THE RELATION OF THE TITANIFEROUS MAGNETITE DEPOSITS OF NORTHEASTERN MINNESOTA TO THE DULUTH GABBRO

BY

THOMAS M. BRODERICK

A DISSERTATION WITH ACCOMPANYING MAPS, PHOTOGRAPHS, AND DIAGRAMS, SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF MINNESOTA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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THE RELATION OF THE TITANIFEROUS MAGNETITES OF NORTHEASTERN MINNESOTA TO THE DULUTH GABBRO.

T. M. BRODERICK.

PART I. GENERAL GEOLOGY.

Introduction.

The titaniferous magnetite bodies of the Duluth gabbro in northeastern Minnesota are well known from various scattered references which indicate some differences in the character of the ores from different places. The Minnesota Geological and Natural History Survey found it desirable to compile the available data, and to go over the ground systematically, classifying the deposits. Several types have been found. A survey bulletin describing the results of this study is now in preparation. This paper is concerned chiefly with an investigation of the origin of the various types of magnetite deposits. The work has been carried out under the supervision of F. F. Grout, whose interest and many suggestions are especially appreciated.

Location.—The magnetic iron ores discussed in this paper occur in the Duluth gabbro in Cook and Lake counties, in northeastern Minnesota. The westernmost outcrop of ore is near the southwestern corner of T. 62 N., R. 10 W. Outcrops of ore occur at many places in a belt extending about fifty miles northeastward from this point, and within a few miles of the northern boundary of the gabbro. The greater number of the deposits lie within this strip, parallel to the boundary of the gabbro. Important occurrences of ores a few miles outside of this belt extend the general area southward in Ranges 3 and 4 west. The area is north of Lake Superior, and the eastern end lies within a few miles of the boundary between Minnesota and Canada.

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Topography.—The topography of the area underlain by the Duluth gabbro is that of an undulating plain. There are few elevations of more than 100 feet above the general level. Steep rocky hills with vertical escarpments of ten to twenty feet are common. There are many lakes, most of which are of irregular shape and shallow. In the eastern part of the area, however, where the banding of the gabbro is pronounced, the lakes are long, narrow and deep, extending parallel to the banding of the country rock. The drainage of the southern part of the area is into Lake Superior; that of the northern part is into the Hudson Bay basin, through the Rainy and Nelson rivers. The whole area has been glaciated, but there is little drift. The southernmost outcrops of the magnetites are close to the northern edge of the moraine deposits which border the north shore of Lake Superior. Glacial striæ are abundant, and show the general direction of ice movement to have been S–SW.

Stratigraphy.

Geologic Column.—The Duluth gabbro lies near the southern edge of the pre-Cambrian shield of North America and in entirely surrounded by pre-Cambrian rocks. The geologic column for the area is as follows:[1]

Quaternary System	
Pleistocene series—Drift	
Unconformity	
Algonkian System	
Keweenawan series	Duluth gabbro and Logan sills with associated granite and flows
Unconformity	
Huronian series	
Upper Huronian (Animikie group)	Rove slate Gunflint formation (Iron-bearing)
Unconformity	
Lower-Middle Huronian	Intrusive rocks, acid and basic Knife Lake slate Agawa formation (iron-bearing) Ogishke conglomerate

[1] Clements, J. Morgan, "The Vermilion Iron-bearing District of Minnesota," U. S. Geol. Survey Mon. 45, p. 33, 1903.

Unconformity	
Archean System	
Laurentian series	Granite and other intrusives
Keewatin series	Soudan formation (iron-bearing) Ely greenstone (a basic igneous and largely volcanic rock)

Descriptions of Formations.—The Ely greenstone is chiefly altered basalt; the color is green, of various shades. Amygdaloidal and spherulitic structures are common, and the texture is from fine to coarse grained. Hornblende, augite, plagioclase, quartz, titaniferous magnetite, and apatite are the primary minerals. Interbedded rocks, probably volcanic tuffs, occur in the greenstone, most of which shows considerable alteration by weathering and dynamic action, which has made it schistose.

The Soudan iron-bearing formation consists largely of interlaminated bands of finely crystalline quartz and iron oxides. Locally there are interstratified slaty and conglomeratic phases. It is believed that the Ely greenstone was poured out upon the sea floor, and that after quiescence the Soudan formation was deposited, chiefly as a chemical precipitate. Subsequent dynamic metamorphism has caused the Soudan formation and the Ely greenstone to be closely infolded.

The material making up the Ogishke conglomerate consists of pebbles and boulders of greenstone, granite, porphyry, chert, and jasper in a finer grained matrix derived from the same sources. Near the contacts with the Snowbank granite and the Duluth gabbro, it has been metamorphosed to schist. It is unconformable with the underlying formations but grades upward with increasingly finer material, into the Agawa iron formation or the Knife Lake slate.

The Agawa iron-bearing formation is found as a very thin bed, above the Ogishke conglomerate. It resembles the other iron formations of the Lake Superior region.

The Knife Lake slates are variable in their original composition. There are argillaceous, cherty, graywacke, conglomeratic, and tuffaceous modifications. Locally, where dynamic action has been effective, they are altered to micaceous or amphibolitic schists and gneisses. Near the contact with the Duluth gabbro they have been altered to hornfels. The primary minerals of the Knife Lake slate are feldspar, quartz, brown mica, pyroxene, and hornblende. The dynamic metamorphism of the slates has resulted in complex folding. Many of the lakes in northeastern Minnesota are on the synclines where the easily eroded slates outcrop.

The Gunflint formation, originally a cherty iron carbonate, is exposed in the vicinity of Gunflint Lake. Contact metamorphism has transformed it into a banded magnetite rock, which contains a great variety of minerals, such as fayalite, cordierite, quartz, and many others.

The Rove slate forms the northern boundary of the gabbro, east from sec. 26, T. 65 N., R. 4 W. The formation consists of slate, with quartzite and graywacke phases.

The Duluth gabbro and Logan sills intrude the above formations. The gabbro which encloses the magnetite deposits is discussed below.

The Duluth Gabbro.

Lithologic Character.—The chief original mineral constituents of the Duluth gabbro are plagioclase, augite, hypersthene, olivine, a little brownish green hornblende, biotite, apatite, magnetite and ilmenite. The plagioclase is a basic labradorite.

The texture of the gabbro is distinctly granitoid and is about the same at the contact as more remote from it. Ophitic and poikilitic textures also occur.

The principal variations of the gabbro are due to the relative proportions of the plagioclase, augite, olivine, and magnetite. The normal rock is a gray, medium- to coarse-grained granitoid aggregate consisting of basic labradorite and augite, with small but variable amounts of olivine and magnetite and is unusually fresh. With increase in the plagioclase the gabbro becomes anorthosite. Troctolite is formed by the decrease in the augite, leaving plagioclase and olivine as the essential constituents. Increase in the amount of magnetite gives the magnetite concentrations approaching iron ore.

Minor variations in texture give rise to gabbros of different size of grain, and to rocks of ophitic and poikilitic textures. In the latter, large augite and olivine crystals surround the lath-like plagioclase.

Fluxion structure is conspicuous in the parallel orientation of the plagioclase crystals. Banded structure is especially noticeable in the eastern part of the area in which the magnetite bodies occur. In these areas of banded gabbro there are bands of plagioclase-magnetite rock, which, though but a few feet in thickness, extend about a mile along the strike.

Relations to Other Rocks.—The Duluth gabbro may be of the same age as the Logan sills. It intrudes the Keweenawan flows and it has been thought that the intrusion has cut across the Upper Huronian beds, uplifting them in part of the area.[2] However, the absence of any record of Huronian rocks above the gabbro indicates that it followed approximately the plane of unconformity at the base of the Keweenawan.

Mode of Occurrence.—The Duluth gabbro has been called a laccolith, and it is one of the largest known of such intrusive masses. Its maximum diameter is 140 miles, and its maximum thickness is in the neighborhood of 50,000 feet.

Contact Metamorphism.—The gabbro has metamorphosed all the rocks with which it is in contact. Its effects upon the Ely greenstone, the slates, and the Gunflint iron formation have been described.[3] Some of the contact phases of the intruded rocks closely resemble certain rocks and types of ore within the gabbro, suggesting that the latter are included blocks of similar contact rocks.

The Gunflint iron-bearing formation, originally a cherty iron carbonate, has been metamorphosed to a coarse-grained banded rock, consisting essentially of magnetite, quartz, and fayalite,

[2] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior region," U. S. Geol. Survey Mon. 52, p. 202, 1911.

[3] Grant, U. S., "Contact Metamorphism of a Basic Igneous Rock," Geol. Soc. America Bull., Vol. 11, p. 503, 1900.

Zapffe, Carl, "The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," Econ. Geol., Vol. 7, p. 145, 1912.

Clements, J. Morgan, *op. cit.*, p. 351.

in varying proportions in the different bands. There are numerous other minerals, chiefly ferromagnesian silicates, in smaller and variable amounts. Its texture is coarse-grained xenomorphic; in some cases larger crystals enclose the smaller ones poikilitically. The color varies with the mineral composition of the bands; the rocks high in magnetite are black, some of the quartzite phases are white, but the usual color is a greenish black. Certain beds in the Gunflint formation, probably originally of a shaly nature, have been altered to the sugary-textured hornfels which has been called muscovadite.

The bands with a high proportion of magnetite and the ferromagnesian silicates, especially when quartz is absent, closely resemble igneous rocks, and their separation from the Logan sills which intrude them is, in places, difficult. These phases of the Gunflint, consisting essentially of magnetite, fayalite, and pyroxene, resemble some of the magnetite rocks within the gabbro which probably were formed in the same way. Bayley[4] has even included some of these puzzling variations of the metamorphosed Gunflint as "peripheral phases" of the gabbro itself. Elftman[5] and others, and in particular U. S. Grant[6] agreed that they are contact rocks and the latter gives in considerable detail his reasons for regarding them as contact metamorphic rocks rather than phases of the gabbro.

Contact action on the Ely greenstone has resulted in the following changes: The augite, in ophitic relation with the plagioclase, has altered to hornblende, with preservation of the ophitic texture. Biotite has been developed in most cases and many specimens show large plates of biotite and hypersthene, which enclose the other minerals. In other cases the metamorphosed rock shows more magnetite and brownish green hornblende than would be expected from the recrystallization of the greenstone,

[4] Bayley, W. S., "Massive Rocks of Lake Superior Region," *Jour. Geology*, Vol. 2, pp. 814–825, 1894; Vol. 3, pp. 1–20, 1895.

[5] Elftman, A. H., "The Geology of the Keweenawan Area in Northeastern Minnesota," *Amer. Geol.*, Vol. 22, p. 145, 1898.

[6] Grant, U. S., "Contact Metamorphism of a Basic Igneous Rock," *Geol. Soc. America Bull.*, Vol. 11, pp. 507–508, 1900.

and Clements suggests that there is some addition of material from the gabbro. The grains of the recrystallized greenstone are more or less rounded in outline, giving what has been called by Bayley, granulitic texture; by Fouque, globular texture; and by Salomon, the contract structure.[7] (See Fig. 37.) The texture is one of those figured by Rosenbusch as being typical of the contact rock known as hornfels.[8] The contact metamorphosed greenstone, where fresh, is a greenish gray rock. It has less resistance than has the unaltered greenstone, and on weathering it becomes a crumbly, brown mass called muscovadite by early observers.

The metamorphic changes in the Knife Lake slate may be seen along the east shore of Gabenichigami Lake and on the islands. The metamorphism increases toward the contact. The width of outcrop of the contact zone is one quarter to one half mile. Near the contact, the metamorphism has resulted in the production of a hornfels much like that derived from the greenstone—a brown, sugary-textured, crumbling rock. The faint appearance of bedding in places is the only remaining field evidence of the original character in some of the outcrops. Slaty cleavage disappears, and the rock loses its splintery nature, and becomes massive. Weathering goes deeper. From a texture so fine that minerals can be recognized only with difficulty, it becomes coarser and coarser, and some of the rocks in hand specimen immediately at the contact resemble an igneous rock more than a sediment. Large plates of biotite and other ferromagnesian minerals can be seen. In thin section the slate is composed of a confused aggregate of minerals of such fine grain that it is almost impossible to distinguish any but quartz. The cloudy appearance is cleared up as the contact is approached, the size of grain increases; green and brown hornblende, biotite, plagioclase, magnetite, and quartz appear, with other minerals. Still nearer the contact green pyroxene appears. Biotite and hypersthene

[7] Winchell, A. N., "Chapter in the Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, p. 398, 1911.

[8] Rosenbusch, H., "Element der Gesteinslehre," 3d ed., p. 113, 1910.

are developed in some specimens in large plates, enclosing the other minerals. It is suggested[9] as an explanation of the characteristic development of brown mica, hypersthene, and magnetite close to the contact, that magnesium and iron were transferred from the gabbro to the contact rocks. However, in general, those who have studied the contact metamorphism of these rocks agree in emphasizing the process of recrystallization as the dominant one. Addition of material is regarded as of very minor importance.

The intruded granites show very little contact alteration. The Rove slate contact shows the development of the muscovadite type of rock. The spotted contact types also occur, with development of cordierite.

Inclusions of the rocks invaded by the gabbro are frequent, especially near the northern border which represents the floor of the gabbro. Fig. 36 shows the location of xenoliths of the banded quartz magnetite phase of the Gunflint iron formation. A few of these have been described,[10] others are known only from private reports, and the present explorations.

The contact effects of the gabbro upon inclusions were of the most profound nature, and the process of recrystallization was carried further than in the rocks bordering the gabbro. There is evidence of the addition of titanium on a large scale to some of the inclusions, and it is highly probable that other materials were added. The difficulty of recognizing the true nature of an inclusion of the iron-bearing formation which has been altered to a coarsely crystalline aggregate of olivine, pyroxene, and magnetite, and which has received titanium emanations from the surrounding gabbro, is apparent. Observers have naturally classified such bodies as segregations of the gabbro magma. Evidence that many of them are inclusions is cited later.

Within the gabbro, especially within a few miles of the northern border, there is a great abundance of inclusions of a

[9] Clements, J. Morgan, *op. cit.*, p. 345.

[10] Grant, U. S., Geological and Natural History Survey of Minnesota Final Report, Vol. 4, pp. 417, 456, 1899.

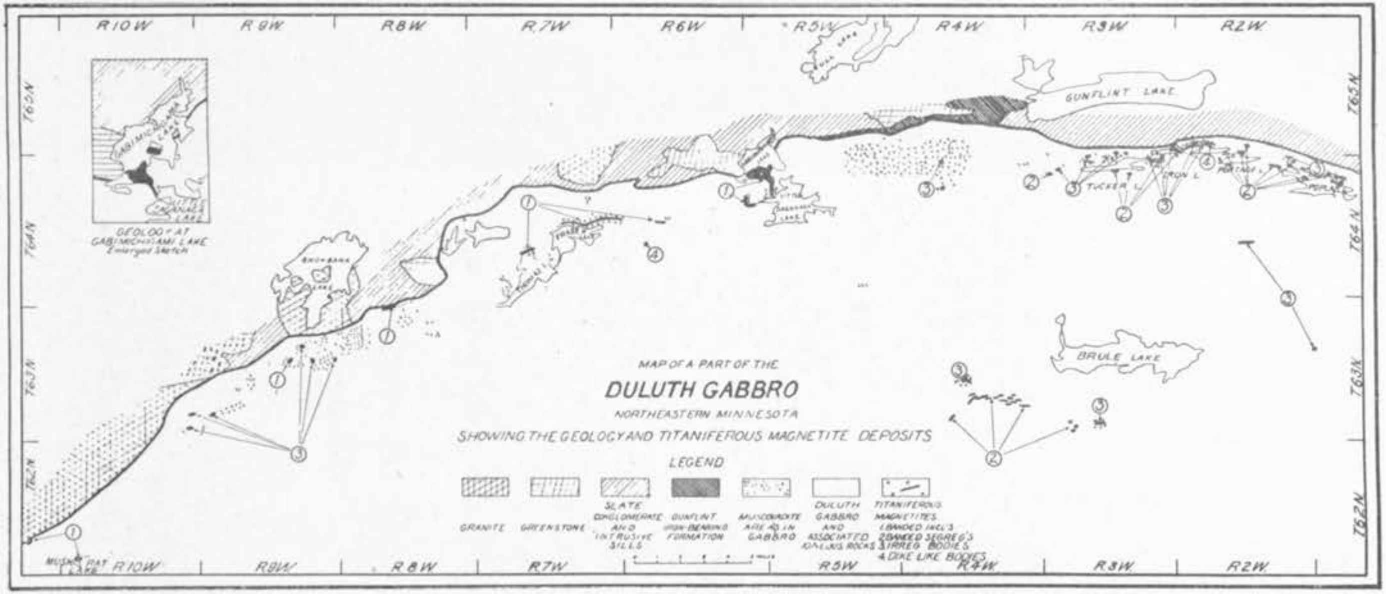

FIG. 36. Map of a part of the Duluth gabbro.

rock which has been called muscovadite, or granulitic gabbro. The locations of many outcrops of this rock are shown in Fig. 36. In a study of the ores of the gabbro, one of the first problems to be solved is the origin of this rock. The magnetite deposits of certain types are almost invariably associated with the muscovadite, in many cases so related to it that a solution of the origin of the muscovadite would go far in establishing the same origin

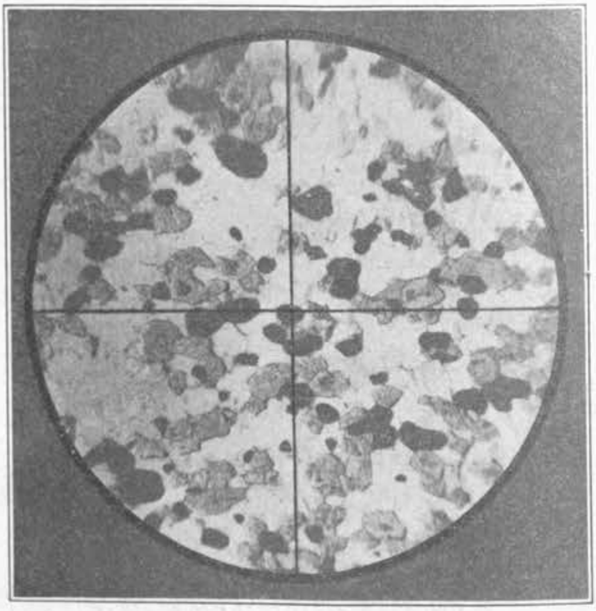

FIG. 37. Texture of hornfels developed in slate, greenstone, and other rocks, at the contact with the Duluth gabbro. Ordinary light × 20.

for the associated magnetite. Without giving a full account of the varied opinions of the nature of the rock held by geologists who have studied it, it may be stated that it was generally considered a fine-grained gabbro.[11]

Microscopically, the rock, if fresh, is a light or dark gray,

[11] Grant, U. S., Geol. and Nat. Hist. Survey of Minnesota Final Report, Vol. 4, p. 478, 1899.

Grant, U. S., "Contact Metamorphism of a Basic Igneous Rock," *Geol. Soc. America Bul.*, Vol. 11, pp. 509–510, 1900.

Bayley, W. S., *loc. cit.*

finely textured, crystalline aggregate of uniform grains. The weathered muscovadite is a brown, crumbly, granular product. As shown by Grant,[12] the minerals are basic plagioclase, augite, olivine, magnetite, hypersthene, and biotite. In most cases only two or three of these minerals occur in a given section. The texture is granitoid, with allotriomorphic, equidimensional grains, in many cases with rounded outlines, giving a hornfels texture. (See Fig. 37.) The size of grain is less than one fifth that of the average gabbro. The gabbro cuts the muscovadite in dikes and stringers. Areas of muscovadite vary in size from a few square feet to many acres, and they are completely surrounded by gabbro. Contacts between the two are as a rule sharp. All of the known inclusions of banded Gunflint iron formation are associated with muscovadite. In many cases the muscovadite has a contorted appearance.

A study of the rocks, in the field and laboratory, furnishes considerable evidence that the muscovadite within the gabbro is of the same origin as that developed along its northern border by contact metamorphism of the intruded rocks, the main difference being that the material within the gabbro was subjected to more intense metamorphism, because it was surrounded on all sides by the magma.[13]

There are indications of some slight fusion and assimilation of some of the inclusions in the gabbro. As suggested below, the dikes and stringers of magnetite which occur in association with the hornfels are probably fused iron formation, the magnetite melting completely and separating from the more viscous muscovadite. There is some evidence that there has been assimilation of magnetite by the gabbro, because in the vicinity of some of the magnetite inclusions, the gabbro is richer in magnetite than it is at some distance away. However, the gabbro does not become so high in magnetite that it is confused with the inclusion itself. Another point that seems to indicate assimilation is that a quartz

[12] Grant, U. S., Geol. and Nat. Hist. Survey Minnesota Final Report, Vol. 4, pp. 478–479, 1899.

[13] The evidence leading to this conclusion will be considered in a paper now in preparation.

gabbro, described in detail by Winchell,[14] is but a few hundred feet from the large inclusion of Gunflint formation in Sec. 12, T. 64 N., R. 6 W. Part of the inclusion is a white quartzite. Since the quartz is not a constituent of the normal phase of the gabbro, it is likely that it was assimilated from the nearby inclusion. There is also clear evidence of differential action of the gabbro upon the rocks at the northern contact. The gabbro forms great embayments into the Knife Lake slate and the Ogishke conglomerate, while the Ely greenstone projects into the gabbro. Either the gabbro has had a greater corrosive effect upon the slates and conglomerates, or these rocks are more subject to stoping action because of their physical properties, than is the greenstone. Perhaps both differential assimilation and stoping caused the gabbro to encroach upon some of the contact rocks and not upon others. The form of the inclusions of slate and greenstone can be explained only by assuming that they became plastic. Instead of the sharp points and edges which they would have if they had not become softened, they finger out into the gabbro and have a smeary, contorted appearance, with rounded edges. Although the evidence seems to indicate that fusion and assimilation took place, it was apparently of a very local nature. Winchell's idea of the formation of the entire gabbro mass by fusion of the earlier rock does not appear to be justified by the evidence. It is certain that the gabbro could not have been fused in place, by heat from above or below, because neither the roof nor the floor of the mass has been fused.

In summary, the effects of the intruding gabbro on the contact rocks and inclusions may be briefly stated to be as follows: There is a well-marked contact zone except where granite has been intruded. This contact zone outcrops for one quarter of a mile or more from the contact. Stoping has resulted in the formation of many inclusions of the intruded rocks. Recrystallization, with perhaps some addition of magnesium and iron near the contact, has been the chief metamorphic process operative. Ad-

[14] Winchell, A. N., "The Gabbroid Rocks of Minnesota," *Amer. Geol.*, Vol. 26, p. 348, 1900.

dition of titanium to some of the inclusions has taken place on a considerable scale. The Gunflint formation has become a banded rock, whose chief minerals are quartz, magnetite, olivine, and pyroxene in very variable proportions. The alteration of the greenstone, the shaly phases of the Gunflint, and the slates of several formations gives a hornfels consisting of rounded grains of feldspar, quartz, hornblende, magnetite, biotite and pyroxene. Pyroxene is developed especially near the contact, and the rocks most affected resemble igneous rocks. Inclusions of this hornfels have been called granulitic gabbro. The metamorphism has probably been effected by recrystallization under deep-seated static conditions, at high temperature, and influenced by abundant moisture.[15] There are several facts which suggest that there may have been assimilation and fusion of the wall rocks on a small scale by the gabbro. These facts are the dike-like stringers of magnetite in hornfels; the distorted appearance of the hornfels, as though it had once been plastic; the altered mineral composition of the gabbro in the vicinity of some inclusions, such as higher magnetite content, and the presence of quartz; and the great embayments of the gabbro into certain formations along its contact.

PART II. THE MAGNETITE ORES OF THE GABBRO.

Introduction.

The iron ores of the Duluth gabbro in Lake and Cook counties have long been objects of spasmodic prospecting and much of the land has been taken up by various development and mining companies. The area north of the Duluth gabbro has been mapped in detail by the United States Geological Survey.[16] The

[15] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, p. 134, 1911.

[16] U. S. Geol. Survey Monographs 45 and 52. Singewald, J. T., Jr., "The Titaniferous Iron Ore in the United States," U. S. Bur. Mines Bull. 64, pp. 93–110, 1913. Singewald spent one week in a small part of the area in which the deposits occur. Frequent references are made to the ores in the publications of the Minnesota Geological and Natural History Survey, but detailed investigations had not been made.

general impression gained by reading what little has been written regarding these ores is of a discouraging nature. However, it has been recognized by various individuals and companies that the results of a thorough investigation of the possibilities have never been published, and they have sent many parties into the gabbro area. Largely on the basis of conversations with various men who have examined these ores, the writer would venture the statement that there has been at least one party investigating them every summer for at least thirty-five years. Many of the deposits have well-beaten trails leading to them from the nearest waterways since, on account of the relative inaccessibility of the country, travel is almost entirely by canoe. There have been many scattering references, in both published and private reports, to deposits of other metals besides iron. Among these may be mentioned gold, silver, nickel, copper, vanadium, and chromium. One company, on the basis of faulty or deliberately fraudulent analyses, spent thousands of dollars in drilling in rock reported to contain nickel in paying quantities. It is believed that practically every known outcrop of magnetite ore within the gabbro was seen by members of the parties engaged in the present work, and detailed magnetic surveys have been made of the most important representatives of the various types of magnetite deposits. Specimens were taken, and subsequent analyses and petrographic examination, together with the results of the field work, form the basis of the following discussion of the origin of the ores.

Geologists have recognized two general types of ore: masses of included iron formation, and the segregations in the gabbro. In the separation of these two types investigators[17] have placed most dependence upon two criteria.

[17] Winchell, N. H., and Winchell, H. V., "The Iron Ores of Minnesota," Geol. and Nat. Hist. Survey Minnesota Bull. 6, pp. 125, 126, 1891.

Winchell, H. V., Geol. and Nat. Hist. Survey Minnesota Seventeenth Ann. Rept., pp. 80, 81, 1888.

Elftman, A. H., "The Geology of the Keweenawan Area in Northeastern Minnesota," *Am. Geol.*, Vol. 22, pp. 140–145–146, 1898.

Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, pp. 204, 546, 561, 1911.

1. The segregations of the gabbro are usually titaniferous; the included sedimentary ores are non-titaniferous.

2. The included sedimentary ores are banded, with more or less quartz associated with them.

The first of these criteria is a laboratory test, and in some of the citations to which reference has been made, it is regarded simply as a final test which will serve to confirm the decisions made on the basis of the second criterion.

Thus, the general opinion of the observers has been to classify the banded quartz-bearing magnetite rocks as inclusions, and those which are not banded quartz-bearing rocks as segregations of the gabbro, especially if a laboratory test shows the presence of titanium. It is shown below that the criteria as stated above are not dependable. Not all the Gunflint inclusions consist of banded quartz-magnetite rock, nor are they all non-titaniferous. Therefore additional criteria are needed to separate the segregations from the included ores.

A convenient classification of the magnetite deposits of the gabbro, for the purposes of the discussion of their origin, is as follows:

1. Inclusions of banded Gunflint iron formation.
2. Banded segregations of the gabbro.
3. Irregular bodies of titaniferous magnetite.
4. Dike-like bodies of titaniferous magnetite.

Inclusions of Banded Gunflint Iron Formation.

Distribution.—The banded quartz-magnetite inclusions of the Gunflint iron formation occur at frequent intervals within a few miles of the contact of the gabbro, from the eastern end of the Mesabi district, at Birch Lake, to Little Saganaga Lake. (See Fig. 36.) These inclusions are more numerous and extensive than the literature indicates. In this territory there is almost none of the iron formation in place along the contact of the

Grant, U. S., Geol. and Nat. Hist. Survey Minnesota Final Report, Vol. 4, pp. 417, 418, 456, 457, 1899.

Clements, J. Morgan, "The Vermilion Iron-bearing District of Minnesota," U. S. Geol. Survey Mon. 45, pp. 421–422, 1903.

gabbro. Along the contact farther east, the iron formation in place first outcrops a few miles east of Gabemichigami Lake.

Petrographic Character.—Petrographically these inclusions resemble the Gunflint in place where it has been metamorphosed by the gabbro. The minerals are chiefly quartz, magnetite, fayalite,[18] pyroxenes and amphiboles in various proportions and combinations. Plagioclase, if present at all, is in small amounts. Most of the rocks arê coarsely crystalline and all the grains are xenomorphic, giving the rock a granitic texture. In some cases the ferromagnesian minerals are developed in poikilitic plates. The minerals in many cases are rounded, giving the granulitic textures. In most cases they are arranged in bands which vary in thickness from a fraction of an inch to several feet. The rocks are commonly greenish black in color.

Mode of Occurrence.—Most of the inclusions occur well within the gabbro and are entirely surrounded by it. They outcrop as east-west ridges, or on the southern slope of east-west ridges. Their length varies from 750 feet to 3 miles; their width of outcrop from 60 to 650 feet. Many of them extend east and west, and thus approach conformability with gabbro structure. Their outlines are fairly regular. The banding in many of them strikes east-west, and dips to the south. Evidently they are tabular bodies or xenoliths broken off parallel to the original bedding (now represented by the banding), and conveyed into the gabbro, finally coming to rest in haphazard positions. Some of them show sharp contacts with the gabbro.[19] In every case they are associated with the hornfels inclusions.

As examples of the peculiar nature and variability of these inclusions, the types found in a single series of outcrops in Sec. 7, T. 64 N., R. 5 W., may be cited. The inclusion of which these outcrops are a part, projects down into the gabbro as a long point. It is connected with the Animikie outcrops on the southeastern

[18] Winchell, N. H., Geol. and Nat. Hist. Survey Minnesota Final Report, Vol. 5, pp. 638, 703, 1900.

Zapffe, Carl, "The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," Econ. Geology, Vol. 7, p. 152, 1912.

[19] *Loc. cit.*, p. 457.

shore of Gabemichigami. The outcrops may be followed from a point about 200 paces east and 125 paces south of the northwest corner of Sec. 7, northeastward around the base of a low north-facing cliff, thence southeastward to the shore of Little Saganaga Lake. The inclusion itself includes a great variety of rock types. There are many outcrops of hornfels, some of them having a conglomeratic appearance (perhaps pseudo conglomerate like that described by Clements).[20] The greater number of the outcrops are magnetite ores. Some of them are banded with quartz, others are olivinitic and pyroxenitic, with no quartz. There is one outcrop of almost pure titaniferous magnetite 25 feet square.

Another inclusion, in Sec. 12, T. 64 N., R. 6 W., of which the northernmost outcrop is 535 paces N. 22° E. of the southwest corner of Sec. 12, shows the same variation in rock types. It can be followed south by an almost continuous outcrop to the line between sections 12 and 13, where it turns east and can be followed almost half a mile. This is probably an inclusion, for it is surrounded on all sides by gabbro, is not in structural conformity with the Gunflint in place, and is some distance above the supposed base of the gabbro. The most conclusive evidence is obtained by taking magnetic readings on the inclusion itself and on the gabbro within a few feet of it. The magnetic variations are high above the inclusion, but those taken on the gabbro a few feet away, along the line of strike of the inclusion or across it, are normal. This indicates that these Gunflint outcrops are not projections of the rock in place, for with such a thin covering of gabbro as there would be a short distance from the outcrops the magnetic needles would be seriously affected.

The possibility that these "inclusions" may be in place has been recognized. Grant[21] regards at least one of these Animikie areas within the gabbro as being included. He has suggested that some of the others may be in place. Van Hise and Leith regard these areas as included Gunflint formation rather than

[20] Clements, J. Morgan, "The Vermilion Iron-bearing District of Minnesota," U. S. Geol. Survey Mon. 45, p. 344, 1903.

[21] *Loc. cit.*, pp. 417, 456.

Gunflint in place.[22] The magnetic readings, such as are described above, indicate that several of the Animikie outcrops within the gabbro are inclusions. The rocks are referred to throughout this paper as inclusions.

Titanium Content.—One of the criteria most used in separating the Gunflint iron formation (both in place and as inclusions in the gabbro) from the magnetic concentrations of the gabbro is the presence or absence of titanium. All discussions of the

TABLE I.

ANALYSES OF INCLUSIONS OF BANDED GUNFLINT FORMATION COMPILED FROM VARIOUS SOURCES.

Location.			Per Cent. Fe.	Per Cent. TiO_4.	100 TiO_2: Fe.	Remarks.
Sec.	T.	R.				
23	62 N.	11 W.	27.10	0.33	1.2	
30	62	10	53.68	12.00	22.4	Concentrates
30	62	10	53.46	2.00	3.7	"
30	62	10	61.94	0.00	0.00	"
30	62	10	29.77	1.58	5.3	Crude ore
30	62	10	30.10	1.19	4.0	" "
15	63	9	45.02	9.45	21.0	" "
28	64	7	52.80	3.85	7.3	" "
18	64	6	39.20	1.20	3.0	" "
18	64	6	12.10	0.76	6.3	" "
18	64	6	39.12	1.01	2.6	" "
14	64	7	38.65	0.90	2.3	" "
14	64	7	33.20	0.62	1.9	" "
14	64	7	40.00	0.30	0.75	" "
14	64	7	35.10	0.42	1.2	" "
14	64	7	39.10	10.61	27.0	" "
14	64	7	40.90	0.35	0.9	" "
14	64	7	24.55	0.41	1.7	" "
17	64	6	41.85	8.94	21.4	" "
17	64	6	39.10	7.83	20.0	" "
12	64	6	53.14	8.90	16.7	Concentrates
7	64	5	51.10	21.54	42.0	Crude ore
7	64	5	34.60	8.28	24.0	" "
7 and 12	64	5 and 6	56.16	0–6	0–10.7	" "

chemical nature of the Gunflint in place, so far encountered, agree that it is practically non-titaniferous. Many analyses support this statement. The maximum percentage of TiO_2 reported in any analysis which the writer has seen is .11 per cent. Since these rocks are at the contact or very close to the gabbro,

[22] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, p. 203, 1911.

and have not received any notable contribution of titanium, the supposition that the included fragments of the same formation should also be non-titaniferous would seem to be justified. A few analyses have been made which support this view. However, many other analyses show that the titanium of the inclusions is higher than that of the formation in place. All the available analyses of the included Gunflint formation have been tabulated and their titanium content expressed as a fraction of the iron content by the ratio $100TiO_2 : Fe$. (See Table I.) It is seen that of the 23 analyses of the Gunflint inclusions, there are but two which show a percentage of TiO_2 as low as that given as the maximum showed by the Gunflint in place. The titanium content is variable in different parts of the same inclusion. For example, in the analyses cited from the Fraser Lake inclusion (Sec. 14, T. 64 N., R. 7 W.) the ratio $100TiO_2 : Fe$ varies from .75 to 27.0. The inclusions to the east of those at Fraser Lake, in sections 18 and 17, T. 64 N., R. 6 W., show ratios of 2.6 to 21.4. Inclusions near the northwestern part of Little Saganaga Lake show a ratio of 0 to 42.0.

Source of Titanium.—It is apparent that titanium is present in the Gunflint inclusions in variable amounts, in practically all cases much higher than the titanium of the Gunflint in place. One might attempt to explain these high titanium results by assuming that they represent gabbro ore. Thus in a description of the Fraser Lake inclusion, the origin of part of it was left uncertain until it was found whether or not it was titaniferous.[23] In the case of the Muskrat Lake inclusion, there was some difficulty in distinguishing between the gabbro, which is high in magnetite in that vicinity, and the included ore. However, it is shown below that there are no clear cases of gabbro ore west of Range 3 W. These Gunflint inclusions under discussion are all west of Range 5 W. It would indeed be a remarkable coincidence if all the segregations in this part of the gabbro happened to occur just where a Gunflint inclusion lodged. It seems much

[23] Grant, U. S., Geol. and Nat. Hist. Survey Minnesota Final Report, Vol. 4, pp. 417, 456, 1899.

more reasonable to explain the higher magnetite of the gabbro in the vicinity of some of the inclusions by a partial assimilation of the inclusions. Again, the writer has not seen in the vicinity of any of the Gunflint inclusions, any of the feldspar magnetite gabbro which is considered the only type of iron ore that is certainly a segregation of the gabbro. It is possible that some of the pyroxene olivine magnetite aggregates, which are developed in the metamorphism of the Animikie, have been mistaken for gabbro in the vicinity of the inclusions, just as they have been at the contact.

Various analysts have found considerable titanium in these ores and since it is unlikely that they represent gabbro segregations, it is probable that the titanium content is due to emanations from the gabbro.

Examples of magnetites formed by emanations at igneous contacts are not rare. Most of them are non-titaniferous, but a few contain considerable amounts of titanium, in spite of statements to the contrary.[24] Singewald has described the Cebolla district as a contact metamorphic deposit of titaniferous magnetite, associated with a basic igneous rock.[25] Bayley[26] in discussing the origin of some of the titaniferous magnetites of New Jersey, classifies some of them as of pneumatolitic origin. Van Hise and Leith[27] state that at Champion, Michigan, in the Marquette district, certain titaniferous magnetite ores may represent a direct contribution from the intrusive. Foye[28] describes titaniferous magnetite deposits which he believes were

[24] Krusch, P., "Die Untersuchung und Bewertung von Erzlagerstätten," p. 179, 1907.

Beyschlag, Krusch und Vogt, "Die Lagerstätten der nutzbaren Mineralien und Gesteine," Vol. 1, p. 351, 1909.

[25] Singewald, J. T., "The Iron Ore Deposits of the Cebolla District, Gunnison County, Colorado," ECON. GEOLOGY, Vol. 7, pp. 560–573, 1912.

[26] Bayley, W. S., Geological Survey of New Jersey Final Rept., Vol. 7, pp. 147–156, 1910.

[27] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, p. 553, 1911.

[28] Foye, W. G., "The Relation of the Titaniferous Magnetite Ores of Glamorgan Township, Haliburton County, Ontario, to the Associated Scapolitic Gabbros," ECON. GEOLOGY, Vol. 11, p. 680, 1916.

derived from underlying syenite intrusives by "gaseous transfer."

Similarly emanation of titanium from the Duluth gabbro is believed to have taken place and probably explains the titanium content reported in some of the included hornfels. It is stated[29] that the Gunflint formation in place has had titanium added in small quantity at the immediate contact with the gabbro. An inclusion would be able to take up that material from the gabbro on all sides, and therefore be much more likely to have additions of material. It is very probable that since TiO_2 was added, iron was also, thus enriching the iron content of the rock.

Age.—The identity of these inclusions with the Gunflint iron-bearing formation of the Animikie or upper Huronian is certain. This fixes their age as upper Huronian.

Economic Possibilities.—Van Hise and Leith[30] state that the time may be distant, if it ever comes, when the Gunflint ores in place can be concentrated with a profit. It is certain, if the ore in place can not be profitably mined, that mining these inclusions would not pay. Two factors which might in time make the undisturbed ores more valuable are the large amount available and the lack of titanium. The inclusions, on the other hand, are small in size, have a very uncertain extent in depth, and in many cases are high in titanium. Even should the inclusions later be proved to be in place, their commercial possibilities would not be so great as those north of the gabbro on account of their high titanium content. At best they are not to be considered as a present possibility for mining.

Banded Segregations of the Gabbro.

Introduction.—There is but one type of ore within the gabbro to which the term segregation can with certainty be applied. The term segregation cannot be applied to any deposit of magnetite within the gabbro, simply because it contains TiO_2. It

[29] Zapffe, Carl, "The Effects of a Basic Igneous Intrusion on a Lake Superior Iron-bearing Formation," Econ. Geology, Vol. 7, p. 152, 1912.

[30] Van Hise, C. R., and Leith, C. K., "The Geology of the Lake Superior Region," U. S. Geol. Survey Mon. 52, p. 204, 1911.

has been shown that even the non-titaniferous Gunflint formation, when caught in the gabbro as an inclusion, is impregnated with titanium. In distinguishing true segregations of the gabbro, then, we are forced to use criteria other than the titanium content. These criteria are considered in the following discussion.

Distribution.—The westernmost deposit of the type of ore which is undoubtedly a segregation of the gabbro is in Sec. 6, T. 64 N., R. 3 W. There are numerous outcrops of the same type within fourteen miles east of this point. Most of them are less than one half mile from the northern boundary of the gabbro (Fig. 36). Another strip of outcrops of this type extends across the southern part of towns 63 N., R. 3 and 4 W.

Petrographic Character.—These ores are essentially plagioclase, feldspar, magnetite, and ilmenite, with minor variable amounts of augite and olivine. Apatite and biotite are the chief accessories. In thin section or hand specimen, the plagioclase crystals are automorphic, standing out in cross section as white lathes against the black background of magnetite (Plate XLI.*C*). The plagioclase is a basic labradorite and has clearly crystallized before the magnetite. The crystals are tabular, about one half inch long, and lie with their shorter dimensions parallel. The texture is coarse-grained. The rounding of grains is not as characteristic a feature in this type of ore as in the included Animikie type. The olivine, if present, has its characteristically rounded outline, but the plagioclases have relatively sharp angles.

Mode of Occurrence.—It occurs in all cases as bands relatively high in magnetite, in a banded gabbro. The feldspars are parallel to the banding of the gabbro, which is parallel to its nearest contact. In many cases the dip of the band was taken by observing the dip of the tabular feldspar crystals. The bands of ore grade into gabbro by decrease in magnetite, at the ends as well as at the top and bottom. The surface outcrops vary in length from a few feet to one mile. The thickness of the bands, of which several parallel ones may make up a single deposit, varies from less than one inch to about five feet. There is little data for estimation of their depth. If the theory of the convection currents in the gabbro during its cooling, as proposed by Grout,[31] is correct, these bands of magnetite gabbro may extend down the dip to great depths, since the convection currents are supposed to have moved down the dip of the gabbro parallel to its floor. They would then have the shape of ribbons, their length being parallel to the dip. Detailed magnetic readings indicate that the ore is not merely a surface concentration and the buried magnetic poles are so deep that they do not influence the dip needle.

Titanium Content.—The available analyses have been gathered and tabulated with the calculation of the quantity $100TiO_2$: Fe to afford a basis of comparison. (See Table II.) Some of the analyses were made on crude ore, others upon magnetic concentrates. The ratio of iron to titanium varies considerably.

TABLE II.

ANALYSES OF BANDED SEGREGATIONS OF THE GABBRO COMPILED FROM VARIOUS SOURCES.

Location.			Per Cent. Fe.	Per Cent. TiO_2.	100 TiO_2: Fe.	Remarks.
Sec.	T.	R.				
27	63 N.	4 W.	50.43	22.02	43.7	In concentrates
21	63	4	49.11	18.87	38.4	" "
25	63	4	56.62	10.00	17.7	" "
18	63	1	41.25	12.00	29.1	" "
7	63	1	33.07	10.04	30.3	
6	64	1	37.75	21.29	56.4	Crude ore
2 and 3	64	2	52.46	2.26	4.3	
2 and 3	64	2	58.60	13.95	24.0	
1	64	3	40.05	22.05	55.0	" "
36	65	3	38.87	16.80	43.2	" "
27	63	4	43.90	15.06	34.3	
36	63	9	50.74	11.81	23.3	Concentrates
29	63	9	7.86	4.77	60.7	Crude ore

Economic Possibilities of Titaniferous Ores in General.—It is not the purpose of this paper to discuss in detail results of concentration tests, the objections to titanium in iron ores, or any other metallurgical problems which must be solved before use is made of these ores. It is sufficient to state that iron ores con-

[31] Grout, F. F., manuscript in preparation.

taining over 1 per cent. of titanium are objectionable.[32] The procedures suggested for their treatment include elimination of titanium by magnetic concentration, lowering the titanium content by mixing them with non-titaniferous ores, smelting in electrical furnaces, and the production of iron-titanium alloys, not attempting to eliminate the titanium. Concentration tests have proved that it is almost impossible to reduce the titanium content of most of the ores sufficiently to make them economically available. Metallographic studies[33] have shown that the titanium is present in three distinct forms: (1) in rounded crystals of ilmenite intergrown with the magnetite as is any other rock-forming mineral; (2) in the form of ilmenite tablets, intimately intergrown with magnetite, along the octahedral parting planes of the magnetite; (3) replacing iron in the magnetite molecule itself. In this last case, no degree of fineness of crushing would allow of magnetic separation of the two. In intergrowths of ilmenite along the parting planes of the magnetite, metallographic investigation has shown that the crushing would have to be carried to such a degree of fineness as to be impractical. Only where the ilmenite occurs in rounded grains of a size comparable with that of the other minerals of the ore, has the mechanical separation proved uniformly successful.

In the magnetite ilmenite intergrowths, the ilmenite is arranged parallel to the octahedral faces of the magnetite, in tablet-like forms. The method of metallographic investigation is to cut a random section through the ore, polish the surface, and treat it with hydrochloric acid. The magnetite is acted upon by the acid and the ilmenite is not affected. This leaves a bright lattice work of lines which represent the intersection of the planes of the ilmenite tablets with the polished surface. Fig. 38 shows that in a random section through an octahedron of magnetite there are four possible directions of the lines in the lattice work.

[32] Holmes, J. A., Preface to J. T. Singewald's "The Titaniferous Iron Ores in the United States," U. S. Bureau of Mines Bull. 64, p. 8, 1913.

[33] Singewald, J. T., Jr., "Microstructure of Titaniferous Magnetite," Econ. Geology, Vol. 8, p. 214, 1913.

Brunton, Stopford, "Notes on Titaniferous Magnetite," Econ. Geology, Vol. 8, p. 680, 1913.

Economic Possibilities of the Minnesota Segregated Ores.—The foregoing facts show that regardless of the size of these titaniferous deposits, they will not be available as ore for some time.

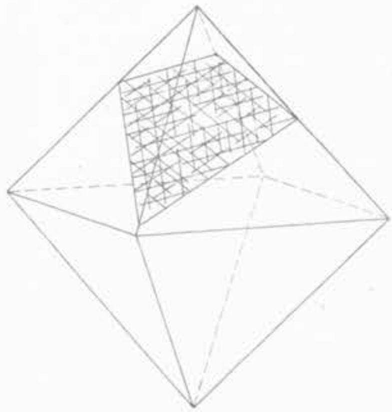

FIG. 38. The four possible directions of ilmenite tablets in a random section through an octahedron of magnetite.

Even the solution of the separation of titanium would not bring the Minnesota deposits into immediate importance because of other more important deposits elsewhere in the United States.

Irregular Bodies of Titaniferous Magnetite.

Introduction.—The remaining two types of ore do not show such distinctive characteristics as those previously discussed. They are not banded with quartz, nor are they feldspathic, grading into the gabbro. They appear to be highly metamorphosed Gunflint inclusions, but no definite statement of their origin can be made.

Distribution.—Most of the prospects in northeastern Minnesota are irregular bodies of titaniferous magnetite. They are found over the entire area of the gabbro which contains iron ore.

Petrographic Character.—The minerals are chiefly olivine, pyroxene, and magnetite; plagioclase is entirely absent in most cases. Where present it is later than the magnetite and the crystals are xenomorphic and small. The color of the ore is greenish black to black. The texture is coarse to fine granular. In many cases the grains are rounded.

Mode of Occurrence.—In size, the bodies vary from a few square feet in area to bodies three quarters of a mile long and 250 feet in width. Most of them are aligned east and west though not so elongated as in the segregations of the gabbro already described. The ore bodies are irregular in shape and cut across the banding of the gabbro with sharp contacts. Hornfels inclusions are almost invariably associated with these ores. In many cases the ore appears as a thin crust or plaster, a few inches thick, spreading out over an outcrop of gabbro or hornfels. In some cases the hornfels and ore appear in contorted alternating bands as though they were both at one time plastic. In other cases they have a more uniformly banded, almost gneissic appearance.

TABLE III.

ANALYSES OF THE IRREGULAR BODIES OF TITANIFEROUS MAGNETITE, COMPILED FROM VARIOUS SOURCES.

Location.			Per Cent. Fe.	Per Cent. TiO_2.	100 TiO_2 : Fe.	Remarks.
Sec.	T.	R.				
25	63 N.	10 W.	29.95	12.28	40.9	Crude ore
36	63	10	46.83	3.74	8.9	" "
36	63	10	44.92	15.27	34.0	" "
36	63	10	49.40	16.30	33.0	
36	63	10	49.81	16.03	32.0	
30	63	9	57.45	9.55	16.6	Crude ore
29	63	9	10.29	7.40	71.8	" "
14	63	9	24.17	20.52	84.9	" "
21	63	4	51.16	2.62	5.1	
21	63	4	51.40	14.73	28.7	
1	64	3	12.40	9.83	79.3	Crude ore
1	64	3	30.72	17.18	55.9	" "
1	64	3	34.08	21.05	61.8	" "
1	64	3	29.04	18.52	63.7	" "
36	65	3	51.31	20.00	38.9	Concentrates
36	65	3	52.46	2.23	4.25	
33	63	3	56.46	11.32	20.1	Concentrates
1	64	2	43.98	26.13	59.4	" "
31	65	2	58.48	12.09	20.7	
7	64	1	38.42	30.37	79.0	Crude ore
7	64	1	42.92	30.32	70.7	
5	64	1	29.49	19.48	66.0	

Titanium Content.—The titanium content of these ores is variable, and apparently higher than that of the ores previously considered. (See Table III.)

Origin.—These ores have been called segregations of the gabbro. No one, so far as the writer is aware, has suggested that they are not related to the gabbro in origin. It has been supposed that the presence of titanium was sufficient in itself to identify them with the gabbro. Similarly, irregular bodies of titanic iron ore are known in other localities as segregations in basic intrusives.[34] All the minerals of the ore are those of the gabbro.

However, there is considerable evidence that these deposits are inclusions of Gunflint iron formation, perhaps originally low in silica. It has been shown that the presence of titanium in a deposit of magnetite within the gabbro is of no use as a criterion in determining its origin. Undoubted inclusions of Gunflint iron formation have received titanium from the gabbro in considerable amount. At Little Saganaga Lake are masses of iron ore, identical in texture and mineral composition with these ores. They are unquestionably phases of the Gunflint inclusions already described. The same type of ore appears as a phase of the Gunflint formation in place. Whereas the typical gabbro ore is a banded feldspar magnetite rock, conformable with the bands of the gabbro, and grading into it, most of these irregular bodies show no banding, but cut across the structure of the gabbro and have sharp contacts with no gradational phases, such as are mentioned as characteristic of the segregations in other localities.[35] Their almost invariable association with hornfels, the metamorphosed inclusions of other rocks, suggests that the origin of the two rocks was similar, especially since the undoubted segregations of banded feldspar magnetite ores are not associated with hornfels. The relative order of crystallization and abundance of the plagioclase of this ore as compared with the undoubted gabbro type suggests a different origin for the two types. In the gabbro ore feldspar is the chief gangue mineral, and is earlier than the magnetite. In the type under discussion, the feldspar is in most cases lacking or small in amount, and later than the magnetite. The evidence indicates that these

[34] Lindgren, Waldemar, "Mineral Deposits," p. 749, 1913.
[35] *Ibid.*

ores are metamorphosed iron formation rather than segregations of the gabbro. If they were segregations differentiated in depth, and later intruded into the earlier phases of the gabbro, they would show intrusive forms which have not been observed.

Economic Possibilities.—The possibility of future utilization of these ores appears to be more remote than the utilization of the banded feldspar type. The objection to the titanium is of equal force in both cases, but the chances of the extent in depth are more uncertain. If they are inclusions their depth is probably small. The type of magnetic readings in the vicinity of these bodies indicates that this is the case.

Dike-like Bodies of Titaniferous Magnetite.

Distribution.—These ores resemble those of the type just discussed. They occur chiefly in the region about Iron and Tucker lakes, and in parts of the area south of Brule Lake.

Petrographic Character.—They have, in general, a much higher proportion of magnetite than the other types of ore. The gangue minerals are chiefly olivine and pyroxene. Plagioclase is very minor in amount and is xenomorphic and later than the magnetite. Some of the smaller dikes are almost pure magnetite (or titaniferous magnetite). The texture is granitoid and in many cases the grains are rounded.

TABLE IV.

ANALYSES OF THE DIKE-LIKE BODIES OF TITANIFEROUS MAGNETITE, COMPILED FROM VARIOUS SOURCES.

Location.			Per Cent. Fe.	Per Cent. TiO_2.	100 TiO_2: Fe.	Remarks.
Sec.	T.	R.				
19	64 N.	6 W.	46.50	29.80	64.1	
15	64	6	40.80	2.31	5.7	

Mode of Occurrence.—In length the outcrops of dikes vary from less than one foot to probably 20 feet, and in thickness from less than one inch to a few feet. The dikes finger out into hornfels and there are irregularly shaped branching forms.

The relationship to the hornfels, invariably associated with them, is clearly intrusive (Plate XLI.*B*). The contacts with the wall rock are sharp and the dikes run in various directions without regard to gabbro structure. Inclusions of hornfels and gabbro are numerous. These inclusions are in most cases rounded (Plate XLI.*A*).

Titanium Content.—The analyses are of samples of bodies of small size and show a great variability of titanium.

Origin.—The origin of these ores is similar to the type last discussed. Dikes of titanic iron ore are not uncommon in basic intrusives and are usually regarded as having been segregated in depth, and then injected into the earlier crystallized rock.[36] The intimate association of these magnetite dikes in the Duluth gabbro with hornfels suggests that they are derived from inclusions which were brought to the point of fusion by the heat of the gabbro.

If the magnetite dikes were differentiates of the gabbro, they would represent an immiscible liquid in the molten silicates. But the banded feldspar ores show that feldspar was in excess in the gabbro magma. Plagioclase clearly crystallized first. It is difficult to understand how magnetite, being in such small proportions to the feldspar as to reverse the normal order of crystallization, could at the same time form an immiscible liquid with no feldspar in it. Newland[37] suggests in explanation of this reversal of the normal order that the magnetite separated first as an immiscible liquid, and after the gabbro proper had solidified, the magnetite separate was shot into it, catching up fragments of solid material during its upward progress. These fragments would give the appearance of a reversal of the normal order of crystallization. This explanation will not hold for the Minnesota rocks. The plagioclase which is associated with the magnetite is not fragmental. The usual explanation advanced as a reason why one mineral crystallizes before another, is that at some temperature (below the fusion point of the mineral in question), the magmatic solution becomes saturated with it, and

[36] Lindgren, Waldemar, *loc. cit.*

[37] Newland, D. H., "Geology of the Adirondack Magnetic Iron Ores," N. Y. State Museum Bull. 119, pp. 152–153, 1908.

EXPLANATION TO PLATE XLI.

FIG. A. Dike of magnetite; with inclusions of gabbro and hornfels. Iron Lake, Minn.

FIG. B. Relation of magnetite stringers to the hornfels. Iron Lake, Minn.

FIG. C. Automorphic plagioclase in magnetite, one half size.

~~Polished surface of banded galena ore (Fig. 23) showing irregular, fractured nature of tetrahedrite and sphalerite inclusions. (× 2.)~~

A.

B.

C.

as a result, it crystallizes. This was the case with the plagioclase. It crystallized before the magnetite; hence the proportion of magnetite must have been small. On the other hand, if magnetite (with some olivine and pyroxene) separated as an immiscible liquid, it must have been in excess. The two conditions in the same magma apparently are incompatible. The writer suggests the following as an explanation of the segregations and dikes: The gabbro magma had such a low content of magnetite that the other minerals, particularly plagioclase, crystallized first. Convection currents, which were prominent during the crystallization of the gabbro,[38] caused the earlier products of crystallization to be carried to the bottom of the chamber for final deposition. Thus the gabbro at the bottom is not at all rich in magnetite. Then came a period in the crystallization when the magma became saturated with respect to magnetite and it also began to crystallize, and was carried toward the bottom of the mass by the convection currents, together with many of the still unlodged automorphic crystals of plagioclase of the previous period. Thus, some little distance from the northern boundaries of the tongues of the gabbro are bands of the plagioclase magnetite rock grading into gabbro. The period of crystallization of the magnetite was relatively short, as is evidenced by the narrowness of the bands. Bands high in magnetite occur in a zone only a few hundred feet thick, measured perpendicular to the dip.

In the case of the dikes some of the pieces of iron formation which are known to have been included in the gabbro were probably heated to a temperature high enough to melt the magnetite which they contained. Magnetite has a melting point lower than that of most rock-forming minerals. It melts at 1225° C., while ilmenite, labradorite, and olivine (poor in iron) melt at 1450°, 1475°, and 1750° C. respectively. Daly[39] states that the surface temperature of the lava of Mauna Loa may be as high as 1300° C. and that the melting point of basalt, about 1100° C., may be exceeded by 200° or 300° C. Therefore it is not impossible that

[38] Grout, F. E., manuscript in preparation.

[39] Daly, R. A., "Igneous Rocks and their Origin," pp. 210, 212, 258, 1914.

the magnetite of some of the inclusions would be fused, and the whole inclusion become pasty. The contorted smeary appearance of some of the hornfels indicates that it had been rendered semi-liquid. We may imagine, then, an inclusion which had become a softened viscous body, still keeping enough coherence to prevent it from being swept entirely away by the convection currents of the gabbro, thus losing its identity. Part of the liquid magnetite would undoubtedly be assimilated by the gabbro, but some of it within the body of the inclusion might filter out into small local chambers, surrounded on all sides by the semi-molten hornfels, and on further cooling be forced into the solidified hornfels and gabbro in its vicinity, as dikes, such as are shown in Plate XLI.*B*. The high content of titanium which some of these bodies have is easily explained by emanation or diffusion from the gabbro. Ilmenite and magnetite are soluble, in the liquid state, over a large range of proportions, judging from the intergrowths of the two minerals which are found. The solubility of ilmenite in the silicate magma was probably small. The transfer of ilmenite to the softened inclusion would simply be a matter of diffusion of a substance from solution in one liquid to another liquid in which it is much more soluble.

Economic Possibilities.—Most of the dikes and stringers which have been considered as prospective ore bodies are too small for serious consideration. The possibility that they lead to large bodies of ore underneath the surface, as has been suggested by various private reports, is too unlikely to warrant further expenditure upon them at present. Even though larger bodies might be found, the objections which have been advanced for the other deposits would still operate to prevent their profitable exploitation.

SUMMARY.

Inclusions of the Gunflint iron-bearing formation in the Duluth gabbro are much more numerous and extensive than has hitherto been supposed. The gabbro has developed certain types of contact rocks along its northern boundary, whose characteristics are noteworthy in the study of similar rocks found within the gabbro. One of these contact types is a fine-grained hornfels, which Winchell named muscovadite. It is formed by the contact alteration of slate, conglomerate and basalt. Many areas of a similar hornfels, within the gabbro mass, are regarded as being chiefly metamorphosed inclusions of these rocks. Another contact type is developed by metamorphism of the Gunflint iron-bearing formation, which is changed to banded quartz magnetite rocks with pyroxene and fayalite in variable amounts. Where quartz is lacking, the coarse fayalite pyroxene magnetite aggregates bear such a close resemblance to igneous rocks that they have been mistaken for peripheral phases of the gabbro. Many bodies of magnetic ore within the gabbro, formerly regarded as magmatic segregations, are shown to be more probably inclusions of these less siliceous phases of the Gunflint formation. There is some evidence that the gabbro has assimilated material from the inclusions, and that there has been fusion of some of the included materials, particularly magnetite.

The several types of magnetic ores within the gabbro are: inclusions of Gunflint iron formation, segregations of the gabbro, and other bodies whose mode of origin is less certain. The generally accepted distinction of inclusions of Gunflint formation and segregations of the gabbro, on the basis of the presence or absence of titanium or quartz bands, is erroneous, it being shown that the inclusions contain titanium in varying amounts, and that they are not in all cases banded, nor quartz-bearing. The ores are classified and discussed under the following headings:

1. Inclusions of banded Gunflint iron formation.
2. Banded segregations of the gabbro.
3. Irregular bodies of titaniferous magnetite.
4. Dike-like bodies of titaniferous magnetite.

The banded inclusions are easily recognized, being essentially the same as the types developed by the contact metamorphism of the Gunflint iron formation. They are banded quartz magnetite rocks, with variable amounts of pyroxene and olivine. Quartz may be absent in parts of these inclusions, as in parts of the Gunflint iron formation which at the contact have been mistaken for peripheral phases of the gabbro. Analyses show that there is a variable amount of titanium in these ores. Since the Gunflint formation is almost non-titaniferous, it is certain that the gabbro gave up titanium to the inclusions.

The magnetites which are certainly segregations occur as narrow bands grading into the gabbro. The chief gangue mineral is plagioclase, which crystallized before the magnetite. These segregations have a high titanium content.

The irregular bodies of titaniferous magnetite do not contain the quartz which is characteristic of the recognizable Gunflint inclusions, nor do they contain plagioclase, which characterizes the segregations of the gabbro mentioned above. The gangue minerals are chiefly olivine and pyroxene. In most cases these deposits show structures that do not conform to those of the gabbro. They are associated with hornfels and the titanium content is high. The evidence suggests they are inclusions of that phase of the contact metamorphosed Gunflint formation which after recrystallization has no quartz. The titanium may be accounted for as derived from the gabbro.

The dike-like bodies are invariably associated with the hornfels, intruding it and containing inclusions of it. They resemble most closely the type last discussed, and their origin is probably the same It is belived that they are small inclusions of the Gunflint iron formation, in which the magnetite was fused by the gabbro, the remainder of the inclusions forming the hornfels. The fusion would not be difficult, since the inclusions were surrounded by a magma at a temperature above the melting point of magnetite.

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SOME FEATURES OF MAGNETIC SURVEYS OF THE MAGNETITE DEPOSITS OF THE DULUTH GABBRO.

T. M. Broderick.

INTRODUCTION.

This paper outlines the methods used and some of the results obtained in making a magnetic survey of the magnetite deposits of the Duluth gabbro. Certain unusual features of the magnetic fields encountered are described and explanations for them suggested. The field work was carried on by F. F. Grout and the writer for the Minnesota Geological and Natural History Survey in preparation for a bulletin on the titaniferous magnetites of northeastern Minnesota.

The magnetite deposits in the gabbro area are of two distinct modes of origin. Some of them are clearly segregations of the gabbro, while others are metamorphosed inclusions of the sedimentary Gunflint iron-bearing formation. The segregations of the gabbro consist essentially of magnetite and plagioclase feldspar and they occur as bands which grade into the normal phases of the banded gabbro by decrease in the amount of magnetite. The highly metamorphosed inclusions of sedimentary iron formation are in many cases banded, but the bodies occupy haphazard positions with respect to gabbro structures. The chief minerals of the inclusions are magnetite, quartz, fayalite, amphibole, and pyroxenes. Plagioclase feldspar, so characteristic of the segregations of the gabbro, is almost entirely lacking in the inclusions. Titanium in the mineral ~~element~~ ilmenite occurs in variable amounts in the deposits of both classes. As will be shown, the magnetic fields produced by these two types of deposits are very different.

METHODS AND GENERAL RESULTS.

Introduction.—Magnetic work on the gabbro was carried out with certain modifications, according to the usual methods employed in the Lake Superior region. The instruments used were the dip and dial compasses. Hotchkiss has described the uses, mechanism and other features of these instruments.[1] Two types of magnetic traverse were made, (1) those in the nature of general reconnaissance, and (2) mapping a magnetic area in detail.

Reconnaissance Methods and Results.—The usual method of magnetic reconnaissance work on a large area is to make traverses, generally on north-south section and quarter section lines, reading the instruments every hundred paces. By connecting places of abnormal attraction, from one traverse line to another, magnetic belts or lines are obtained, which usually give the strike of a magnetic rock, in some cases an iron formation. Later, more detailed magnetic work and drilling may result in the discovery of ore bodies in an area even where there are no outcrops. There are numerous features which made this type of reconnaissance work of almost no value in the work in the Duluth gabbro. In the first place, prospectors have already reported practically all the outcrops which have the least appearance of being high in iron. They were naturally on the lookout for ore because of the proximity of the Vermilion and Mesabi ranges. The region has many outcrops and very thin drift, so that the information gathered from these sources, together with the many published references to ore outcrops, is likely to be fairly complete, and the chances of locating new deposits by magnetic traverses correspondingly poor. Most of the magnetic bodies are long and narrow, extending east and west. Their influence upon the dial compass is therefore almost nil. Since the ore outcrops at the surface the dip needle is not affected a short distance away, so that a north-south traverse with readings at one hundred pace intervals would be very likely to miss a strip of ore. Many of the ore bodies are only a few hundred paces in length, greatly reducing the chances of finding them by magnetic traverses one half mile or one mile apart. Many of the inclusions are extremely variable in their composition, therefore variable in their disturbing influence upon the earth's field. On some of the iron

[1] Hotchkiss, W. O., "Mineral Lands in Part of Northwestern Wisconsin," Wis. Geol. and Nat. Hist. Survey Bull. 44, pp. 75–133.

ranges, magnetic lines are traced by dip needle variations of one half degree. On the Duluth gabbro, the readings over the normal country rock vary as much as twenty degrees. Finally, it was found that magnetic readings upon some of the largest magnetite deposits showed no more variation than could be obtained over the normal gabbro. All these factors should tend to discourage attempts to search for new bodies of ore in the gabbro by the reconnaissance method here discussed.

Detailed Methods and Results.—Detailed or close magnetic surveying, starting from an outcrop of magnetite, is to be recommended for approximately mapping the ore body. It consists in taking closely spaced readings. In much of the work the dip needle was read at the corners of 12½-foot squares, and the dial compass on 25-foot squares. For practical purposes readings on 50-foot squares should be sufficient. By this method apparently unrelated ore outcrops one half mile apart were found to be on the same band of magnetite gabbro. On the other hand, ore bodies apparently connected were found to be disconnected. There was an area several miles in length where there were so many outcrops of ore that it seemed fairly certain that they formed a continuous band. Detailed magnetic work, while it served to extend most of the patches of ore beyond the outcrops, shows conclusively that the area, instead of being underlain by a continuous band of ore, is underlain by gabbro in which there are short bands of ore. Thus, in some cases, the magnetic observations served to increase the apparent value of a prospect, in others to decrease it.

After obtaining a clear conception of the various types of ore, one finds that it would be a simple matter to determine much concerning the type of ore by the magnetic properties of the deposits, even though there might be no outcrops. The banded gabbro ores give a magnetic belt which runs parallel to the strike of the banding of the gabbro. In some cases the magnetic belt is entirely negative, that is, it causes the north end of the needle to be repelled. This type of ore shows a minimum of the erratic effect due to local polarity. Fig. 14 shows a portion of one of

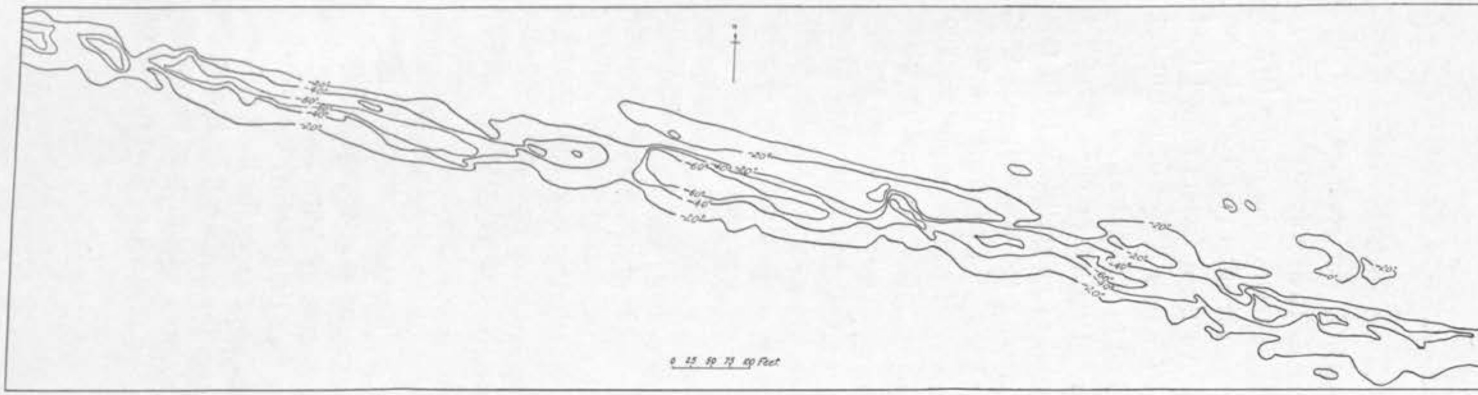


FIG. 14. Contour map of dip needle deflections over a narrow segregation band of magnetic ore in the Duluth gabbro. All deflections negative, contour interval 20°.

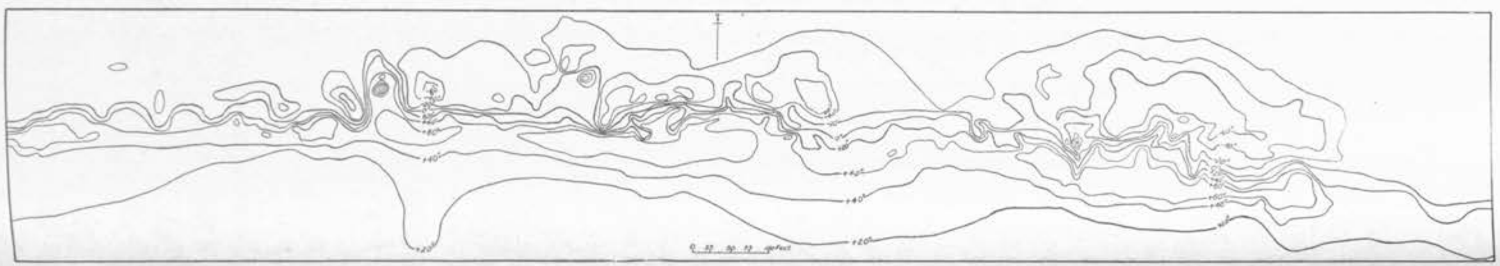


FIG. 15. Contour map of dip needle deflections over a highly metamorphosed inclusion of sedimentary iron formation in the Duluth gabbro, a belt of negative deflections north of a belt of positive deflections. Contour interval 20°.

these belts with the dip needle readings mapped as contours. Such a map closely corresponds to the "maps of vertical intensity" issued by the Canadian Department of Mines. Contrasted

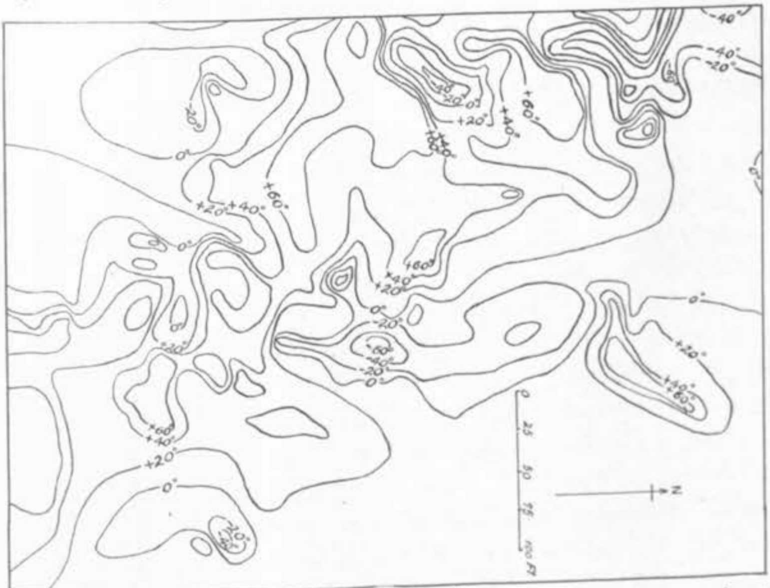


FIG. 16. Contour map of dip needle deflections over a highly metamrophosed inclusion of sedimentary iron formation in the Duluth gabbro. Distribution of negative and positive deflections very erratic. Contour interval 20°.

with the magnetic fields of the gabbro bands are those of the inclusions. Fig. 16 is a contour map of the dip readings over a part of an inclusion. There are high positive and negative dips within a few feet of each other. The magnetic disturbance caused by the whole inclusion is not strong enough to offset the local effects of the irregular distribution of the magnetite near the surface. Still a third type of magnetic field is shown by Fig. 15. This bears some resemblance to the diagram of the dip variations of the gabbro bands, in that the contours run in an east-west direction, and they show considerable regularity. However, there are several points which serve to differentiate this magnetic field from that of a band in the gabbro. The general direction of the contours, instead of running parallel to the banding in the gabbro, cuts across it. The field is divided in two parts, being negative to the north and positive to the south. The deposit is probably an intensely metamorphosed inclusion of a sedimentary iron-bearing formation.

INTERPRETATION OF PECULIAR TYPES OF MAGNETIC OBSERVATIONS, PARTICULARLY NEGATIVE DIPS.

Introduction.—There are interesting results obtained which have a bearing on the theory of magnetic fields produced by magnetic deposits in the earth. Smyth[2] has mathematically worked out the nature of the disturbances of the earth's field by iron ore bodies. Hotchkiss[3] has done the same from an experimental side. The complex conditions in the field, such as the great irregularity of some of the structures, the depth of drift, the irregular topography, the lack of information as to the structural relations of the magnetic formation, all make the proper correlation of cause and effect in magnetic fields a matter of extreme difficulty. The disadvantageous effect of a thickness of drift over the bed rock may be realized by drawing a new surface line about half an inch above the ones shown in Figs. 17–19. The general effect would be to lessen the field intensity (roughly indicated by the degree of crowding of the lines), decrease the amount of variation of the dip needle, and to widen the zone of abnormal readings. The efforts of Hotchkiss and Smyth have been to arrive at certain conclusions as to proper interpretation of certain types of disturbed magnetic fields, in terms of structure, size, depth of burial, and other unknown conditions of the formation causing the disturbance. Their results are all based on the assumption that the nature of the disturbance of the earth's field by a magnetic body is conditioned chiefly by the magnetism induced in the body, since it attained its present structural attitude in the earth's crust.

One of the most common and perplexing questions of magnetic observations is the meaning of negative dip needle deflec-

[2] Smyth, H. L., U. S. Geol. Survey Mon. 36, Chap. 2, Pt. II.

[3] Hotchkiss, W. O., "Mineral Lands in Part of Northwestern Wisconsin," Wis. Geol. and Nat. Hist. Survey Bull. 44, pp. 75–136.

tions. The term "negative" is used in the discussion to describe those deflections of the dip needle in which the south end is depressed or attracted. This is the general usage of the term among those who work with the dip needle in the Lake Superior region. Hotchkiss[4] makes it clear that there are two causes which will give negative readings, a lowering of the intensity of the field, or a flattening of the inclination of the field. He states that negative readings are due almost entirely to the former cause. There are several types of magnetic fields in which negative dip-needle readings are obtained. In one type high negative readings are obtained scattered among equally high positive readings. These are usually interpreted as being derived from greenstone or from bodies like the Gunflint inclusions described above, where the magnetite is bunchy, and close to the surface. In other cases, there may be a narrow zone of negative readings due to a local lowered field intensity, along a line of the usual positive type. These types of negative readings are common and not difficult to recognize, and should not cause concern. However, the type of negative field shown in Fig. 14 is exceedingly rare. Its description and interpretation is given below.

Negative Lines.—Fig. 14 shows a magnetic line of negative attraction. It is to be noted that the only positive readings obtained were entirely local and erratic and constituted a fraction of a per cent. of all the readings taken. Authorities on magnetics agree that it is not uncommon to have a positive line along which there is a zone of negative readings. However, this line differs essentially from those which are partly positive and partly negative. Hotchkiss[5] has described a similar line which was found in Wisconsin. This line can be followed for about five miles. A few miles south there is a positive line. The two converge to the eastern part of the area. Hotchkiss suggests that the structure of the magnetic body is synclinal, pitching westward. Dobie[6] suggests the following as an explanation of the negative character of the line. Magnetite has high magnetic

[4] Hotchkiss, W. O., *op. cit.*, p. 103.
[5] Hotchkiss, W. O., *op. cit.*, p. 341.
[6] Dobie, Walter, unpublished thesis written at the University of Wisconsin.

retentivity. Therefore, when a magnetic formation becomes polarized by induction in the usual manner, its negative pole being near the outcropping part of the formation, it may retain its original polarity even if it should become folded and eroded so that its formerly buried positive pole would be brought near to the surface. It should be kept in mind that an outcropping negative pole attracts the positive end of the dip needle, giving a positive line and vice versa. On the basis of this theory, he considers that the southern positive line is obtained from the original outcropping negative pole, and the northern negative line from the originally buried positive pole of the formation, brought to the surface by folding and erosion.

It would be almost impossible to interpret magnetic readings if it were necessary to explain any magnetic observations on such a basis. In all such interpretations up to this time it has been assumed that the character of the magnetic field above an ore body is determined by the magnetism induced by the earth's magnetic field in the ore since it attained its present position. On this assumption it is supposed to be possible to determine approximately the dip, strike, depth of burial, and size of ore bodies. If it should be found that the magnetic field around any formation in the Lake Superior region were conditioned in any way by a previous attitude of the formation, such determinations would be impossible. All the disturbed formations in the Lake Superior region, and there are few which are not disturbed, would give effects of a magnetism induced in them before they were deformed.

However, there are several objections to Dobie's theory. In the first place, it is possible that the magnetite was formed originally at the time of the dynamic action, so that the structural position of the magnetite at the present time is the only position which it has ever occupied. Granting that the magnetite of the formation may have existed when it formerly occupied another position in the earth's magnetic field, it would seem unlikely that it would retain the induced polarity after suffering dynamic action. Deformation of any particular rock takes place in the zone of fracture or in the zone of flowage for that rock. If the magnetite bed were folded in the zone of fracture, it would have suffered intense mechanical disturbances, such as crushing and abrasion. This would tend to throw the parts of the formation entirely out of alignment, rotating them into haphazard positions, thus completely destroying the magnetic identity of the formation as a whole. If the folding took place by flowage, the process would be even more effective in destroying the magnetic properties of the body. Folding in the zone of flowage takes place by recrystallization, which involves molecular movement. Assuming that magnetite is magnetic under the conditions of rock flowage, the effect of the increased molecular mobility would be to give the molecules greater freedom in magnetically orienting themselves according to the demands of the changing positions which the formation would occupy with respect to the earth's magnetic field during folding. This would result in the destruction of the original magnetic properties of the body. However the magnetic inversion point of polarized magnetite is about 550° C.,[7] which would be exceeded in the zone of flowage. At this temperature polarized magnetite begins to lose its magnetism, and is no longer even capable of being attracted by a magnet. Although on cooling it regains its susceptibility to being attracted, it does not regain its polarity. In order to be polarized again, it must be properly treated in a magnetic field and the polarity it thus acquires is in no way related to that which it had before being heated. Finally, it would seem improbable that a magnetic body could remain in magnetic discordance with the field which originally magnetized it, throughout Keweenawan and post-Cambrian times. The earth movement which would form a syncline of this sort was probably pre-Keweenawan.

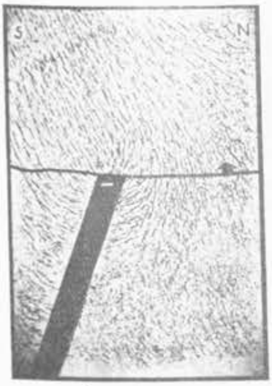
It is therefore necessary to attempt to explain the character of the few known negative lines on the same basis upon which we explain the magnetic properties of other iron formations, that is, that the magnetic phenomena shown by such bodies are due to their present position in the earth's field. Fortunately, the

[7] Sosman, R. B., "Some Problems of the Oxides of Iron," *Jour. Wash. Acad. Sci.*, Vol. 7, p. 63, 1917.

features of the magnetite bodies which form the several negative lines in the Duluth gabbro which have been investigated and mapped in great detail are simple and known. There is no drift, and outcrops along the lines are numerous. The bed rock is everywhere within a few feet of the surface, which is nearly flat in the vicinity of many of the ore bodies. The width of the magnetite bands is fairly constant. One of the lines will serve for an example of the type. The strike of the magnetite band is a little south of east. It dips about 15° to the south and extends so far in depth that the buried magnetic pole does not affect the instruments. Its width, across the dip, is about four feet. The width of outcrop is thus about fifteen feet. It grades into lean gabbro at the top and bottom, and at each end. The topography is level for some distance on each side of the belt. It can be followed by magnetic observations for about a mile. The explanation of negative lines, advanced by Dobie, could not be applied here, because, in addition to the objections urged above, the folding of the Keweenawan gabbro has been very slight.

Dip needle readings were taken every 12½ feet over the entire belt. Fig. 14 is a dip contour map of a part of the line. Instead of the outcropping pole being a negative pole, as it is in the ordinary case, it is a positive pole, attracting the negative pole of the dip needle. Theoretically, the conditions under which this may occur are very limited.

In order to show experimentally what these conditions would be, the types of disturbance of some fairly uniform magnetic fields by a bundle of soft iron wires placed at various angles in them were investigated. The field in these diagrams was produced by a series of bar magnets in parallel position, and it may be considered as representing the earth's magnetic field. The bundle of wires is intended to denote an iron formation in the earth, outcropping as shown in the figures. Care was taken to render the wires absolutely neutral before each experiment. In Figs. 17 and 18 the outcrop shows that an iron formation in these positions would attract the north end of the needle, that is, the magnetic line obtained from a formation dipping as these do would be essentially a positive line. The lines of force converge and enter the outcrop in these cases, making the induced polarity at the outcrops negative. Fig. 19 shows the opposite effect. The lines of force of the field are actually repelled by the end of the



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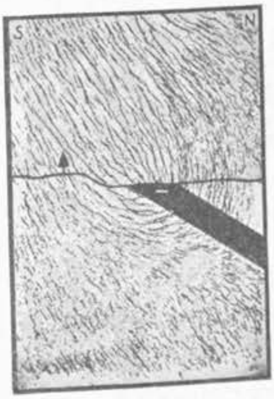

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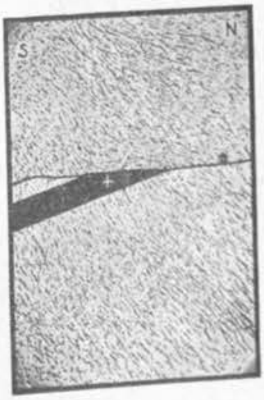

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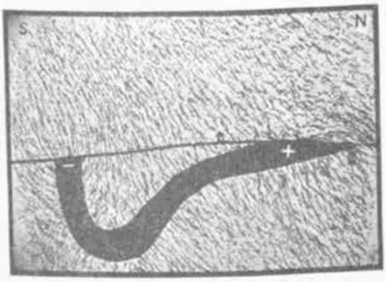

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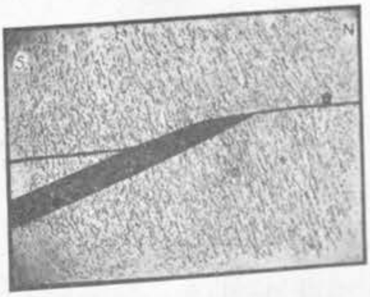

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FIGS. 17, 18, 19, 22, AND 23. Experiments designed to show the distortion of the earth's magnetic field by tabular bodies of magnetite lying in various altitudes.

"iron formation." A counterbalanced dip needle would have its south end depressed over the outcrop, and for some distance to the north and south. The polarity of the outcrop would be positive in this case.

These diagrams show that it is experimentally possible to produce "outcrops" which would give either positive or negative lines, by varying the inclination of the bar to the field. In some cases, a negative line, then, may be capable of being interpreted as caused by a magnetic formation whose angle of dip lies within certain limits. To be able to say just what these limits are would be of great practical value in exploration work, in case other similar lines should be found.

The following suggestions are made bearing on the probable angles of dip which would give the negative lines. A neutral bar of a magnetic substance, placed in parallel position in a magnetic field, acquires an induced polarity (Fig. 20 *a*). The posi-

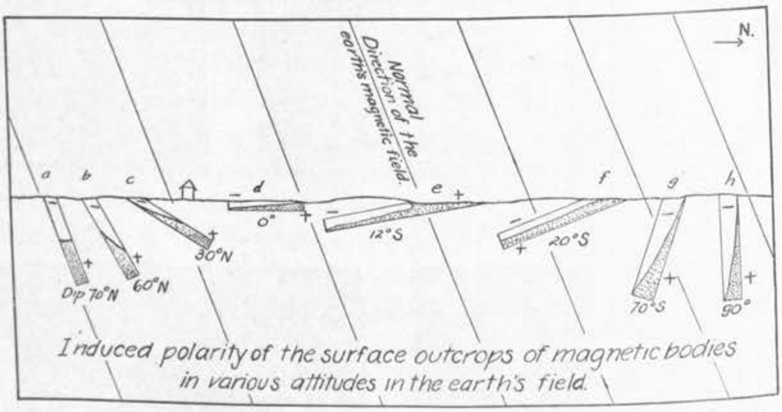

FIG. 20. Induced polarity of the surface outcrops of magnetic bodies in various attitudes in the earth's field.

tive pole would be at (or very near) the end of the bar which lies in the direction in which a free moving north seeking pole in the field would move. As the bar is rotated from the parallel position, the polarity becomes related more and more to the sides, and less to the ends, until finally, when the bar is perpendicular to the field, it is entirely related to the sides (Fig. 20 *f*). However, if the bar is turned but a few degrees from the perpendicular position, the ends will show some polarity. In order to make the application to magnetic bodies in the earth clear, the inclination of the lines of the field (drawn undistorted in this figure) with the horizontal has been made 70°, approximately the inclination of the earth's field in the Lake Superior region. The horizontal line represents the surface, and the upper end of the bar the outcrop of a magnetic formation. The theoretical limitations of the dip of formation which would give a negative line can be deduced from the figure. In the positions *d, e, f,* the bar makes an angle of 70°, 82°, and 90° with the field. These angles correspond to a dip of 0°, 12°, and 20° to the south. Dips between the theoretical limits of 0° and 20° south would give a negative line, because the outcrop has north polarity. If the normal inclination of the earth's field were 75°, the limitations would be 0° to 15° dip to the south. A point deep within the earth on these beds would actually be "up-stream" in the earth's field as compared with a point on the outcrop of the beds. These limits assume a horizontal surface. If the surface rises to the south, there would be more freedom. Fig. 21 shows a hypothetical case which would give a negative line over the northern out-

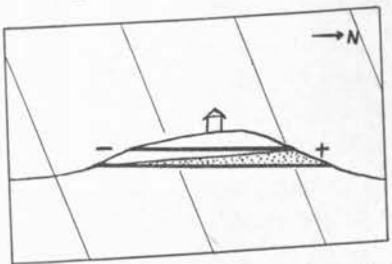

FIG. 21. Positive pole of north dipping magnetic body exposed by erosion.

crop of a formation dipping gently to the north. Fig. 22 shows a structure which might produce a negative line similar to that described by Hotchkiss, the flat southward dipping limb of the syncline affording the negative line and the northward dipping limb the positive line.

This explanation of negative lines is given strong support by the results of recent work of the Minnesota Geological Survey on the magnetite ores of the eastern Mesabi range. There the Biwabik iron-bearing formation dips about seven degrees to the south. The magnetic field is not so simple as those produced by the narrow bands in the gabbro, due to the variable nature of the different beds of the Biwabik formation, several hundred feet in thickness. In spite of this, the great majority of several thousand dip-needle readings were negative. Since the dip of the formation is about seven degrees to the south, this result is what would be expected if the proposed explanation of negative lines is correct.

Magnetic Bodies with No Attraction.—If a few degrees difference in the angle of dip of an iron formation is sufficient to change the character of the dip-needle variations from positive to negative, theoretically there should be an intermediate angle of dip such that there would be no effect upon the earth's field. This rare condition was discovered in the magnetites of the gabbro. It was found that there were long east-west bands of titaniferous magnetite ore outcropping on a south-facing slope, with practically the same southward dip, dimensions, etc., as the one which gave the negative belt described above, over which the variations of the needles were no greater than those obtained over the normal type of gabbro. It was thought that this might be pure ilmenite, because the ore was known to be high in titanium, until it was found that pieces broken off and held near the needles had a marked influence on them. Here, then, were outcrops of magnetic material, which apparently produced no measurable distortion of the earth's field. The writer has not heard of any other cases of the sort. Fig. 23 shows an attempt to duplicate these conditions. A soft iron bar, bevelled as shown, was placed in a field at right angles to its direction of lines of force. There was no noteworthy distortion of the field. The dip of these bands of magnetite which gave no magnetic variations, as closely as could be determined, was about 18° south, just about at right angles to the earth's field, as in the hypothetical case of Fig. 23. Therefore a magnetic formation at right angles to the earth's field would not affect the dip needle, and in a drift-covered region would probably remain undiscovered.

Summary.—On the whole, though one may be inclined to doubt that the change of a few degrees of dip of a formation would be sufficient to change the character of the resultant magnetic line from positive to negative, the theory appears to have some support. In the case of the gabbro ores, where the absence of drift allows the various factors involved to be determined, field evidence seems to favor this interpretation and experiments essentially reproducing actual conditions give further evidence of the validity of the theory. The rarity of negative lines is wholly in agreement with the explanation of the conditions governing them; the proper angle of dip is seldom obtained in the field.