and Leith[5] consider the water probably shallow, because of the predominance of silicates over carbonates, the structural differences from the Cuyuna iron formation, and the lack of outcrops farther north. An additional evidence appears in the flat form of pebbles in the central conglomerate.

3. Texture of the deposit. The cherts with algal structure appear to be primary in their form and texture. Much of the remainder of the formation is filled with granules, pebbles, concretions, and nodules, indicating more or less reworking since precipitation. Throughout most of the iron formation the granules uniformly show certain mineral and structural peculiarities which have led to the suggestion that they are not ordinary fragmental sedimentary grains. (See Plate IX D.) Leith has argued that the granules of greenalite are forms that may develop in colloidal precipitates by surface tension; or, as he suggested in his earlier paper, by the replacement and coating of organic remains, in some such way as the granules of the Clinton iron formation are supposed to have formed. No doubt there are granules that are best explained as forms resulting from surface tension on precipitates, but there are also many pebbles which could not have formed from any process other than mechanical wear. Associated with fragmental pebbles, granules of similar fragmental origin are certain to be numerous. The writers believe, therefore, that much of the texture

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[4] Harder, E. C., and Johnston, A. W., Geology and iron ores of the Cuyuna district, Minnesota: U. S. Geol. Survey Bull. 660-A, p. 16, 1917.

[5] Van Hise, C. R., and Leith, C. K., *op. cit.*, pp. 214, 604, and 613.

has been modified since precipitation. Over half of the main magnetite deposit of the east Mesabi has the characteristic pebbly texture.

4. The alternation of deposition. The alternation of sediments of several sorts in the iron formation as a whole indicates a probable alternation in the source of supply. The larger alternation of slate and chert shows that deposition occurred under different conditions. On the other hand, the smaller, more often repeated alternation of magnetite with chert having a granule or pebble structure is not taken to mean any essential difference in the source of supply or agents of transportation, but rather an alternation of conditions acting on the material already deposited.

Primary modification of the deposit.—As has been suggested, the repeated alternation of material in the beds now found is believed to be a significant fact in connection with the history of the iron formation. There are hundreds of alternations of fine magnetite and coarser fragmental layers. Rhythmic sedimentation is in some cases due to a rhythmic supply of differing materials. In a broad way, the supply may be ferruginous at one time, slaty at another, and cherty at another. If the material had been derived from volcanic sources, as has been suggested, it seems improbable that these supplies would alternate as many times as the sediments indicate. It is unlikely that there were so many successive flows. Volcanic rhythms should produce alternations on a large scale. Furthermore, climatic rhythms are also larger features. The detailed alternation of beds from a tenth of an inch to 6 inches thick is more likely attributable to seasonal or other occasional changes in conditions. These changes would affect a chemically depositing sediment only if in shallow water, and emphasize the conclusion reached above as to the conditions of deposition.

The conglomerate and granular beds of the lower parts of the magnetite zones are very suggestive as to the conditions that must have prevailed. Most of the pebbles are flat, and vary widely in the degree of rounding. They include no fragments of the neighboring granite and schist, but many closely resembling the underlying beds of iron formation. Their size and angularity indicate no distant source. The irregularity suggests washed lumps of partly hardened mud, or precipitate. The most probable source of the pebbles is a part of the iron formation itself. However, no signs of erosional unconformities have been found in the iron formation. Such a conglomerate is to be classed as *intraformational,*—one formed of material recently deposited and without any extensive transportation. Such conglomerates are reported from several limestone formations with characteristics that are so similar as to warrant giving this siliceous bed the same name.[6] The conglomerate part of the formation, as well as some of the granules, may therefore be attributed to a recent precipitate more or less broken up by wave action. The freshly broken fragments would be large and angular pebbles, those washed about for a longer time would be more rounded, and the smaller grains would become rounded granules.

Most of the pebbles are magnetite. This might mean that an original ferruginous layer resisted the breaking action of the waves longer than some of the freshly deposited silica. Other pebbles, however, suggest another explanation. Many pebbles are cherty with a border of magnetite. It seems that at the time the pebbles were rounded (or possibly since then) some process *enriched* them in iron. Since it is believed that the pebbles formed in shallow water, the logical explanation is that standing water acted on the ferruginous chert, enriching it, much as the ores of the Lake Superior region are being enriched at the present day,—by solution of silica, and possibly, but only to a small extent, by deposition of iron in its place.

This assumption of leaching of silica in a sea where silica was accumulating does not appear plausible unless, as was true in this case, some alternation of conditions is indicated. In a shallow sea the contribution of iron and silica from a magmatic or other source may furnish plenty of material for deposition. But at a distance from the source any addition of fresh water, say from a heavy rain on the adjoining land, would crowd back the depositing solutions and replace them by water that would dissolve and oxidize the deposits, until diffusion and convection again brought in the stronger solution.[7] The volume of fresh water which leached the silica may not have been great enough to modify the composition of the depositing solution very much, after it was mixed by diffusion and general circulation. So the next deposit of iron is not necessarily leaner, or more siliceous than the first. Occasional storms might agitate the waters enough to break up the deposits and round the grains, but the special richness of the conglomerate in iron oxide is thought to be due to a primary leaching of the silica. The enrichment is considered primary because it is believed to have occurred before the overlying layer was deposited. While this enrichment is chemically the same, it is not such an enrichment as has occurred on the main Mesabi range in late geologic periods. That enrichment has been accomplished by circulating ground waters, and may be as deep as the waters carry solvent action. The primary enrich-

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[6] See for example, Foerste, A. G., Intraformational pebbles in the Richmond group: Jour. Geology, vol. 25, p. 289.

[7] Van Hise and Leith note that some greenalite was probably oxidized at the time of deposition. *Op. cit.*, p. 537.

ment here considered probably occurred at the bottom of shallow standing water and its effects were superficial. Nevertheless if each thin bed is superficially enriched, the formation as a whole shows the effect. From this point of view the magnetite pebbles may be those which were most thoroughly leached. There may be an analogy in the Cretaceous hematite conglomerates of the west Mesabi, but this is doubtful. The best magnetite is so characteristically associated with conglomerate that there is a strong suggestion that the taconite has rich layers only where leached.

In continuation of this argument, it is well to consider the end products of such processes of leaching and wave action as are here suggested. Eventually the silica might all be leached from a surface layer, and the residual iron compounds, thoroughly oxidized, might be pretty well pulverized. The conditions in deep water may also be such that a little leaching of silica might occur, leaving only a layer of iron oxide along the bottom. When deposition was resumed, this powdery ferric oxide, however formed, would lie on the irregular bottom as a layer of relatively pure ore. This is exactly the condition of the magnetite beds now alternating with conglomerate.

The suggestion here given as to the origin of the pure magnetite in no way conflicts with the possibility, suggested by Van Hise and Leith,[8] that some oxides may have been precipitated directly in very pure form. Precipitated oxides, however, would be expected to alternate with precipitated chert rather than with a conglomerate.

After any accumulation of oxides, the next precipitate would tend to cement any such layers into fairly firm masses, and the next storm would break them up into pebbles of iron oxide. This is the effect suggested by such outcrops as are shown in Plate IV A, where a bed of magnetite stops abruptly and there are near it some fragments that look as if they were just broken off. Thus both the enrichment of chert pebbles and the breaking up of greatly enriched iron oxide beds furnish ore pebbles to the conglomerate.

The development of nodules in the magnetite deposits is probably not a phase of primary deposition, but is believed to be an effect that developed soon after deposition. In the main conglomerate beds no clear nodules have been noted, but in the thin beds above the algal cherts, the structures can hardly be given any other interpretation. (See Plate VI B.)

Both silica and iron are known to be subject to concretionary rearrangement, and on the west Mesabi some common chert nodules may be seen. There are a few small concretions containing both iron oxide

[8] *Op. cit.*, p. 527.

and quartz in concentric bands. It is not generally supposed, however, that most of the small granules involved any concretionary action after their deposition. They have been considered in the preceding paragraphs as fragmental and precipitated granules. The peculiarity of the nodules here illustrated is that, though rounded and elliptical in outline, the internal texture is granular like the matrix and finer parts of the conglomerate. It is evidently a fragmental accumulation which has been incorporated or included in a nodular cement. The nodules are mostly elongated and show gradations into continuous beds of similar material, as shown in the figure (Plate VI B). Both the rounded forms and the irregular layers contain septaria cracks (Plate VIII). Between the nodules are thin beds of magnetite, and the nodules themselves contain considerable magnetite, so that the formation contains about 20 per cent of iron.

The conspicuous irregularity in the bedding is probably more closely related to these several primary modifications than it is to the original precipitation. Solution surfaces resulting from leaching normally show rounded forms; concretions are irregularly rounded, and the compression of loose sediments against the rounded lumps would no doubt produce some such wavy bedding planes. Considerable irregularity may be due to the shrinkage of voluminous colloidal precipitates during consolidation and recrystallization. The septaria cracks show that some such shrinkage occurred.

Metamorphism.—It can hardly be assumed that the primary deposition and reworking of the iron resulted in the formation of magnetite. The precipitation of magnetite in water at ordinary temperature is not a reaction commonly observed in nature. There is reason to believe that the precipitate was a chert with ferrous silicate and ferrous carbonate and more or less limonite. The oxidation and formation of intraformational conglomerate probably produced limonite. The change from these minerals to magnetite is a kind of metamorphism that may occur in several ways. Probably the ferrous iron of the silicate and carbonate and the more oxidized limonitic beds reacted directly to form magnetite. If the oxidation was very complete, a reducing agent is available in the organic matter, known to have been present in certain beds. These and other reactions have been sufficient, during the long ages of recrystallization under heat and pressure, to make most of the iron oxide of the Mesabi formations magnetite.[9]

The occurrence of magnetite and hematite as adjacent pebbles in a conglomerate, or as an intergrowth, has already been mentioned, but the alteration just outlined offers no explanation of the different state

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[9] This is not recognized by Van Hise and Leith. It is not necessary to appeal to the reduction or oxidation by water as suggested by them, *op. cit.*, pp. 172 and 527.

of oxidation of such associated minerals. The ease of alteration of ferric oxides to magnetite may be related to certain conditions in the primary ore. There might be differences in hydration, or different admixtures of hydrous minerals. There might be differences in porosity; different amounts of the organic reducing agent; or other peculiarities of mineral association. Any of these conditions may affect the later metamorphism to hematite or magnetite.

The development of several silicates and the coarse grain of much of the taconite may also be attributed to general metamorphism, but have had no very great influence on the value of the deposits.

Dynamic metamorphism is indicated by the folded layers and tension cracks. Scattered veinlets of quartz and magnetite probably developed under conditions of great heat and pressure.

The contact metamorphism of the iron formation as a whole has been discussed above. It has recrystallized the magnetite near the gabbro, increasing the size of grain and ease of magnetic separation. It apparently added no appreciable amounts of either iron or titanium.

Lack of secondary enrichment.—It is likely from the broader relations of the gabbro that much of the Virginia slate and even the iron formation had been eroded before the gabbro was intruded.[10] There may have been enriched portions of iron formation, but if so they have probably been eroded since Keweenawan time. The uniformity of the iron content in the fresh taconite from east to west on the Mesabi indicates that before the metamorphism just described there was no enrichment of the rocks now found on the east Mesabi of any such local sort as that now in progress. Since Keweenawan time enrichment has occurred in a few favorable areas.

The three mines of hematite in the east Mesabi are all in the western end of the area, and represent the gradation to the conditions of enrichment on the main range. East of the Spring mine there is practically no effect of weathering. Swamp waters may attack the formation to a depth of a few inches, but they impoverish it rather than enrich it. The porosity is said to be less than 1 per cent, as compared to 5 per cent farther west.[11] This difference in porosity is thought to be more important than the mineral composition in determining enrichment, for the magnetic oxides are found all across the range, and the magnetite east of Mesaba has in some cases been altered to the ferric form.

Résumé of the history.—Deposition occurred probably in shallow water by precipitation, mainly as an organic process, resulting in lean ferruginous cherts, with more or less siderite, ferric oxide, and greena-

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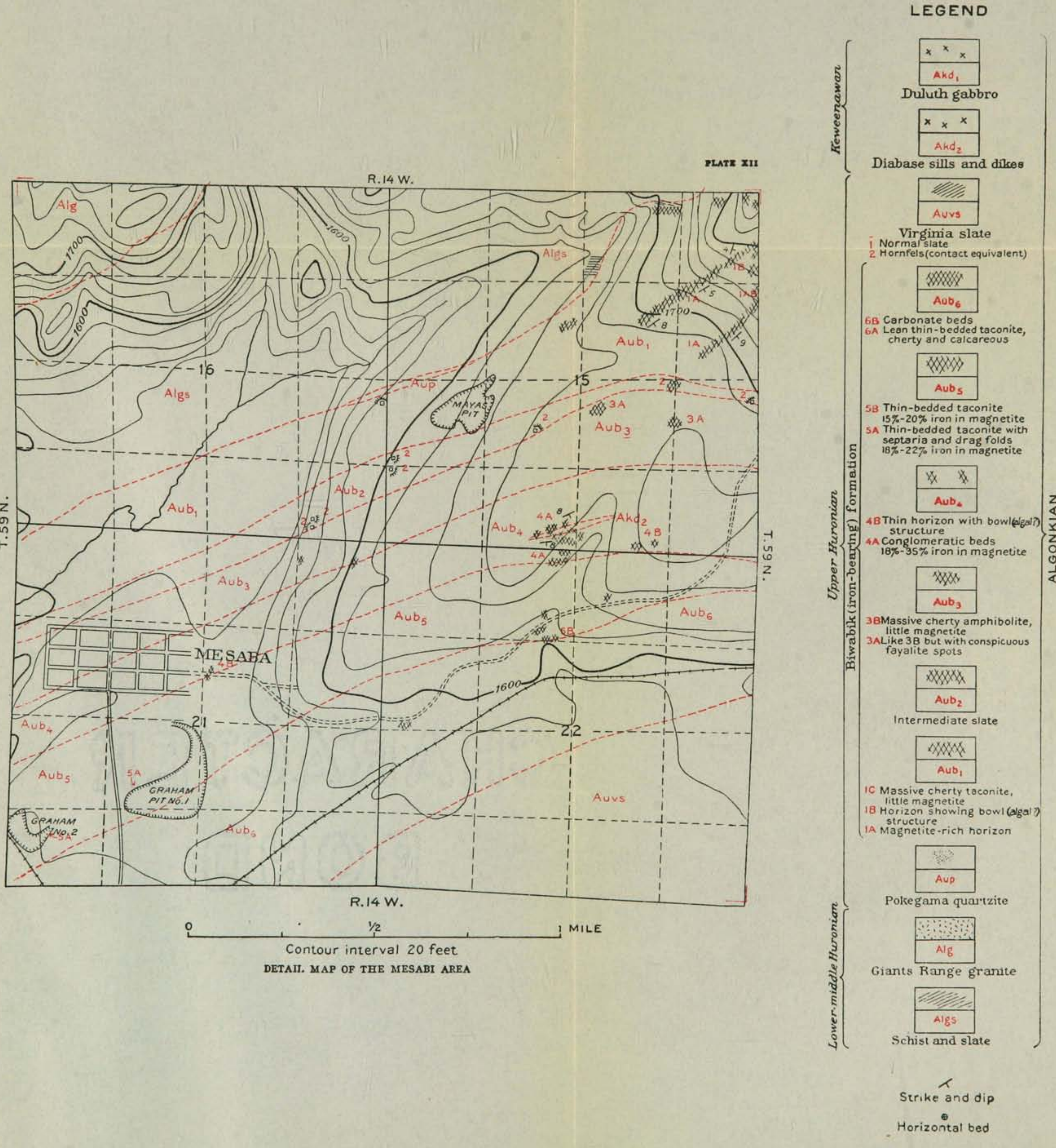
[10] Grout, Frank F., The lopolith: Amer. Jour. Science, vol. 46, pp. 518-20, 1918.

[11] Van Hise and Leith, *op. cit.*, p. 554.

PLATE XII



DETAIL MAP OF THE MESABI AREA

lite. Alternating with periods of precipitation came periods of solution, leaching, oxidation, and wave action, producing intraformational conglomerates, granular rocks much richer in iron, and probably some layers of pure ferric oxide.

The richer deposits of magnetite are so characteristically in the granule and conglomerate zones that we are led to believe that the primary leaching was a determining factor in the development of richer magnetites from lean ferruginous cherts, greenalite rock, etc. Later when covered with other layers, there may have been more or less concretionary rearrangement. Deep burial under slates developed heat and pressure that recrystallized a great deal of the formation. The iron minerals reacted at this time with each other and with organic matter, and possibly with other reducing or oxidizing agents producing magnetic oxides of iron. The recrystallization produced shrinkage cracks, and some regional movements developed folds, but seem to have had no important effects on the formation. Contact action by the Duluth gabbro and sills made a great difference in the texture of the deposits at the east end. Erosion has exposed the metamorphosed beds without any important weathering effects on the minerals.

CHAPTER IX

DETAILS OF THE DISTRICTS

The Mesaba area (*Plate XII*).—The two pits of the Graham mine at Mesaba are the most important recent operations of the east Mesabi. No detailed examination was attempted, but the walls of both pits show septarian concretions indicating that the enrichment occurred at the upper magnetite horizon. The algal jasper beds seem to have been somewhat resistant and escaped enrichment, for considerable amounts appear in the dump.

The Mayas mine, at the lower magnetite zone, was worked for some hematite of fair but variable quality. It was reopened in 1918 for some manganese that was recently discovered.

One of the best exposures of algal structure appears in the jasper northeast of the town along the road.

Greenalite, the amorphous green ferrous silicate considered by Leith to be the primary precipitate of most of the iron formation, was found in its best development in the material on the dump of a deep well at the north side of town. Many test pits at the south of the Mayas mine have dumps of rock resembling greenalite.

South of the area mapped in detail, in sec. 34, T. 59 N., R. 14 W., is a drill hole, reported by Van Hise and Leith[1] to penetrate some slate and then, passing 576 feet of iron formation, to go a number of feet into diabase. Diabase outcrops were not seen west of a thin sill exposed on the south side of sec. 15, T. 59 N., R. 14 W.

Magnetite rock that appears to have over 20 per cent of iron in magnetic form outcrops in both the upper and lower horizons. The lower horizons are well exposed in the N.E. ¼ sec. 15, T. 59 N., R. 14 W. The higher horizon is exposed near the road, along the south side of sec. 15 and the north half of sec. 22, T. 59 N., R. 14 W., and seems to represent the same body of magnetite as the larger exposures farther east.

No detailed work has been done south of the iron formation, but the approximate contact of the slate and gabbro south of Mesaba is easily determined by the outcrops along the railroad.

The Spring mine area (*Plate XIII*).—The Spring mine lies in a valley between hills of Lower-Middle Huronian slates on the west, and a bluff of slate and slaty taconite on the east. The ore has an easterly dip, and was enriched down even under the slate outcrops. The floor of the ore body is partly the Pokegama and partly older formations. The concentration and enrichment are discussed in Chapter V.

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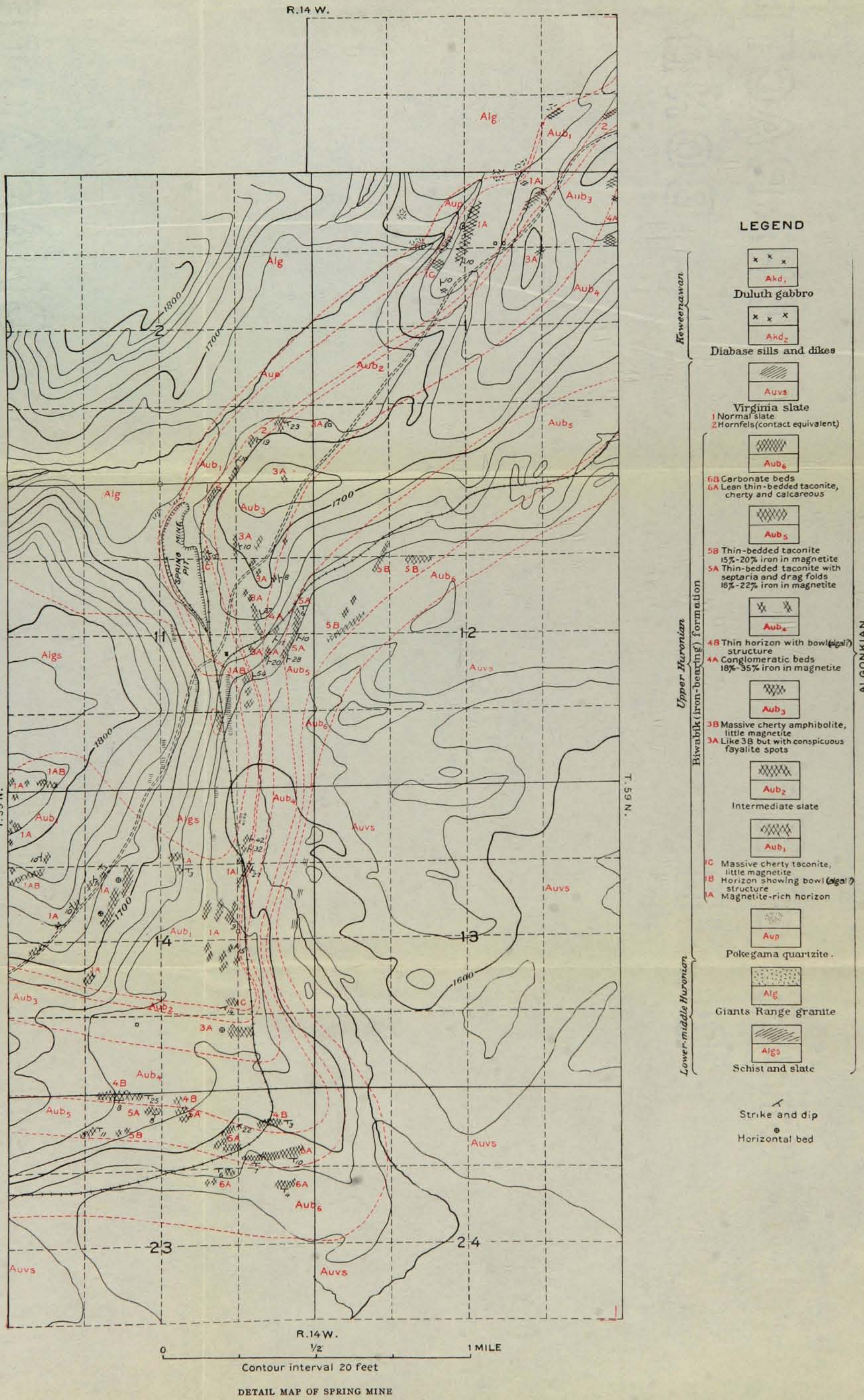
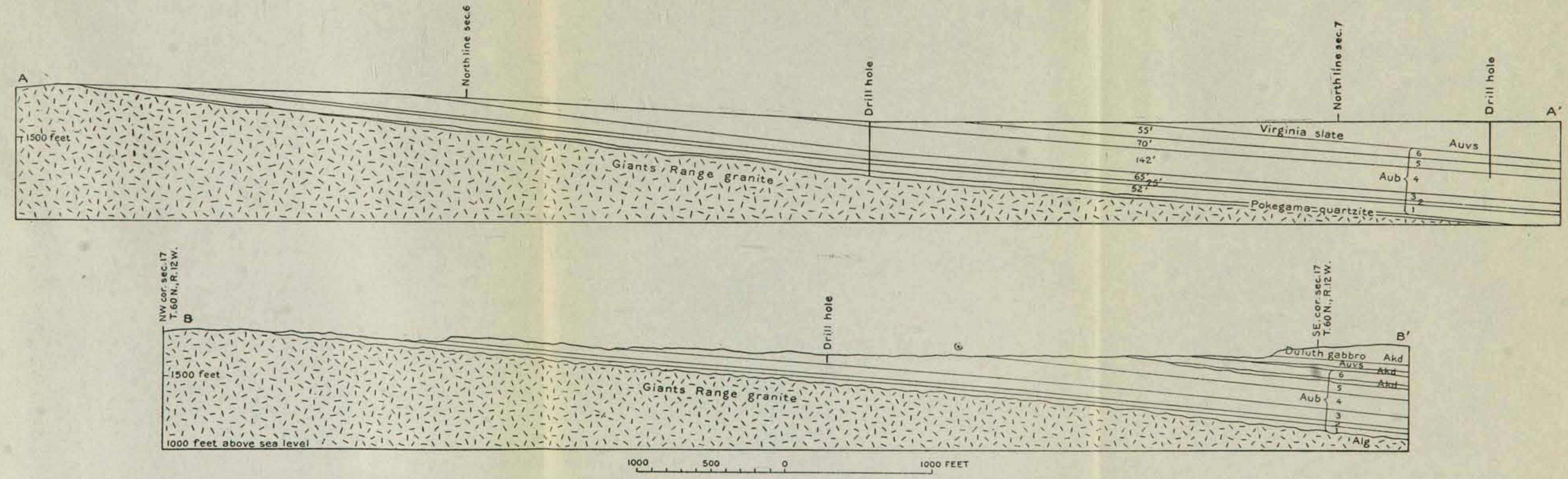
[1] Van Hise, C. R., and Leith, C. K., The geology of the Lake Superior region: U. S. Geol. Survey Mon. 52, p. 177.



DETAIL MAP OF SPRING MINE

PLATE XIV



AA'. CROSS SECTION OF THE IRON FORMATION EAST OF THE SPRING MINE

BB'. CROSS SECTION OF THE IRON FORMATION IN SEC. 17, T. 60 N., R. 12 W.

AUB$_1$, LOWER CHERTY BEDS. AUB$_2$, SLATE. AUB$_3$, SLATY TACONITE. AUB$_4$, CONGLOMERATE TACONITE, OR UPPER CHERTY BEDS. AUB$_5$, THIN BEDDED TACONITE. AUB$_6$, LEAN UPPER TACONITE.

The old pit was pumped out in 1917 for further exploration. It is referred to as the "Silverton property," but is locally still called the Spring mine because of a strong spring that issues near by.

The casing of an old drill hole in the western part of sec. 14, T. 59 N., R. 14 W., has a flow of water from artesian pressure. The beds no doubt outcrop in the hill half a mile north. The water is very clear and apparently not ferruginous.

The fold in this area is the largest in the east Mesabi, and may have been a factor in determining the location of the ore of the Spring mine. It is close to the change in bedrock below from granite to slate, but the slate stands at a higher level than the granite under the iron formation. There are intrusives which may be related to the structure. The outcrops may be interpreted as the fold shown on the map and block diagram. The steep dips of the beds in the narrow part of the fold, along the railroad, show that the folding was very sharp. It is possible that some faulting may have occurred also. Small faults may be seen in the slate. The discovery of some outcrops far to the south along the east side of sec. 23 makes the curve considerably sharper than it was previously supposed to be. (See Figure 6.)

It is in the northern part of this area that the Giants Range granite has been supposed to give way to the Embarras granite, a later intrusive on the east. No such intrusive could be found.

The exposures along the railroad south of Spring mine include several that were the bases of interpretation of the geologic history. In the N.E. ¼ of N.E. ¼ sec. 14, T. 59 N., R. 14 W., a few feet east of the railroad, iron formation conglomerate lies on the eroded edges of Huronian slate, with a striking unconformity.

In the S.W. ¼ of S.W. ¼ of the same section, the railroad passes some outcrops of slaty beds that resemble a phase of Virginia slate. The outcrops, however, can be followed directly west in a belt that passes between beds of iron formation, and they are undoubtedly outcrops of the intermediate slate. The slaty outcrops have conspicuous garnet metacrysts, which under the microscope prove to be filled with minute amphibole needles.

The magnetite bodies show some features that differ from those farther east. The upper magnetite horizon is relatively narrow, but the lower, by reason of increased thickness and relatively flat variable dip, shows a broad important area. A preliminary sampling of the area indicates over 27 per cent of iron in form for magnetic concentration, in an area of almost half a square mile. The thickness of this lower formation is indicated by some drill holes in the next sections east of Spring mine. They show over 40 feet of this lower bed, containing about 30 per cent of iron. Drilling was done in both sec. 1

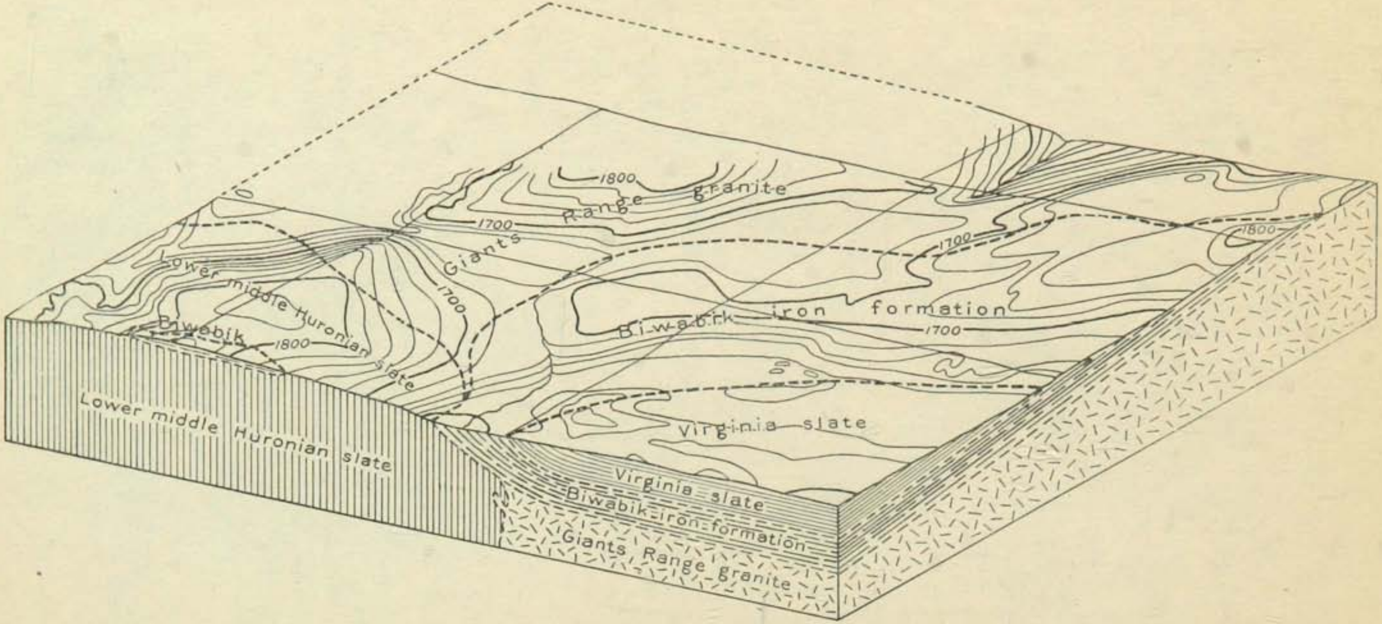
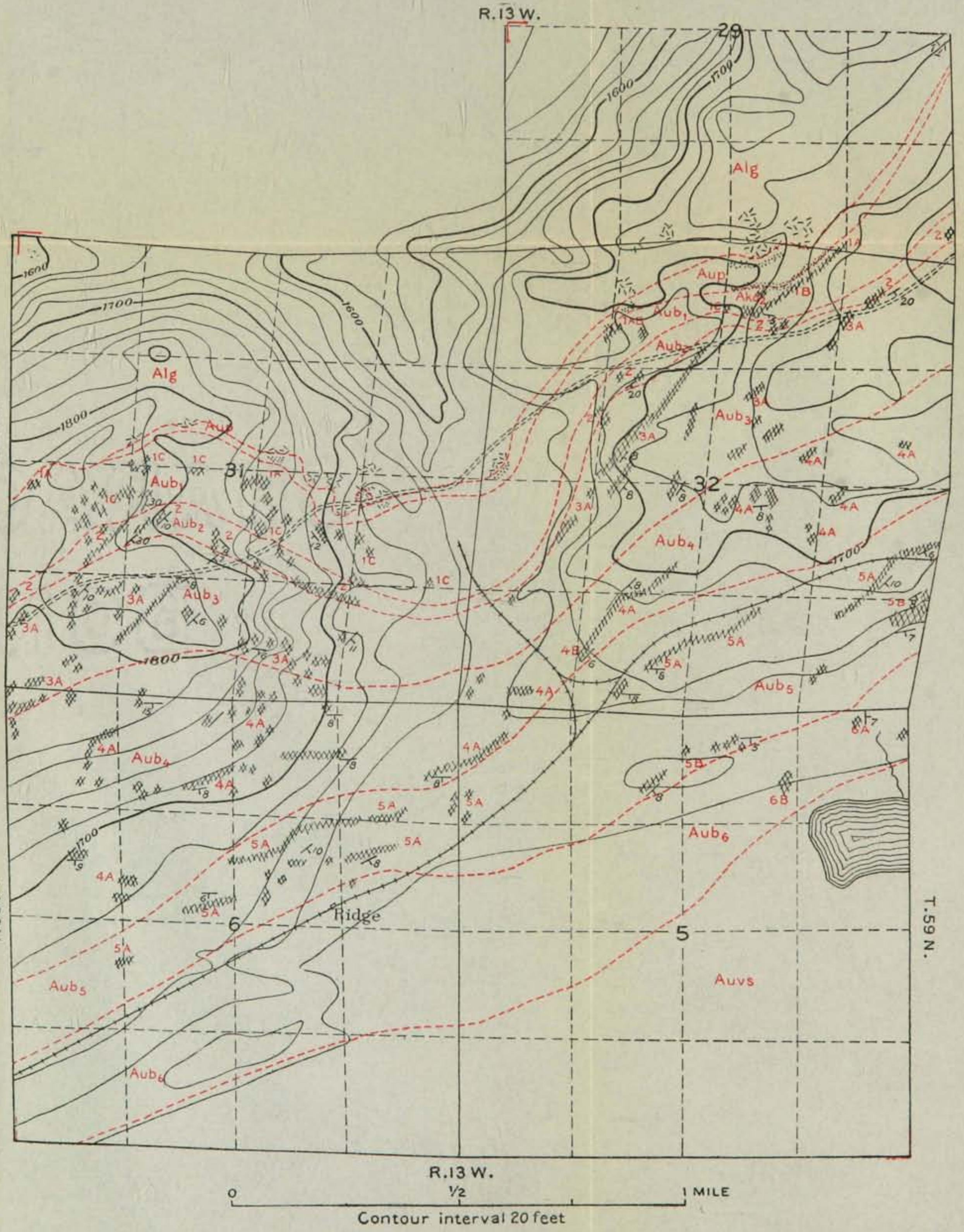


FIGURE 6. BLOCK DIAGRAM OF THE FOLD NEAR SPRING MINE

PLATE XV



DETAIL MAP OF THE RIDGE AREA

and sec. 12, T. 59 N., R. 14 W., and indicates 50 feet or more of the upper body of over 20 per cent magnetite, and from 10 to 61 feet of the lower body in different places. Most of the lower magnetite body lies close to the granite. Plate XIV A, showing the structure, is based on accurate measurements of drilling.

The Ridge area (*Plate XV*).—The branch of the railroad running along the east Mesabi formerly had a side line turning north just east of Ridge. This passed through a valley transverse to the range. On each side of this low place the exposures of the several divisions of iron formation are very clear. Through most of the four sections mapped, the outcrops are numerous and horizons easily distinguished. Along the south side, however, the limit of the formation is concealed in swampy land.

A few paces east of the center of sec. 32, T. 60 N., R. 13 W., is a small ravine running south through the richest part of the magnetite beds and the intermediate jasper with algal structure. A sample from a bluff 10 feet high showed nearly 40 per cent of iron in form for magnetic concentration.

The northern, lower magnetite belt here seems to become less continuous than it is west of Spring mine, though the several outcrops may be connected under the drift. The lower magnetite beds show more oxidation and leaching than in most outcrops. The lower slaty beds have many soluble silicates and are similarly leached and enriched, developing oölitic or concretionary structures with limonite composition.

A small diabase dike intruding the lower horizons of the Biwabik formation, outcrops in the N.W. ¼ of the N.E. ¼ of sec. 32.

Over 60 drill holes were once put down in sec. 6 and adjoining parts of sec. 5 and sec. 7., T. 59 N., R. 13 W., and the cores have been recently reviewed. They can be correlated closely with the data from outcrops and other drilling. The upper magnetite body is 212 feet thick and the lower about 42 feet thick. (See Figure 4 and Plate XIV.)

The Jericho area.—Two properties in this area have been more or less prospected. Many test pits were put down a little northwest of the center of sec. 28, T. 60 N., R. 13 W., northwest of the old "Syndicate camps." The dumps show a mixture of magnetite and ferric oxides, but enrichment has not apparently yielded a large rich body of ore. The compact specimens on the dump indicate that leaching has not been as thorough as in many places farther west, though evidently silica has been leached. Within a mile southeast of these prospects, in a swampy area, there is a highly ferruginous spring, indicating that iron as well as silica is being removed from the rocks.

The other prospect is the recent opening in magnetite in a bluff south of the railroad siding at Jericho. This bluff is in the gradation zone between good magnetite deposits north and the lean taconite south. The tests were made on quarry samples and were not good enough to encourage further work. The exposure can be followed southwest nearly a mile along the strike, with fairly uniform character. North of the railroad are a few outcrops of more promising magnetite.

Through most of this area the outcrops are few, and the drift is apparently thick. In all of sec. 27, T. 60 N., R. 13 W., only two small outcrops were found. These are of the lean upper beds. This of course makes the boundaries as mapped somewhat uncertain.

The Iron Lake area (*Plate XVI*).—The southern part of this area is characterized by a series of diabase ridges formed by outcropping sills 10 to 20 feet thick. These can be followed with considerable accuracy for a mile or more, and extend with some interruptions much farther. The sills conform to the bedding wherever observed and can be used in some cases as a guide to the structure of the other beds. The dip of the sills is so slight in some places that the topographic slope exceeds the dip, and there are numerous outliers and inliers outcropping in a way which interferes somewhat with the regularity of the belts mapped. The sills are the only conspicuous outcrops in the southern area, and it is only in a few places that their roof and floor rocks are well exposed. The whole series has been previously interpreted as a single sill, half a mile wide, but there are at least four in this area. The tops of several of these diabase ridges are a hornfels, clearly derived from slate. Without much question the Virginia slate is continuous from Mesaba to Dunka River.

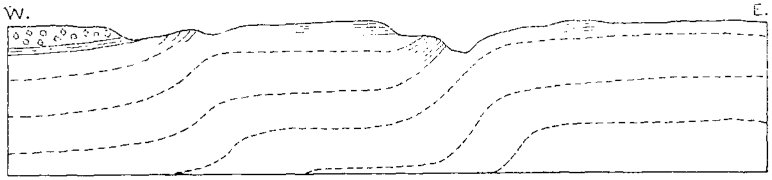
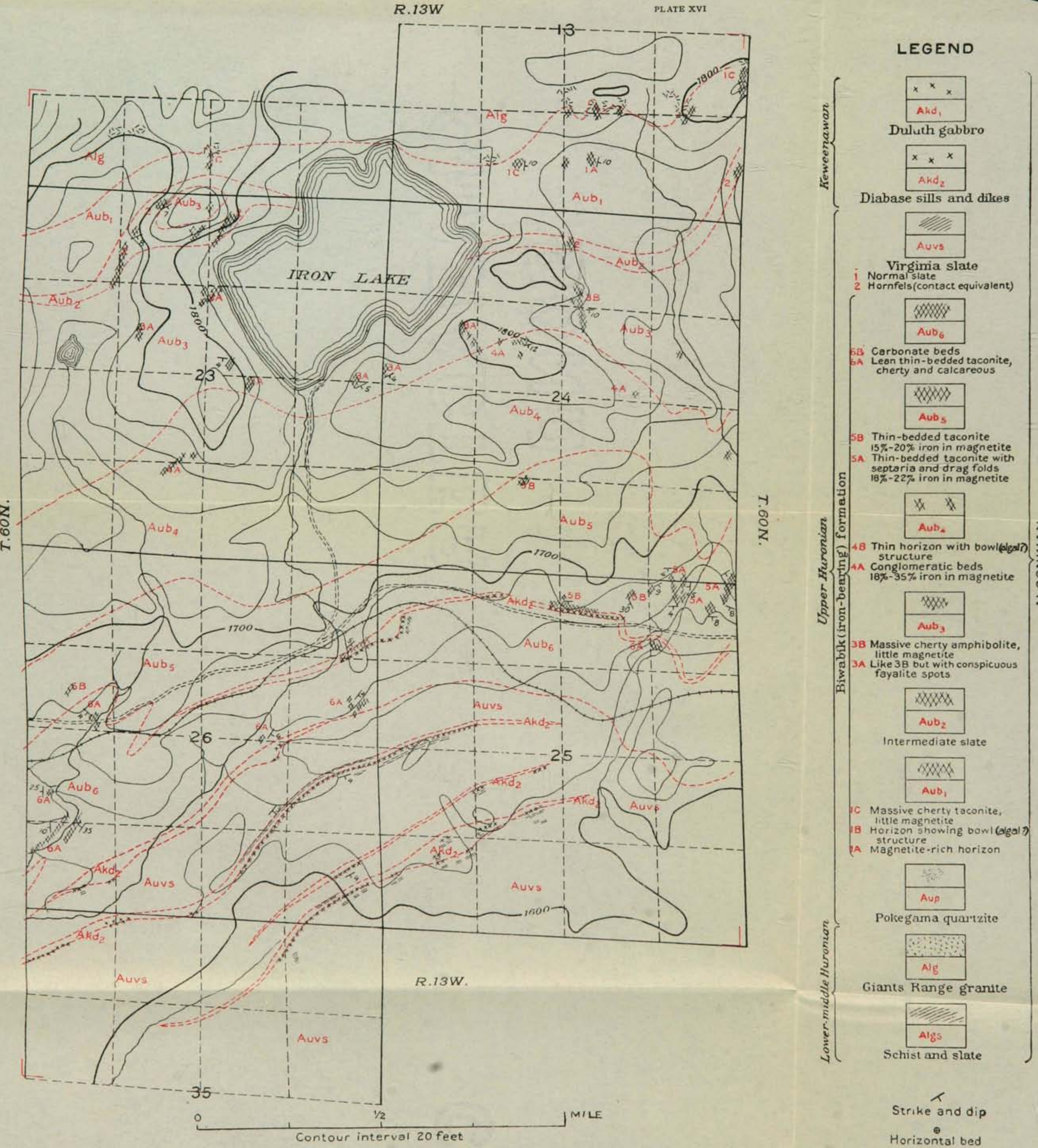


FIGURE 7. SKETCH OF A CROSS SECTION 200 PACES SOUTH OF THE NORTH SIDE OF N.E. ¼ SEC. 25, T. 60 N., R. 13 W., SHOWING OUTCROPS AND (IN BROKEN LINES) THE STRUCTURE SUPPOSED TO EXIST BELOW

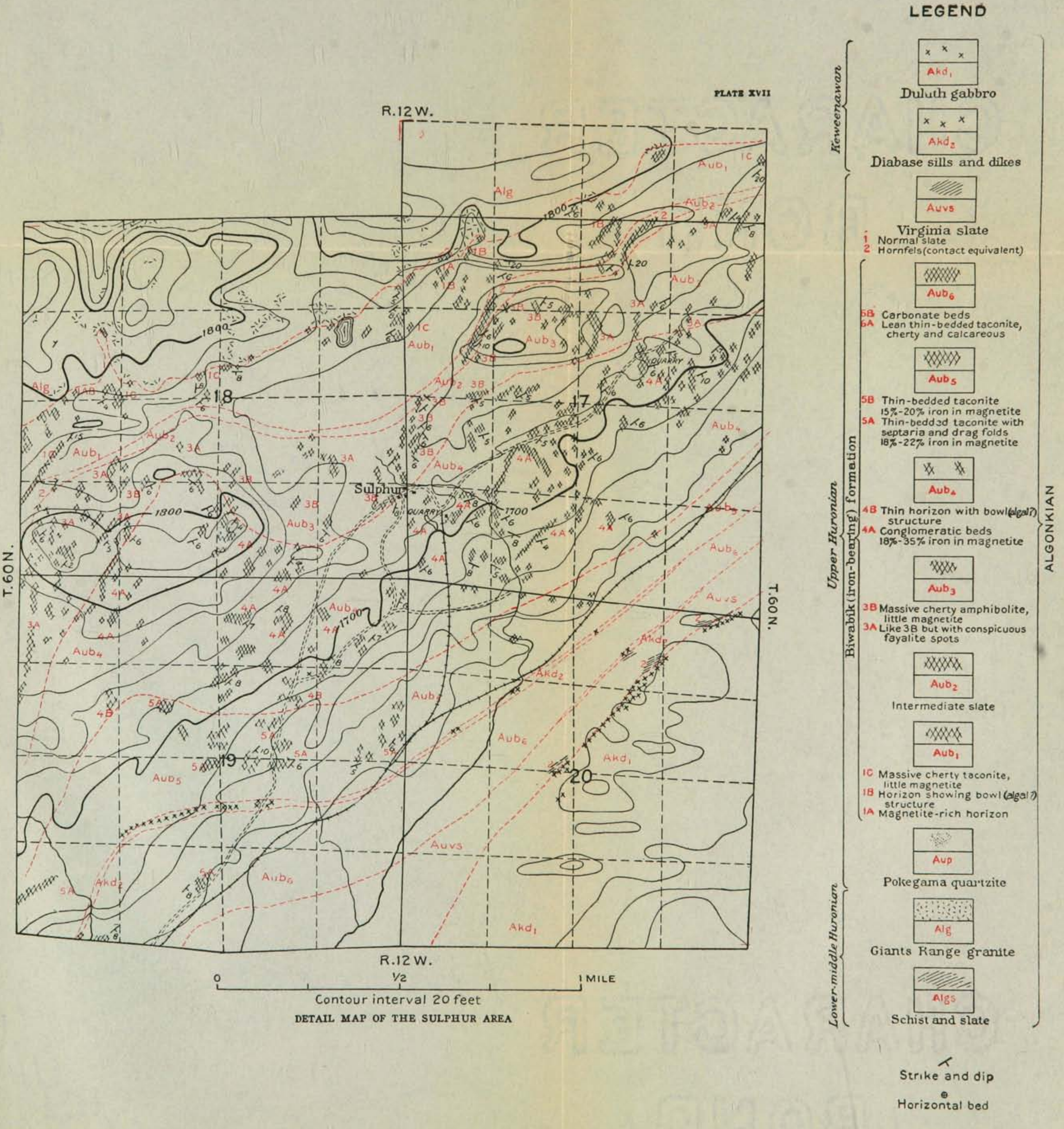
Two parts of this area show sharp and exceptional folds a few hundred feet wide. One is in the southwest corner of sec. 26, and one in the N.E. ¼ sec. 25, T. 60 N., R. 13 W. It is assumed from the outcrops in these places that the folds involve the beds above and below to some extent. Figure 7 shows the outcrops in sec. 25, in a cross section interpreting them as two folds. Such a structure, however, may have resulted from displacement along two faults. Figure 8 shows the similar structure in sec. 26.

PLATE XVI



DETAIL MAP OF THE IRON LAKE AREA

PLATE XVII



DETAIL MAP OF THE SULPHUR AREA

In the Sulphur area there has been considerable exploration of a magnetite body which has been followed into this area in sec. 24, T. 60 N., R. 13 W., with little apparent change in character. In sec. 26 it is probably similar, but outcrops are not so numerous.

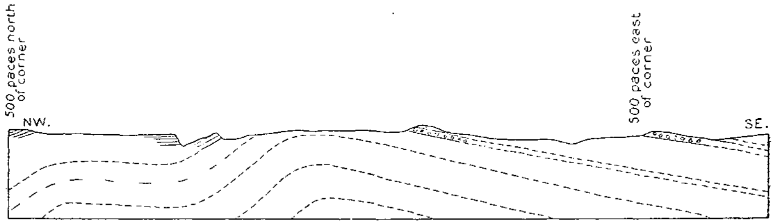


FIGURE 8. SKETCH OF A CROSS SECTION NEAR THE S.W. CORNER SEC. 26, T. 60 N., R. 13 W., SHOWING OUTCROPS AND (IN BROKEN LINES) THE STRUCTURE SUPPOSED TO EXIST BELOW

A strong magnetic pole appears in the magnetic map of this area, located in the east central part of sec. 24. The dip needle gives fairly high readings and the compass needle points in from all sides with surprising regularity. These results were not duplicated anywhere along the range and were thought worthy of a drill exploration. Four holes were put down about 50 feet in rock. Certain layers proved to be rich, but one of the holes struck a concealed mass of diabase, and as a whole the drilling failed to explain the magnetic attraction. The explanation may possibly be found in the topographic situation,—there is a deep valley cutting the beds,—or in the folded or faulted structure, described above.

The Sulphur area (*Plate XVII*).—The outcrops in secs. 18 and 19, T. 60 N., R. 12 W., have long been noted as rich in magnetite. They are located on a hill slope that spreads them out to a greater width than in most of the areas. The irregularity in the belt is due more to the topography than to folding. Practically the whole south slope is a conspicuous outcrop of conglomerate taconite. The amount of iron is about the same as that in the equivalent beds all along the range. Very little hematite is to be found in this area. This is attributed, probably correctly, to the proximity of the gabbro on the southeast.

Along the boundary of the iron formation and the granite, the contact shows more clearly than elsewhere the unconformity between the Upper Huronian and older formations. Not only is there a prominent conglomerate in many places, but there are exposures enough to outline an older erosion surface of considerable relief. Figure 2, page 6, is a section along the general trend of the contact, across the line between secs. 17 and 18, T. 60 N., R. 12 W.

The diabase belt on the map is traced by outcrops well across into sec. 20, but a second sill is revealed by the drilling. The sill between Aub_5 and Aub_6 has been penetrated in several places by recent drilling. The characteristic texture of Aub_5 appears in the core just below the diabase, but there are 20 to 40 feet of this in which the magnetic iron content is less than 20 per cent. It is evident that the upper part of Aub_5 is leaner than the bottom, though noticeably of better grade than beds Aub_6.

South of the diabase in sec. 20 there are outcrops of gabbro and altered slate. This is one of the best places along the contact of the gabbro and slate to observe the contact effects of the gabbro. The slate develops the hornfels texture and the appearance of a fine-grained gabbro. There are phases that consist of fragments in a matrix, as if part of the slate had been almost a liquid and gathered in some inclusions. Pegmatitic stringers and many contact minerals appear in the mass.

Drilling has been carried over the magnetite body almost all across secs. 17 and 19, T. 60 N., R. 12 W. The exploration has here demonstrated a fair degree of uniformity of the beds, as suggested by their outcrops, but a lean area is found at the east. About 150 holes have been put down, most of them to a depth of 50 feet in rock, but others to greater depths, to determine the general relations. The drilling operations by two or three companies at different periods have been reviewed and correlated. Several holes were placed for the sake of determining the geological horizons and thickness of the formations. No single hole, however, has been carried through the whole formation. The section shown in Plate XIV B is based mostly on outcrops, topography, and surface measurements of the inclination of the beds.

Two quarries have been opened in the magnetite bodies, and many cars of ore have been shipped to Duluth for concentration.

The Birch Lake area (Plate XVIII).—Between the area at Sulphur and Dunka River there are few outcrops. Those that occur along the granite boundary indicate the continuity of the belt of iron formation. On the southeast, there are outcrops of gabbro, turning north, somewhat abruptly, and at the river there is gabbro within a quarter of a mile of the granite. From Dunka River to Birch Lake outcrops are numerous and mapping can be done in considerable detail. Gabbro and granite and intervening sediments are all clearly exposed.

The contact effects of the gabbro extend all through the sediments in this area and obliterate most of the distinctions between beds. It is here that the bands of magnetite and quartz show the strong contrast in color, suggesting some segregation and intensification of banding during contact action. There is evidence of considerable rearrange-

PLATE XVIII

DETAIL MAP OF THE BIRCH LAKE AREA

LEGEND

Keweenawan

Akd_1 Duluth gabbro

Akd_2 Diabase sills and dikes

Upper Huronian

Auvs Virginia slate
1 Normal slate
2 Hornfels (contact equivalent)

Biwabik (iron-bearing) formation

Aub_6
6B Carbonate beds
6A Lean thin-bedded taconite, cherty and calcareous

Aub_5
5B Thin-bedded taconite 15%-20% iron in magnetite
5A Thin-bedded taconite with septaria and drag folds 18%-22% iron in magnetite

Aub_4
4B Thin horizon with bowl (algal?) structure
4A Conglomeratic beds 18%-35% iron in magnetite

Aub_3
3B Massive cherty amphibolite, little magnetite
3A Like 3B but with conspicuous fayalite spots

Aub_2 Intermediate slate

Aub_1
1C Massive cherty taconite, little magnetite
1B Horizon showing bowl (algal?) structure
1A Magnetite-rich horizon

Aup Pokegama quartzite

Lower-middle Huronian

Alg Giants Range granite

Algs Schist and slate

ALGONKIAN

⟋ Strike and dip

⊕ Horizontal bed

ment, in a thin section of pyroxenite from this area; a black oxide clearly replaces parts of the pyroxene.

Certain beds have been recognized, however. Distinguished from the leaner beds, the beds with over 30 per cent iron in magnetite can be recognized in the central zone of the formation almost to the end of the outcrops of iron formation, in sec. 26, T. 61 N., R. 12 W. The conglomerate horizon could be distinguished nearly everywhere that iron formation was seen, in spite of the fact that it was well impregnated with pegmatitic stringers from the gabbro. There are also in this area beds which can be correlated with the lower cherty algal beds, the intermediate slate, and the upper lean beds just below the Virginia slate. The sediments, from Dunka River north, are steeply and not very regularly tilted, and the strike is variable. Figure 9 is a cross section in sec. 3, T. 60 N., R. 12 W., indicating that the iron formation has been reduced in thickness to 360 feet. The exposed bodies of magnetite are very narrow.

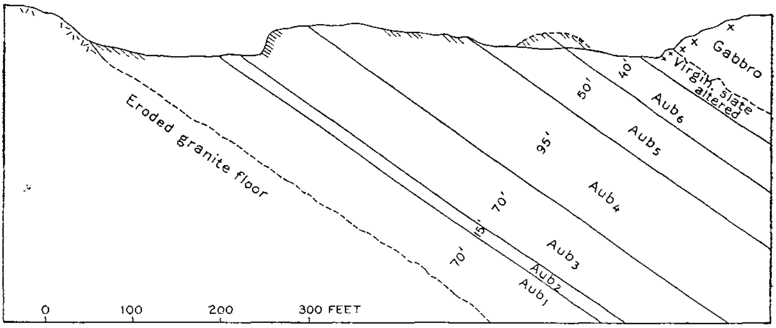


FIGURE 9. CROSS SECTION OF THE IRON FORMATION SOUTH OF BIRCH LAKE, SHOWING OUTCROPS AND DIPS, WHICH ARE EXTENDED UNDERGROUND

Where the exposures are clear the four main divisions of the iron formation can be recognized and can be correlated with those in the areas farther west. Above the lean upper beds of iron formation are some fine grained rocks with a texture and mineral character identical with the hornfels developed from Virginia slate, south of Sulphur Siding. The slate is therefore mapped here much farther north than it has heretofore been shown. It has no slaty character, but is easily distinguished from the coarser gabbro in most places. The gabbro apparently cut down a little irregularly into the sediments, for it reaches through the slate to the iron formation at one place in sec. 3, and another in sec. 35. The last large outcrop of hornfels (slate) is farther northeast in sec. 35.

Several diabase sills and dikes intrude the sediments near the upper beds of iron formation. The sills are porphyritic, but where the enclosing sediments are altered to hornfels, the sills also become hornfels. They contain phenocrysts which are so characteristic that one may identify them with confidence as the equivalent of the diabase sills in the Iron Lake area; but the sills lose practically all trace of their original diabasic texture.

In the northeast corner of sec. 26 outcrops of gabbro and granite come together, definitely pinching out all sediments. The iron formation was formerly mapped as extending to Birch Lake, probably because outcrops are not abundant, and the iron formation can be found again near the granite north of Birch Lake. This patch north of the lake must be considered an isolated remnant like those farther east along the gabbro contact,[2] for the continuous outcrops of iron formation definitely end south of the lake.

Broderick, T. M., Titaniferous magnetites of Minnesota: Econ. Geology, vol. 12, pp. 663-96, 1917.

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1 pl. in pocket

MGS Grout, F.F.
Bull. The magnetite deposits
17 of the eastern Mesabi range,
Copy 4 Minnesota.

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