OPAQUE OXIDES IN SOME ROCKS OF THE BASEMENT COMPLEX, TORRICELLI MOUNTAINS, NEW GUINEA

GEORGE BAKER, *University of Melbourne, Australia.*

ABSTRACT

A study of polished surfaces of the plutonic and metamorphic rocks that form part of the basement complex as exposed in the Torricelli Mountains of New Guinea, reveals magnetite, ilmenite, hematite, rutile, and spinel in various associations and showing a range of textural relationships. Apart from simple crystallization, complex intergrowths have arisen in parts from the unmixing of solid solutions of different pairs of some of the oxides and from eutectic crystallization of others. Among these are already well-known intergrowths, also examples of the rarely observed (insofar as they occur in parent rocks) ex-solution intergrowth of magnetite and hematite and the hitherto unrecorded ex-solution intergrowth comprised of ex-solved rutile lamellae in ilmenite proper. The relationships of the opaque oxides to one another and to the silicate minerals in the different rocks examined, reveal that the oxides have various positions in the crystallization sequence.

A collection of intermediate, basic, and ultrabasic igneous rocks and acid and basic metamorphic rocks from the Torricelli Mountains, has been found to contain a variety of opaque oxides showing interesting textural relationships.

The rocks were collected by A. Coulson in 1944. Some were in situ, others were waterworn pebbles obtained from the Finsch Coast (Fig. 1) and regarded as being derived from the basement complex rocks in the

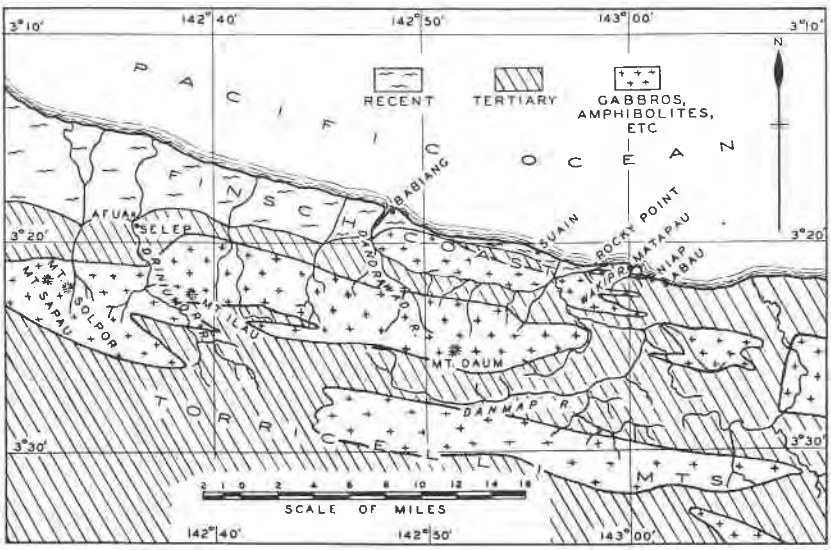


FIG. 1. General geological map of the Finsch Coast-Torricelli Mountains Region on the northern coast of Eastern New Guinea.

Torricelli Mountains, two or three miles away where similar rocks outcrop.

Among the rocks examined for their opaque mineral content are gabbros from Afua on the Driniumor River, Matapau on the Wakip River, Babiang on the Dandrawad River (all these localities are marked on Fig. 1), and from Solyaliu Hill on Tumleo Island (15 to 20 miles northwest of the area shown in Fig. 1). Peridotite was collected from Babiang, amphibolite and granulite from Matapau, and diorite (in situ) from Rocky Point at the eastern end of the Finsch Coast (Fig. 1).

In most of these rocks, magnetite, ilmenite, hematite, spinel, and rutile[1] are present in the proportions and grain sizes normal to basic igneous and metamorphic rocks. They generally do not constitute more than 4 to 5 per cent in each of the rocks examined, but in one or two of the gabbro specimens, they comprise up to 25 per cent of some parts of the rock. Minor amounts of sulfides are present in some of the rocks, but comprise only a fraction of a per cent of any one rock.

The opaque oxides are associated in a variety of intergrowths. Most of the intergrowths revealed by polished surfaces are a direct consequence of crystallization. The following list (Table 1) summarizes the types of textures encountered among the opaque oxides observed in the rocks from the Torricelli Mountains.

It is evident from Table 1 that the more complex relationships among the opaque oxides occur in the Babiang gabbro. This is largely due to the association of rutile with the other oxides. In gabbros lacking rutile, the relationships are simpler, as in the Afua gabbro, where the principal textures are ex-solution intergrowths of magnetite (host) and ilmenite (lamellae). In the Matapau gabbro, magnetite, the principal opaque oxide mineral, is devoid of ex-solution textures and in the Tumleo gabbro, spinel largely takes the place of magnetite. An occurrence of ex-solved hematite lamellae in magnetite host, unusual in natural occurrences, is found in amphibolite from Matapau and occasionally in peridotite from Babiang. Ilmenite acting as host to ex-solved lamellae of hematite, was observed in diorite from Rocky Point. Martitization is confined solely to the metasomatized granulite from Matapau.

The nature and relationships of the opaque oxides and sulfides in these various rock types, are as follows:

Opaque Minerals in Gabbros

Whereas Newhouse (5, p. 16) noted that ilmenite was the dominant opaque oxide in over two dozen gabbros, crystals of magnetite and mag-

[1] The rutile is practically opaque, likewise the spinel.

TABLE 1

No.	Texture or Intergrowth	Containing Rock
(i)	Magnetite with ex-solved ilmenite lamellae	Afua gabbro
(ii)	Magnetite and ilmenite in micrographic intergrowth	
(iii)	Structureless magnetite, without (i) or (ii)	
(iv)	Magnetite with ex-solved hematite lamellae (Also magnetite and ilmenite as in (ii))	Matapau amphibolite
(v)	Magnetite graphically intergrown with olivine and augite, but free of ex-solution phenomena	Matapau gabbro
(vi)	Ex-solved rutile lamellae in the ilmenite lamellae (of ex-solution origin) in magnetite	Babiang gabbro
(vii)	Sub-graphic intergrowths (eutectic) of rutile and ilmenite in the ex-solution lamellae of ilmenite contained in magnetite	
(viii)	Ditto of rutile and hematite in similar lamellae	
(ix)	Magnetite lamellae in the ex-solved ilmenite lamelae contalined in host magnetite	
(x)	Micrographic intergrowths (eutectic) of rutile and magnetite in the cores of ilmenite crystals enveloped by magnetite	
(xi)	Micrographic intergrowths of magnetite—rutile—ilmenite	
(xii)	Micrographic intergrowths of magnetite—rutile—ilmenite—hematite	
(xiii)	Rutile cores to ilmenite crystals enveloped by magnetite (Also excellent examples of (i))	
(xiv)	Granular intergrowths of spinel and magnetite (Also occasional examples of (iv))	Babiang peridotite
(xv)	Spinel the most common oxide. Rare chromite. Structureless magnetite	Tumleo gabbro
(xvi)	Ilmenite with ex-solved bodies of hematite.	Rocky Point diorite
(xvii)	Ilmenite in subgraphic intergrowth with hornblende	
(xviii)	Martitized magnetite	Matapau granulite

netite (host) with ilmenite (lamellae) predominate in six New Guinea gabbros examined.

Afua. Magnetite forms primary crystals and secondary dust-like streaks in a partially serpentinized olivine-hypersthene gabbro from Afua, which is a little over 4 miles inland from the mouth of the Driniumor River. The dust-like streaks of magnetite have been formed along serpentinized cracks in olivine. Primary crystals of magnetite, up to

0.30×0.70 mm. in size and usually of irregular shape, are scattered throughout the rock.

The primary crystals of magnetite contain occasional ex-solution lamellae of ilmenite along octahedral directions. Some magnetite crystals also show occasional micrographic intergrowths with ilmenite. These intergrowths are just detectable under a 1/10 Fl. oil immersion lens, but the lamellae and granules of ilmenite are of sufficient abundance to cause the host magnetite to appear a darker grayish-brown in reflected light than is usual for magnetite.

Certain of the magnetite crystals are free of ilmenite intergrowths. The amount of magnetite present is such that small pieces of the gabbro (measuring $1'' \times 1'' \times \frac{1}{2}''$) can be attracted to an Alnico hand magnet.

Pyrrhotite, pyrite, and chalcopyrite occur in the Afua gabbro as small, isolated grains averaging 0.04×0.08 mm. in size.

Matapau. Minor amounts of small crystals of primary magnetite, chalcopyrite, and pyrrhotite are present in a hornblende-augite-hypersthene-olivine gabbro from Matapau.

The magnetite crystals are occasionally micrographically intergrown with both olivine and augite, but are free of ex-solution intergrowths with other iron oxides. The chalcopyrite in parts replaces some of the pyrrhotite, crystals of which do not exceed 0.12×0.35 mm. in size.

Rare, small particles of a hard and creamy-white mineral, much more brightly reflecting than neighbouring sulfide grains, are found in the Matapau gabbro. The particles are too small for precise determination, the largest being 4 μ across, but the properties indicate a platinoid metal.

Thin sections of the Matapau gabbro, reveal that opaque streaks of dust-like material have been developed along cracks in altered portions of the olivine crystals. In many gabbros, such material is composed of fine particles of magnetite, but in the Matapau gabbro, it consists largely of narrow stringers composed of specks of chalcopyrite and pyrrhotite. Evidently during deuteric alteration of the olivine, sulfur and copper were available in small quantities for combination with the iron released during breakdown of the olivine.

Tumleo Island. An ejected block of gabbro caught up from the basement complex and thrown out by the Lower Miocene volcano at Solyaliu Hill, Tumleo Island (15 to 20 miles northwest of Afua), contains a few grains of opaque oxide minerals.

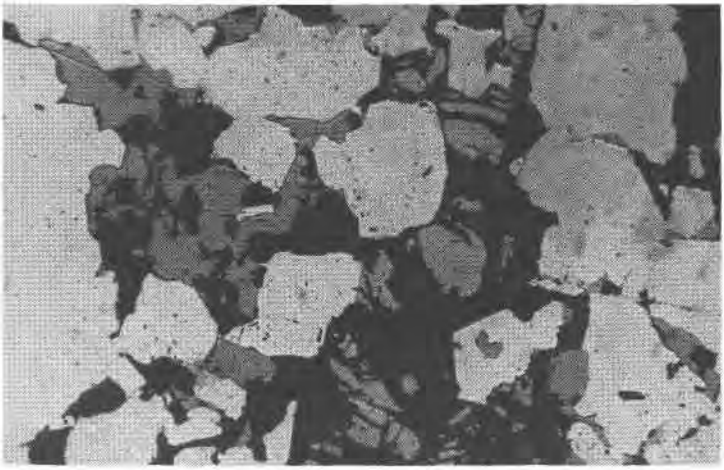
The most frequent of these rarely occurring oxides is spinel, a few crystals of which are scattered through the rock. The spinel is an iron-rich variety with low reflecting properties and in one or two places, brilliant green internal reflections. The intensity of coloration of the spinel is so great, that in thin microscope sections, no transmitted light passes through even the thinnest edges of the crystals. Some of the spinel shows rather brownish-green internal reflections resembling those characteristic of chrome-spinel. In places there occur rare, almost opaque chromite grains showing faint brownish-red internal reflections only at crystal edges and rarely along cracks, when observed in polished surfaces.

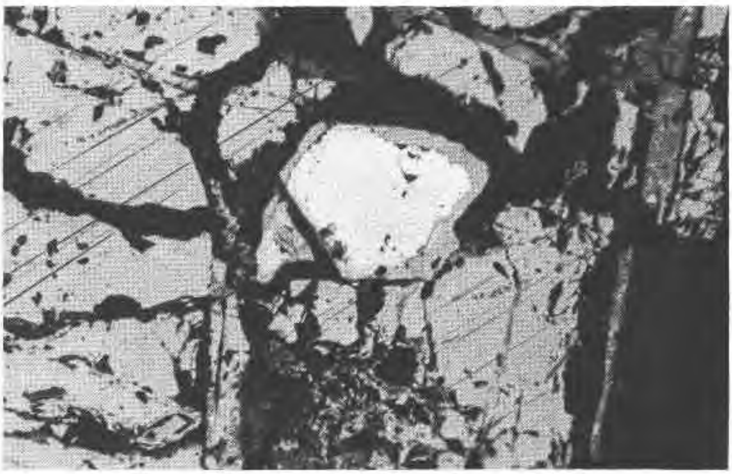
Grains of magnetite are sparse and of minute size in the Tumleo Island gabbro. No ilmenite was detected and the only sulfides are infrequent blebs of chalcopyrite and one or two small crystals of bornite partly altered to covellite.

Babiang. Three different specimens of gabbro were examined from Babiang. In (i), hornblende gabbro, the main opaque oxides consist of occasional magnetite crystals enclosing broad lamellae of ilmenite, with granular intergrowths of rutile. In (ii), an altered olivine gabbro, there is little magnetite and rare pyrrhotite, but in (iii), a partly metasomatized hornblende gabbro, occurs the best array of opaque minerals in the series of rocks under consideration. In this rock, a little epidote has been formed, the hornblende is partly chloritized and the plagioclase feldspars have been slightly altered. The opaque minerals consist of magnetite, ilmenite, rutile, hematite, pyrite, pyrrhotite, chalcopyrite, and a little limonite. The rock is strongly magnetic, due largely to abundant magnetite which is intergrown with ilmenite and rutile. The opaque oxides, which make up to 25 per cent of some polished surfaces of the partially altered hornblende gabbro (Plate I, photo. 1), show complex eutectic and ex-solution intergrowths. Individual areas occupied by the iron and titanium oxides measure up to 15×10 mm. and appear to be moulded around the silicates. They frequently enclose small amounts of hornblende and plagioclase (Plate I, photo. 1), thus indicating fairly late crystallization of the opaque oxides in this gabbro.

The magnetite contains ex-solution lamellae of ilmenite ranging from minute (short and narrow) lamellae in many of the magnetite crystals to broad, long lamellae in a few of them. All the ilmenite lamellae lie along (111) directions in the magnetite, and some of them have been partly altered to leucoxene. The ex-solved lamellae of rutile in ilmenite are few in number, small in size and lie obliquely across the length of the ilmenite lamellae in a regular pattern corresponding to the rhombohedral directions of the ilmenite. Subgraphic intergrowths of rutile and ilmenite (vii in Table 1) and of rutile and hematite, occur in strings and irregular elongated patches along the principal direction of the broader of the ilmenite lamellae. They are sometimes centrally placed, sometimes situated to one side of the broader lamellae, but do not interrupt the finer rutile lamellae.

A few of the ilmenite crystals show well-developed twin lamellae. Twin





EXPLANATION OF PLATE I

Photo. 1. Opaque oxides (grayish-white) in partially altered hornblende gabbro from Babiang, New Guinea. (×150).

Photo 2. Partially altered pyrite crystal (white) with rim of limonite (gray). From partially altered hornblende gabbro, Babiang, New Guinea. (×150). (Other light gray areas are magnetite-ilmenite intergrowths).

lamellae are also well-developed in the rutile crystals associated with magnetite and ilmenite in micrographic intergrowths (xi of Table 1). This twinning often extends through individual portions of rutile having the same optical orientation in the intergrowths, but separated by areas of magnetite.

Whereas Edwards (2, p. 62) records eutectic relationships between rutile and hematite in occasional specimens from Western Australia and Olary, South Australia, in some of which the rutile is in excess and crystallized first as coarse crystals, the sub-graphic intergrowths between this pair of oxides in the ilmenite lamellae of the Babiang partially altered hornblende gabbro, are rather different. Apart from the minuteness of the component crystals in the intergrowths, there is little difference in the amounts of the components, hematite, if anything, being perhaps a little more abundant in most of the micrographic intergrowths, and the two components evidently separated out together at much the same time in the ilmenite lamellae.

Most of these textures in the opaque iron and titanium oxide minerals are already well-known (cf. Edwards, 2, pp. 57–66). It is of interest to note, however, the relationships between the ilmenite lamellae in the host magnetite and the rutile intergrowths and lamellae in the ilmenite lamellae. Graphic intergrowths between rutile and ilmenite (see (vii) in Table 1) are already known (likewise the graphic intergrowths between rutile and hematite), and would indicate the development of eutectoid relationships between rutile and ilmenite (and between rutile and hematite). The ex-solved lamellae of rutile within the broader of the ilmenite lamellae are of interest in that, whereas Edwards (1, Figs. 13 and 14) noted the development of such ex-solution lamellae of rutile in ilmenite-hematite solid solutions, the occurrence of such lamellae in ilmenite proper has not been noted previously. There is here evidence that this slight solubility of rutile in ilmenite-hematite solid solutions, at high temperatures, extends over the whole range of composition from hematite-rich solutions to ilmenite. Within the confines of the narrow walls of ilmenite lamellae, the evidence points to the close spatial association of the two processes—(*a*) eutectic intergrowth and (*b*) ex-solution intergrowth as between rutile and ilmenite. The lamellae of rutile in the ilmenite lamellae are small and cease abruptly against contacts between ilmenite lamellae and host magnetite, while their arrangement indicates precipitation along $(10\bar{1}1)$ directions in the ilmenite.

The pyrite crystals, which were originally euhedral, are surrounded by thin crusts of limonite (Plate I, photo. 2) and contain occasional rounded bodies of pyrrhotite and chalcopyrite.

Opaque Minerals in Peridotite

A partially altered peridotite from Babiang, contains occasional iron oxide minerals, spinel, and rare sulfides.

Ilmenite occurs as occasional small, irregularly shaped grains. Magnetite appears as occasional crystals and as fine particles forming thin stringers in serpentinized portions of the peridotite.

The crystals of magnetite contain minute ex-solution lamellae of hematite, so small that they are only made visible by the use of a 1/10 Fl. oil immersion lens. Some of the larger magnetite crystals, which are up to 0.35×0.60 mm. in size, contain patches of crystals having cubic outline and greenish-brown internal reflections. In reflected light, these cubic crystals have a lower reflecting power than chromite and are evidently the spinel observed in thin sections. Occasionally, the spinel and magnetite form granular intergrowths.

Rare specks of chalcopyrite are up to 5 μ across. Pyrrhotite of similar dimensions is partially replaced by chalcopyrite and in places peripherally altered to limonite.

Specks of a silver white metallic mineral with a creamy tinge, up to 4 μ across, occur more abundantly in this peridotite than in the gabbros and amphibolite from the Torricelli Mountains. They are hard and scale-like and presumably represent particles of platinoid metal.

Opaque Minerals in Amphibolite

An amphibolite from Matapau contains numerous small crystals of magnetite with ex-solution lamellae of hematite, shot through the albite, and larger clots of magnetite and ilmenite crystals as granular aggregates in the hornblende. Smaller grains of magnetite and ilmenite are sometimes confined to cleavage planes in the hornblende.

Some of the larger, as well as many smaller crystals of magnetite, contain lamellae of hematite along (111) planes. The hematite occurs as blades of uniform size and even distribution, thus forming a regular triangular lattice structure in the magnetite (cf. Edwards, 2, Fig. 71). There is no concentration of hematite at the crystal margins of the magnetite, such as occurs where magnetite has been martitized during supergene or hypogene oxidation (cf. Edwards, 2, Fig. 72), so that the intergrowth is evidently due to ex-solution.

Edwards (3, p. 759) has recently described natural ex-solution intergrowths of magnetite and hematite in Fijian beach sands (presumably derived from andesites[2]) and in a waterworn crystal of magnetite from river gravel in the Cairns district of Queensland, Australia. Such intergrowths occur in situ in some abundance in amphibolite from Matapau, New Guinea, and occasionally also in peridotite from Babiang. The specimens examined are waterworn pebbles derived from the nearby Torricelli Mountains.

The proportion of host magnetite to unmixed hematite lamellae in the intergrowth, measured micrometrically, is 88:12, indicating a tempera-

[2] These intergrowths have not been observed in polished surfaces of Fijian basalts and andesitic dykes.

ture of formation of 1,200° C., according to the experimental data of Greig et alia (4). As pointed out by Edwards (3, p. 761), the temperature of formation indicated for intergrowths having approximately 80:20 : : magnetite:hematite, is unduly high for igneous rocks. Although somewhat lower (88:12), the hematite content of these intergrowths also indicates a rather high temperature of formation in the Matapau amphibolite. Some additional, at present unknown factor must have operated, to allow the formation of solid solution under natural conditions at temperatures lower than those found in the laboratory by Greig and his associates (4).

Much of the ilmenite is surrounded by alteration rims of sphene and many of the coarser grains of ilmenite are located in granular aggregates with magnetite, without showing ex-solution intergrowths.

Opaque Minerals in Diorite

A diorite from Rocky Point on the Finsch Coast contains ilmenite, magnetite and chalcopyrite. The rock, which was in situ, shows incipient metasomatism, and is similar to diorite outcropping along the coast easterly to Niap.

The magnetite, which is rare and structureless under oil immersion lenses, ranges up to 0.03×0.06 mm. in size.

Ilmenite crystals up to 0.25×0.35 mm. in size, contain ex-solved, irregularly elongated bodies of hematite arranged in parallel rows along (0001) planes in the host mineral in the same manner as illustrated by Edwards (1, Fig. 4). Occasional, very irregular areas of hematite in the ilmenite, are evidently due to the coalescence of several smaller lamellae. The ilmenite has been partially altered to sphene. Some crystals of ilmenite show subgraphic intergrowths with hornblende (cf. Newhouse, 5, Fig. 1, plate 13), while smaller grains sometimes lie along cleavage directions in the hornblende. Such occurrences indicate that the ilmenite crystallized partly before, partly during hornblende crystallization. The formation of the ilmenite was thus a relatively early phase in the crystallization history of the diorite, as also noted by Newhouse (5, p. 14) in a number of American and other diorites.

Pyrite is the most abundant opaque mineral present in the Rocky Point diorite. It occurs in isolated grains and crystals ranging up to 0.15×0.30 mm. in size. Occasional chalcopyrite grains range up to 0.06×0.12 mm.

Opaque Minerals in Granulite

A garnetiferous granulite from Matapau contains magnetite closely associated with epidote throughout the rock. Metasomatic alteration of the rock has resulted in much of the magnetite becoming martitized. The alteration of the magnetite to hematite during this process, has penetrated from the peripheries of the magnetite crystals, inwards along (111) planes, giving partial pseudomorphs. Sometimes complete, sometimes only partial rims of hematite surround the altered magnetite, and from them, hematite lamellae of uneven width, taper off towards the interiors of the magnetite crystals along the octahedral planes. No crystals of magnetite in the granulite have escaped some degree of martitization and in many, the replacement process is advanced, leaving only a few, small remnants of magnetite. The existence of hematite lamellae as evenly distributed blades of uniform size in a few of the partially altered magnetite crystals, makes it difficult to assess whether such hematite lamellae are due to ex-solution intergrowth or to fortuitous, even alteration along octahedral planes of the magnetite in this granulite from Matapau.

Summary and Conclusions

The opaque oxides in the igneous rocks from the Torricelli Mountains bear out the earlier conclusions of Newhouse (5, p. 33) that the opaque oxides in igneous rocks vary in amount, grain size, habit, species, and position in the sequence of crystallization in rocks of different composition and texture. Of these, perhaps the most fundamental variation is that of the crystallization sequence of the opaque oxides in relation to the silicate minerals, insofar as this must have an important bearing on both ore genesis and petrogenesis. The opaque oxides have crystallized during and shortly after the silicate minerals in some of the rocks (cf. Babiang partially altered hornblende gabbro), prior to them in others (as in the Babiang peridotite), during and prior to them in yet others (e.g. as in the Rocky Point diorite).

The presence in one and the same rock (e.g. the Babiang partially altered hornblende gabbro) of oriented intergrowths arising from the unmixing of solid solutions and of micrographic intergrowths caused by eutectic crystallization, indicates the complexities that may arise during the crystallization of iron and titanium oxides in some rocks, while in most of the rocks, the textural relationships have remained relatively simple. The main factors affecting these differences, are probably to be ascribed to the temperatures of formation of each particular rock, the availability of particular ions required in the intergrowths and the time taken for cooling and crystallization under the prevailing pressures in the basement complex rocks, whether igneous or metamorphic. Where the iron content of the basic gabbroic magma in the Torricelli Mountains region was low (cf. Tumleo gabbro), ample supplies of magnesia and alumina combined with the available iron to form spinel at the expense of magnetite. Where, however, excess of iron occurred (cf. Babiang gabbro) and abundant titania was available, the textural relationships became complex, with the development of magnetite-ilmenite-rutile intergrowths, and the, so far, rarely observed phenomenon of exsolved rutile in ilmenite.

No conclusive evidence is to hand to account for the occurrence of natural ex-solution intergrowths between magnetite (host) and hematite (lamellae) at the temperatures of formation of the containing rocks (amphibolite and peridotite).

Acknowledgments

The author is indebted to Dr. A. B. Edwards of the Mineragraphic Section, Commonwealth Scientific and Industrial Research Organization, for aid in the interpretation of the microstructures revealed by the opaque oxides discussed in this paper.

References

1. Edwards, A. B. (1938), Some ilmenite micro-structures and their interpretation: *Austr. Inst. Min. and Met., proc. n.s.*, no. **110,** 39–58 (16 figures).
2. Edwards, A. B. (1947), Textures of the ore minerals and their significance: *Austr. Inst. Min. and Met.* (Inc.), Melbourne, 1947.
3. Edwards, A. B. (1949), Natural ex-solution intergrowths of magnetite and hematite: *Am. Mineral.*, **34,** 759–761.
4. Greig, J. W., Posnjak, E., Merwin, H. E., and Sosman, R. B. (1935), Equilibrium relationships of Fe_3O_4, Fe_2O_3 and oxygen: *Am. Jour. Sci.*, **30,** 239–316.
5. Newhouse, W. H. (1936), Opaque oxides and sulphides in common igneous rocks: *Bull. Geol. Soc. Am.*, **47,** 1–52 (18 plates).
6. Ramdohr, P. (1950), Die Erzmineralien und ihre Verwachsungen: Akademie-Verlag. Berlin.

Manuscript received Aug. 21, 1951