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THE RELATIONS OF MAGNETITE AND ILMENITE IN THE MAGNETITE DEPOSITS OF THE DULUTH GABBRO*

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Introduction

Of the papers[1] published in America on the titaniferous magnetites as studied by reflected light, only those of Singewald mention the deposits found within the Duluth gabbro. Singewald described the deposits of a limited area. The Minnesota Geological Survey has mapped the deposits in detail and Broderick[2] has discussed the results of much of this work. In connection with further work of the survey on the magnetites of the state the writer has examined the relations of the minerals by reflected light in over 100 specimens of the magnetite ore and gabbro representing every important outcrop. The distribution of these deposits is shown on Figure 36 of Broderick's paper where the details of the geology are also described. The data presented here are mainly limited to the relations of ilmenite and magnetite and the bearing of these relations and other data on the origin of the deposits.

The Relations of Ilmenite and Magnetite

Most of the specimens examined were from the four types of

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[1] Singewald, J. T., The microstructure of titaniferous magnetites: *Econ. Geol.*, vol. **8**, pp. 202–214, 1913; The titaniferous iron ores of the United States: *Bur. of Mines Bull.* **64**, 1913. Brunton, S., Some notes on titaniferous magnetites: *Econ. Geol.*, vol. **8**, pp. 670–680, 1913. Warren, C. H., On the microstructure of certain titanic iron ores: *Econ. Geol.*, vol. **13**, pp. 419–446, 1918. Bayley, W. S., The occurrence of rutile in the titaniferous magnetites of western North Carolina and eastern Tennessee: *Econ. Geol.*, vol. **18**, pp. 362–392, 1923. Osborne, F. F., Certain magmatic titaniferous iron ores and their origin: *Econ. Geol.*, vol. **23**, pp. 724–761, 1928.

[2] Broderick, T. M., The relation of the titaniferous magnetites of northeastern Minnesota to the Duluth gabbro: *Econ. Geol.*, vol. **12**, pp. 663–696, 1917.

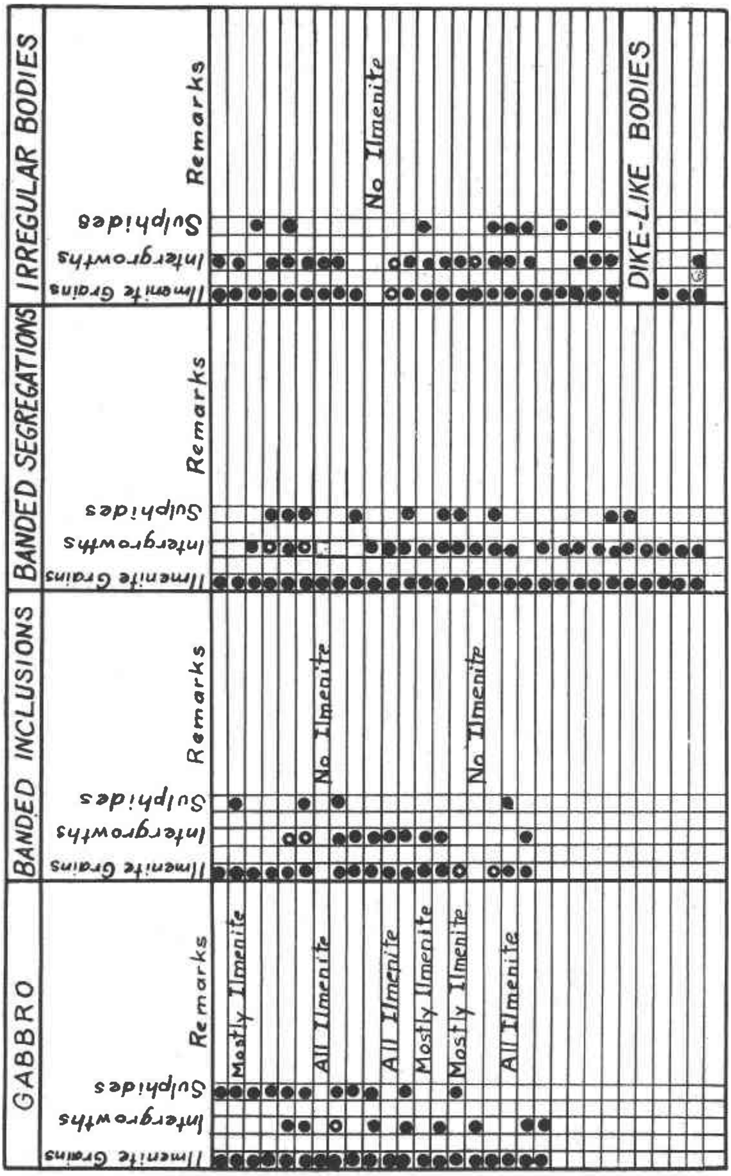

FIG. 1. Tabulation showing the form of ilmenite in magnetite ore and gabbro specimens from various types of deposits in the Duluth gabbro.

titaniferous magnetite deposits as classified by Broderick.[3] These are 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. Several of the specimens were of gabbro found near the magnetite masses and, as might be expected, this gabbro is high in magnetite and ilmenite. An attempt has been made to bring out some of the facts as to the opaque constituents in Figure 1.

As far as could be determined, the titanium occurs mainly as ilmenite which is found abundantly in the ores as grains and as intergrowths of ilmenite along the parting planes of magnetite. Because of the emphasis placed on them, one might think that ilmenite occurs in titaniferous magnetites mainly in the form of intergrowths but this is not true of the deposits in the Duluth gabbro as is shown in Figure 1, nor it is true of deposits in general, according to Singewald. A rough estimate would indicate that not more than 15 per cent of the ilmenite is present as intergrowths.

A glance at Figure 1 shows that ilmenite is found as separate grains in all specimens which show the mineral. The grains vary from microscopic size to a maximum diameter rarely above 5 mm. There is also a great variation in the number of grains on a given polished surface. Some surfaces have only two or three ilmenite grains, whereas others are made up largely of that mineral. A common type is a granular aggregate of ilmenite and magnetite grains of about the same size. A few of the grains of ilmenite when etched show a series of parallel lines or bands and where these are wide enough the dark material may be recognized as magnetite. (See Figure 7). There is a distinct variation in the nature of the surfaces of the polished ilmenite grains. Many show a rough surface due to the presence of innumerable fine pits whereas others in the same specimen are smooth and highly polished. Both types are common and the only explanation which suggests itself is that the difference is due to varying orientation, as in some specimens the pits are elongated in one direction.

In a few specimens minute euhedral crystals of ilmenite were noted in magnetite, but this is an unusual feature.

The intergrowths of ilmenite in magnetite present the most interesting phase of the relations. As shown in Figure 1, 56 out of the 95 specimens tabulated show intergrowths of some kind. These

[3] *Op. cit.*, p. 677.

are of great variety and only the more general types can be noted. On etched polished surfaces, the ilmenite is seen as lines or dashes, rarely dots, but the dots are not found in abundance, nor are they normally aligned along the parting as described by Singewald for other deposits. Warren[4] reported that the dots are usually rutile, and this has been verified by Osborne.[5] Blade-like forms, as viewed in two dimensions, are formed by plates of ilmenite along parting planes in magnetite and are by far the most common form of inclusion. The size of the ilmenite blades varies from extremely minute up to those visible to the naked eye, as is brought out in the series of micrographs shown in Figures 2 to 6, which have been reproduced at the same magnification for comparative purposes. The most minute dashes can be identified only with high power, 200±, but those shown in Figure 2 are easily seen at a magnification of about 80 and are approximately .001 mm. wide and .02 mm. long. The smallest recognized are perhaps not over .0005 mm. wide and .005 mm. long. The largest are about .1 mm. wide and nearly a centimeter long, and may be seen with the naked eye. (See Singewald: *U. S. Bur. Mines Bull.* **64**, Plate 8B). The variation in the number and spacing of the ilmenite lines is equally great. Some magnetite grains are closely crowded with ilmenite lines, as in Figure 4, whereas others have only a few blades, as in Figure 6. The close crowding shown in Figure 4 is remarkable in view of the common occurrence of ilmenite as grains. It might be expected that this ilmenite would have segregated into grains, but for some unknown condition of formation this did not occur.

There is also a great variation in the number of ilmenite blades within the magnetite grains of a given specimen. In some specimens all the magnetite grains are filled with intergrowths, in others part of the grains are free from ilmenite, while adjacent grains have closely spaced ilmenite blades. There is apparently no end to the variety shown by a large number of specimens from this one igneous mass.

In many of the polished specimens ilmenite occurs along the contacts of grains of magnetite, a fact brought out by the grain structure which shows so clearly after etching in hot HCl. Figures 11 and 12 show typical examples of this texture which have been

[4] *Op. cit.*
[5] *Op. cit.*

FIG. 2. Fine dash type of ilmenite intergrowths in magnetite. Tucker Lake, Minnesota. Mag. X 73.

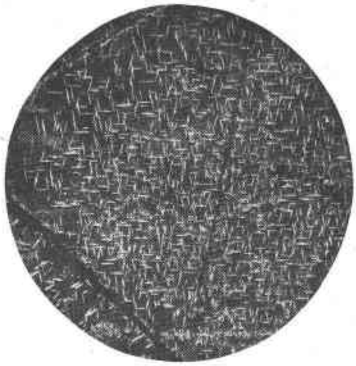

FIG. 3. Coarser dash type of ilmenite intergrowths in magnetite. Iron Lake, Minnesota. Mag. X 80.

FIG. 4. Closely crowded ilmenite plates along the parting of magnetite. Essentially the Widmanstätten structure. Tucker Lake, Minnesota. Mag. X 80.

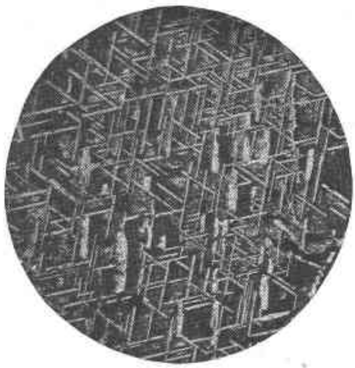

FIG. 5. Fairly coarse intergrowth of ilmenite in magnetite. North shore Pillsbury Lake. Mag. X 80.

PLATE I. Micrographs of etched polished surfaces of titaniferous magnetites from the Duluth gabbro. Shows the gradation in the size of the ilmenite intergrowths.

FIG. 6. Coarsest plates of ilmenite observed in magnetite. South of Snowbank Lake, Minnesota. Mag. X 73 (Etched).

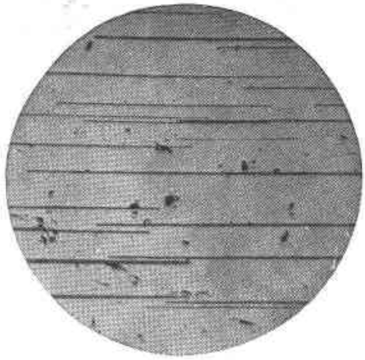

FIG. 7. Parallel intergrowths of magnetite in ilmenite. Homer Lake, Minnesota. Mag. X 80 (Etched).

FIG. 8. Graphic intergrowth of hematite (white) and magnetite. Hematite apparently secondary. Some blades of ilmenite around edges. (Etched). Poplar Lake, Minnesota. Mag. X 125.

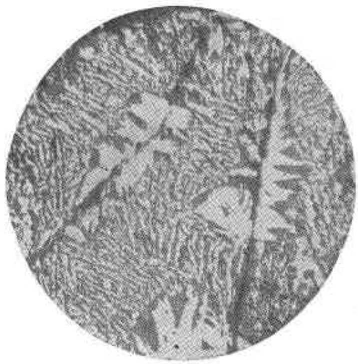

FIG. 9. Graphic intergrowth of ilmenite (white) and hornblende. Anorthositic gabbro, (unetched). Duluth, Minnesota. Mag. X 112.

PLATE II. Micrographs of polished surfaces of titaniferous magnetites from the Duluth gabbro.

attributed by Van der Veen[6] to segregation along grain boundaries during the slow cooling of a solid solution which breaks down into two minerals. This explanation is not entirely satisfactory as the cooling of the tremendous mass of the Duluth gabbro must have been very slow so that one would expect that all of the ilmenite would have been eliminated from the magnetite, whereas often considerable is left as inclusions in the magnetite. The texture represented by Figures 2 to 6 doubtless results from the breakdown of a solid solution as has been shown by Ramdohr.[7]

Textures which have not received much attention heretofore were noted in some of the specimens. These were the so-called graphic intergrowths or pseudo-eutectic textures as they have been recently called by Lindgren.[8] Figure 8 shows a photograph of a specimen from Poplar Lake with a well defined intergrowth which was at first thought to consist of magnetite and ilmenite, but on further study the texture was found to be due to hematite, although ilmenite is also present in small amounts. This texture seemed to have resulted from oxidation as it is limited to a small area around silicate contacts or fractures. A rather common type of intergrowth is represented by Figure 9 in which ilmenite is intergrown with hornblende, presumably of deuteric origin. Plagioclase also appeared intergrown with ilmenite in the polished specimen.

A single thin section of a specimen from south of Brule Lake showed ilmenite as graphic intergrowths with plagioclase, augite, biotite and secondary minerals, particularly chlorite. In this type it seems evident that part of the ilmenite crystallized with the silicates presumably later than the crystallization of the greater part of the magnetite and ilmenite. Osborne[9] has noted that some of the ilmenite crystallized later than the magnetite in the deposits described by him.

The intergrowth described above could scarcely represent an eutectic deposition as ilmenite could not form an eutectic with plagioclase, augite and biotite within the limits of a single thin

[6] Van der Veen, R.W., Mineragraphy and ore deposition. The Hague.

[7] Ramdohr, Paul, Beobachtungen an Magnetit, Ilmenit, Eisenglanz und überlegungen über das System FeO, Fe_2O_3, TiO_2. *Festschrift zur 150 Jahrfeier der Bergakademie Clausthal*, pp. 304–341, **1925.**

[8] Lindgren, W., Pseudo-eutectic textures: *Econ. Geol.*, vol. **25,** pp. 1–13, 1930.

[9] *Op. cit.*

section. The presence of alteration products in some of the intergrowths completely replacing the primary silicate minerals presents an interesting case and emphasizes the difficulty of interpreting these textures.

The greater part of the magnetite in the various deposits is usually granular, a fact which shows up well after etching with hot concentrated HCl. It is common to find subhedral crystals with perhaps one or two faces well developed.

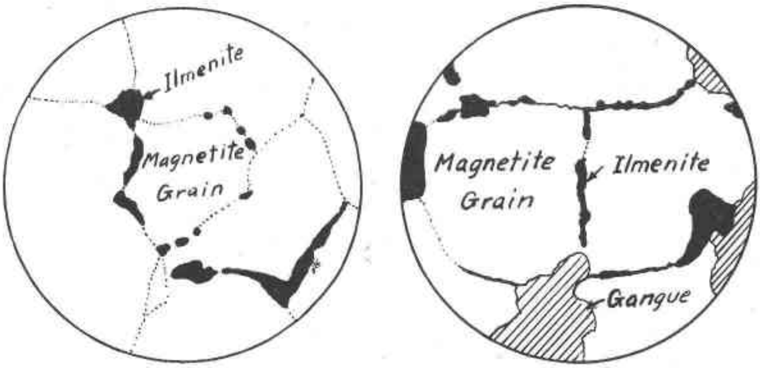

FIG. 10 and 11. Sketches of etched polished surfaces showing the tendency of ilmenite to occur along the contacts of grain boundaries. Figure 10, Thomas Lake, Minn. Figure 11, Little Saganaga Lake, Minn. Mag. X 18.

A noteworthy fact developed during the study is the prevalence of sulphides in the magnetite-ilmenite ores and gabbro. As shown in Figure 1, 31 out of 95 specimens tabulated contained sulphide, normally only chalcopyrite, but rarely pyrite, pyrrhotite, bornite and chalocite. The sulphide is usually present as minute specks and no tendency to segregate into masses was noted. The writer has previously expressed an opinion regarding the significance of this fact in connection with the relative scarcity of epigenetic deposits as a result of the intrusion of basic rocks.[10]

Most of the specimens examined were from outcrops and thus show some weathering. This is superficial, however, as the deposits were well scoured by glacial action. Magnetite is characteristically attacked along fractures and grain boundaries with hematite penetrating the grains along the octahedral planes, as shown in Figure 12. The fractures also pass through ilmenite grains but little

[10] Schwartz, G. M., Contact effects of gabbro and granite on ore deposition: *Econ. Geol.*, vol. **19**, pp. 681–684, 1924.

hematite is developed in them due to the resistance of ilmenite to alteration. No advanced stages of replacement of magnetite by hematite were noted. Evidently oxidation has been very slight

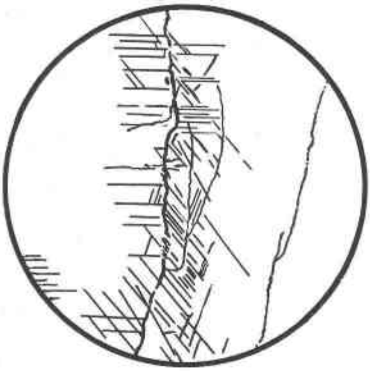

Fig. 12. Sketch of an etched polished surface showing the presence of hematite intergrowths in magnetite along a fracture filled with hematite. Duluth gabbro, Tucker Lake. Mag. 32 X.

since glacial time. The silicate minerals usually show more alteration than magnetite; limonite especially resulting from the alteration of olivine.

Bearing of the Relations on the Origin of the Magnetite Deposits

Broderick[11] recognized four types of magnetite deposits as follows: inclusions of banded Gunflint iron formation, banded segregations of the gabbro, irregular bodes of titaniferous magnetite, dike-like bodies of titaniferous magnetite. Of these the first and last two were believed to be due to the incorporation of iron formation in the gabbro, whereas the second was called a segregation. A study of the field relations of those deposits farthest in the gabbro, southwest of Brule Lake, shows that even there muscovadite (metamorphosed rock included in gabbro)[12] is characteristically associated with these segregations. Grout and Broderick[13] report that in practically every case a magnetite deposit of any size has muscovadite associated with it. This

[11] *Op. cit.*, p. 677.

[12] For description of metamorphic effects of gabbro, see Schwartz, G. M., Contrast in the effect of granite and gabbro intrusions on the Ely greenstone: *Jour. Geol.*, vol. **32**, pp. 89–138, 1924.

[13] Personal communications.

strongly suggested to Mr. Broderick that the banded segregations are only in a limited sense segregations, inasmuch as a considerable part of the iron oxide was supplied by inclusions and passed into the melt only to crystallize out in most cases near to the point of inclusion. The titanium was added to the magnetite as postulated by Broderick for the known inclusions. The addition of titanium to the iron oxide in all cases is indicated by its distribution as brought out in Figure 1, and is suggested by the fact that part of the ilmenite may be slightly later than magnetite. As far as could be determined by the writer, there is no essential difference in the occurrence of ilmenite in the four types of magnetite deposits, although some difference was expected. This is at least strongly suggestive of a common origin for all deposits. The distribution of the deposits is also indicative of some agency other than simply segregation as the known deposits are practically limited to an area along the north and northeast boundaries of the gabbro, where the Biwabik Gunflint iron formation was engulfed. The total area within which deposits are found is not over 15 per cent of the gabbro, and this 15 per cent is adjacent to formations lying below the iron formation.

Quantitative data on the inclusions and amount of assimilation by the gabbro near some of the magnetite deposits have been obtained by Dr. Grout[14] and are suggestive in this connection.

The writer is indebted to Dr. T. M. Broderick and Dr. F. F. Grout for the suggestion regarding the source of much of the iron ore in these deposits.

[14] Grout, F. F., The probable extent of abyssal assimilation: *Bull. Geol. Soc. America.* In press.