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TITANOMAGHEMITE IN IGNEOUS ROCKS

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ABSTRACT

Titanomaghemite, an oxidized titanomagnetite having compositions near the $TiFeO_3$-Fe_2O_3 join or even within the $TiFe_2O_5$-$TiFeO_3$-Fe_2O_3 triangular field in the system TiO_2-FeO-Fe_2O_3, has been found in some Japanese igneous rocks. Microscopically the mineral can be distinguished from titanomagnetite by its bluish gray color in reflected light and the abundance of cracks. Titanomaghemite so far observed occurs largely in rocks in which olivine and hypersthene are partially or completely altered to chlorite and serpentine, but it occurs also in some unaltered lava flows. It is concluded that titanomagnetite crystallizing from magma is oxidized to produce titanomaghemite under a certain condition which may be easily obtained during the cooling process. It is not necessary to consider the special solid solution series between γ-$FeTiO_3$ and Fe_3O_4 in order to explain the formation of titanomaghemite in igneous rocks. The titanomaghemite possesses vacancies of two or three metal ions in a unit cell. The lattice parameters vary with the ratios Fe/(Fe+Ti) and 32(Fe+Ti)/0, and range from 8.359 to 8.419 Å.

INTRODUCTION

Titanomagnetites in igneous rocks are generally considered to have compositions within a triangular field $TiFeO_3$-$TiFe_2O_4$-Fe_3O_4 in the system TiO_2-FeO-Fe_2O_3. Their compositions are explained as belonging either to the $TiFe_2O_4$-Fe_3O_4 solid solution or to the γ-$TiFeO_3$-Fe_3O_4 solid solution (Chevallier and Girard, 1950; Vincent *et al*, 1957). However, some titanomagnetites have compositions outside of the triangular field, lying even near the $TiFeO_3$-Fe_2O_3 join. Such compositions cannot be explained by the two simple solid solution series. Recently, Akimoto and Katsura (1959) discussed the origin of the titanomagnetites outside the triangular field $TiFeO_3$-$TiFe_2O_4$-Fe_3O_4 on the basis of their experiments (Akimoto, Katsura and Yoshida, 1957) and concluded that they were formed by oxidation of the normal titanomagnetite belonging to the $TiFe_2O_4$-Fe_3O_4 solid solution. But they did not discuss the extent to which the spinel phase can exist as a single phase. Basta (1953; 1959) named the titanomagnetites having compositions close to the $TiFeO_3$-Fe_2O_3 join and the TiO_2-Fe_2O_3 join the "titanomaghemites" and also concluded that they were formed by oxidation of the titanomagnetite of the γ-$TiFeO_3$-Fe_3O_4 solid solution.

Titanomaghemite in igneous rocks has been described only rarely. Frenzel (1953) reported maghemite (titanomaghemite) in shonkinite in Katzenbuckel in Odenwald. Basta (1959) summarized the titanomaghemites in South Africa which were early investigated by Wagner (1928), Walker (1930), Frankel and Grainger (1941) and Schwellnus and

TABLE 1. DESCRIPTIONS OF TITANOMAGHEMITE-BEARING ROCKS

Sp. No.	Rock	Locality	Main constituent minerals (titanomagnetite is replaced by titanomaghemite)
1003	Olivine analcite dolerite (sheet)	Atumi, western coast of Yamagata Pref.	Olivine (altered), titanaugite, plagioclase, titanomagnetite, ilmenite, zeolite, hypersthene (partially altered).
2502-6	Quartz-bearing olivine titanaugite dolerite (sheet)	Kingosi in Sidara Basin, Aiti Pref.	Olivine (altered), titanaugite, plagioclase, titanomagnetite, ilmenite, quartz.
2403-3	Olivine andesite (dike)	Orimoto-toge in Sidara Basin, Aiti Pref.	Phenocrysts; olivine (partially altered), augite, plagioclase, titanomagnetite, ilmenite. Groundmass: plagioclase, titanomagnetite, olivine, augite, glass.
HK53051602	Dacitic welded tuff	Kogasira, 8 km. NW of Kagosima, Kagosima Pref.	Phenocrysts; hypersthene, plagioclase, quartz, titanomagnetite, biotite.
	Olivine titinaugite dolerite (sheet)	Warabidaira, 20 km. SSW of Kohu, Yamanasi Pref.	Olivine (altered), titanaugite, plagioclase, ilmenite, titanomagnetite, zeolite.
	Augite hypersthene andesite (lava flow)	Central cone of Hakone Volcano, Sizuoka Pref.	Phenocrysts; augite, hypersthene, plagioclase, titanomagnetite. Groundmass; plagioclase, titanomagnetite, augite, hypersthene, glass.
	Olivine augite andesite (lava flow)	North-western caldera wall of old somma of Hakone Volcano, Sizuoka Pref.	Phenocrysts; olivine (mostly altered), augite, plagioclase. Groundmass: augite, plagioclase, titanomagnetite, glass.
	Scoria	North-western caldera wall of Hakone Volcano.	Phenocrysts; plagioclase. Groundmass: plagioclase, titanomagnetite, glass.
	Augite hypersthene andesite (lava flow)	Usami, eastern coast of Izu Peninsula, Shizuoka Pref.	Phenocrysts; augite, hypersthene, plagioclase, titanomagnetite. Groundmass: plagioclase, hypersthene, augite, titanomagnetite.
	Augite hypersthene andesite (lava flow)	Iwanuma, 20 km. S of Sendai, Miyagi Pref.	Phenocrysts; augite, hypersthene, plagioclase, titanomagnetite. Groundmass: plagioclase, hypersthene (partially altered), titanomagnetite, glass.
	Ferrogabbro (cone intrusion)	Skaergaard in Greenland	Olivine, augite, titanomagnetite (quartz), (hypersthene). (After Wager and Deer, 1939).

Willemse (1943). In this paper, titanomaghemite is defined as a mineral with the spinel structure having a composition close to the $TiFeO_3$-Fe_2O_3 join or within the $TiFe_2O_5$-$TiFeO_3$-Fe_2O_3 triangular field in the TiO_2-FeO-Fe_2O_3 system. This mineral was first found by the present authors in dolerite of Atumi, Yamagata Pref., northern Japan and in welded-tuff of Kogasira, Kagosima Pref., Kyūsyū. Afterward, they also found it in dolerites of Sidara and Warabidaira and in several andesite dikes and lavas of Izu-Hakone district and Sidara in central Japan. It appears that titanomaghemite is not a rare mineral in igneous rocks. The mineral will be found commonly in both intrusive and extrusive rocks, if the reflection microscope is more widely used and chemical analysis made on iron oxide minerals. In the present paper, the mode of occurrence of titanomaghemite in igneous rocks is described, its physical and chemical properties are given and are compared with the previous data.

MODE OF OCCURRENCE OF TITANOMAGHEMITE

Titanomaghemite-bearing igneous rocks so far investigated are the dolerites of Atumi and Warabidaira, the dolerites and andesite of Sidara, the lavas of Izu-Hakone and Iwanuma, the welded-tuff of Kogasira, scoria of Hakone and gabbro of the Skaergaard complex in Greenland. Brief descriptions of the host rocks are given in Table 1. In these rocks, titanomaghemite replaces partially or completely titanomagnetite.

Titanomaghemite in the Atumi dolerite which has been studied by one of the authors (Kushiro, 1959) occurs in olivine-analcite-dolerite of Kayaoka Sheet and analcite-syenite in Sumiyosizaki Sheet. The dolerite and syenite have been subjected more or less to hydrothermal alteration as inferred from the existence of altered olivine, hypersthene and plagioclase. Titanomaghemite 1003, No. 1 in Table 3, which has been analyzed and observed in detail was separated from the surface of the dolerite, 55 m. above the base of the Kayaoka Sheet. The chemical composition of this dolerite is given in Table 2, No. 1. The dolerite is situated near the center of the sheet where hydrothermal solution may have been concentrated at the later stage of magmatic differentiation. Furthermore, the surface of the dolerite has suffered more or less weathering. In this case titanomaghemite replaces titanomagnetite almost completely.

Titanomaghemite 2403 in olivine-andesite dike of Orimoto-toge in the Sidara basin, No. 3 in Table 3, has been partially analyzed. It occurs in the central part of the dike as both phenocrysts and in the groundmass. The degree of replacement of titanomagnetite by the titanomaghemite decreases towards the margin of the dike. Olivine associated with the titanomaghemite is partially or completely altered to carbonate. It is supposed that the central part of the dike has been permeated by hydrothermal solutions or by volatiles. The chemical composition of the central part of the dike is given in Table 2, No. 3.

Titanomaghemite 2502–6 in olivine-titanaugite-dolerite of Kingosi in the Sidara basin, No. 2 in Table 3, occurs near the margin of a sheet. It is associated with chloritized olivine. The relation between the existence of the titanomaghemite and unstable magnetization of this sheet has recently been discussed (Akimoto and Kushiro, 1960). The chemical composition of this dolerite is given in Table 2, No. 2.

In ferrogabbro of the Skaergaard intrusion of which samples were kindly offered by Drs. Uyeda and Akimoto, a small amount of titanomaghemite replaces titanomagnetite along the cracks and the boundary of ilmenite lamellae. The titanomagnetite has fine exsolution lamellae of ulvöspinel. The composition of the titanomagnetite in the ferrogabbro given by Vincent and Phillips (1954) should be corrected in view of the presence of the titanomaghemite.

TABLE 2. CHEMICAL COMPOSITIONS OF HOST ROCKS

	No. 1	No. 2	No. 3	No. 4
SiO_2	49.03	50.74	56.69	71.64
TiO_2	1.48	1.75	0.88	0.43
Al_2O_3	17.43	15.76	16.43	14.88
Fe_2O_3	2.89	4.74	1.30	1.83
FeO	5.32	4.64	7.07	0.50
MnO	0.15	0.14	0.18	0.01
MgO	6.07	4.25	1.63	0.15
CaO	6.25	8.15	4.69	2.10
Na_2O	4.45	3.34	4.70	3.95
K_2O	1.95	0.99	1.58	3.30
$H_2O(-)$	1.18	2.81	0.20	0.35
$H_2O(+)$	3.60	0.86	0.50	0.98
P_2O_5	0.31	0.26	0.42	0.10
CO_2	0.05	1.25	4.02	0.02
Total	100.16	99.68	100.29	100.24

No. 1. Olivine-analcite-dolerite 1003, Atumi.
No. 2. Olivine-titanaugite-dolerite 2502–6, Kingosi.
No. 3. Olivine-andesite 2403, central part of the dike, Orimototoge.
No. 4. Dacitic welded-tuff HK53051602, Kogasira.

TABLE 3. CHEMICAL COMPOSITIONS OF TITANOMAGHEMITES

	No. 1	No. 2	No. 2-*a*	No. 3	No. 4	No. 3-*a*	No. 3-*b*
FeO	11.89	20.25	19.89	15.98	14.84	33.32	45.02
MgO	0.45	n.d.	n.d.	n.d.	0.35	n.d.	n.d.
MnO	2.29	0.99	n.d.	n.d.	0.81	0.76	n.d.
CaO	1.58	n.d.	n.d.	n.d.	0.05	n.d.	n.d.
Fe_2O_3	56.53	45.94	42.76	41.91	66.97	35.02	29.60
Al_2O_3	1.94	n.d.	n.d.	n.d.	1.53	n.d.	n.d.
V_2O_3	0.73	0.53	0.41	0.17	0.38	0.15	0.12
TiO_2	22.63	26.92	20.95	25.45	13.83	20.82	18.63
SiO_2	2.01	0.78	7.30	n.d.	0.87	3.35	n.d.
P_2O_5	0.00	0.00	n.d.	n.d.	0.01	n.d.	n.d.
Total	100.05	95.41	91.31	83.51	99.64	93.42	93.37

No. 1. Titanomaghemite from olivine-analcite-dolerite 1003, Atumi.
No. 2. Titanomaghemite from olivine-titanaugite-dolerite 2502–6, Kingosi.
No. 2-*a*. Titanomaghemite from another part of the same sheet as No. 2.
No. 3. Titanomaghemite from the central part of the dike 2403, Orimototoge.
No. 4. Titanomaghemite from dacitic welded-tuff HK53051602, Kogasira.
No. 3-*a*. Titanomagnetite from the margin of the dike 2403, Orimototoge.
No. 3-*b*. Titanomagnetite from the margin of the dike 2403, Orimototoge.

In most cases, if not all, the titanomaghemite occurs in more or less altered rocks in which olivine and hypersthene are partially or completely altered to chlorite, serpentine and other minerals. This indicates that most titanomaghemite has been formed by the reaction of hydrothermal solutions or volatiles with titanomagnetite primarily formed from magma. Though the minimum oxygen partial pressure necessary to oxidize titanomagnetite at a given temperature is not known, the hydrothermal solutions or volatiles derived from magma may be able to oxidize titanomagnetite. From the fact that the amount of titanomaghemite increases towards the weathered surface of the Atumi dolerite, it is suggested that some titanomaghemite may have been formed by weathering.

It must be noted that titanomaghemite occurs in some apparently unaltered lava flows. In this case, the volatiles or solutions may have attacked only the titanomagnetite, but not silicate minerals.

It is suggested that titanomaghemite and the transitional variety between titanomaghemite and $TiFe_2O_4$-Fe_3O_4 solid solution are common in intrusive as well as extrusive igneous rocks.

OBSERVATIONS WITH MICROSCOPE

In thin section titanomaghemite is opaque, and in polished section it is isotropic and shows intermediate reflectivity between those of titanomagnetite and hematite. The color is bluish gray for the extremely oxidized one which has composition near the $TiFeO_3$-Fe_2O_3 join or in the triangular field $TiFe_2O_5$-$TiFeO_3$-Fe_2O_3 in the system TiO_2-FeO-Fe_2O_3. The difference in color between titanomagnetite and titanomaghemite is emphasized by using oil immersion lens. In most cases, titanomaghemite develops from the margin or cracks of titanomagnetite grains. The boundary between them is generally sharp but complete gradation is sometimes observed. Titanomaghemite often shows irregular cracks. Figure 1 shows gradual change from titanomagnetite to titanomaghemite as revealed by the gradual change in color and in the number of irregular cracks. The analyzed titanomaghemites are generally homogeneous but occasionally contain small amounts of titanomagnetite in the inner parts of some grains which are considered as unoxidized parts of the original titanomagnetite. The titanomaghemites from the Atumi and Kingosi dolerites contain ilmenite exsolution lamellae less than about 4%. Hence the chemical compositions of the titanomaghemites must be slightly different from those suggested by the analyses.

METHODS OF SEPARATION AND CHEMICAL ANALYSIS

The separation of titanomaghemites was carried out by the same method as described in a previous paper (Akimoto and Katsura, 1959)

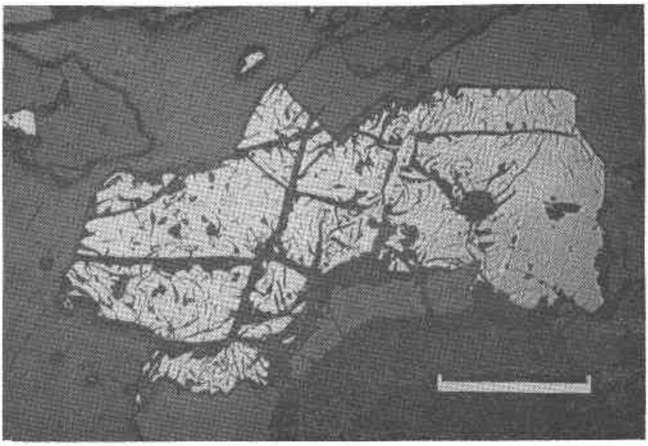


FIG. 1. Titanomaghemite in olivine-analcite-dolerite 1003, Atumi. Gradual change from titanomagnetite (right) to titanomaghemite (left) is revealed by the increase in reflectivity and in the number of cracks. The unit line at lower right indicates 0.1 mm.

except titanomaghemite No. 2 in Table 3. Specimen No. 2 is very fine grained and could not be separated by the same method. Therefore it was purified as follows: 1 gm. of the titanomaghemite roughly separated was suspended in 50 ml. of water held in a platinum dish, then half a ml. of hydrofluoric acid (45%) was added, and the mixture was stirred vigorously. After 5 minutes, a hand magnet was attached to the dish at the bottom from outside in order to fix the ferromagnetic deposit and the solution was removed by decantation. The ferromagnetic fraction thus obtained was washed several times with dilute hydrochloric acid. The purification was thus nearly complete as will be seen by the low SiO_2 content. The chemical analysis of titanomaghemites was made by the method devised by Iwasaki, Katsura, Yoshida and Tarutani (1957). The precision and accuracy of this analytical method are sufficient for the present study.

CHEMICAL COMPOSITIONS OF TITANOMAGHEMITES

Chemical compositions of the titanomaghemites separated from the Japanese igneous rocks are shown in columns Nos. 1, 2, 3-*a*, 3 and 4 of Table 3. In the last two columns of the same table, compositions of unoxidized titanomagnetite and of fairly oxidized titanomagnetite in the dike from Orimoto-toge, Sidara are given for comparison with that of titanomaghemite No.3. Nos. 3-*a* and 3-*b* are from the margin of the dike whereas No. 3 is from the center of the same dike. A gradual increase in

Table 4. Molecular Proportions of Oxides, Atomic Ratios of Fe and Ti, Lattice Parameters and Curie Temperatures of Titanomaghemites

	No. 1	No. 2	No. 2-*a*	No. 3	No. 4
			Mol. %		
FeO	20.62	31.09	34.31	27.69	26.06
Fe_2O_3	44.10	31.74	33.19	32.67	52.56
TiO_2	35.28	37.17	32.50	39.64	21.38
			Atomic ratio		
Fe/(Fe+Ti)	0.755	0.718	0.756	0.701	0.860
32(Fe+Ti)/O	20.63	21.01	21.43	20.71	21.55
			Mol. %		
$\left.\begin{matrix}FeO\\MgO\\MnO\end{matrix}\right\}RO$	23.93	—	—	—	27.13
$\left.\begin{matrix}Fe_2O_3\\Al_2O_3\\V_2O_3\end{matrix}\right\}R_2O_3$	43.48	—	—	—	52.19
TiO_2	32.59	—	—	—	20.68
			Atomic ratio		
R/(R+Ti)	0.773	—	—	—	0.864
32(R+Ti)/O	20.96	—	—	—	21.64
Lattice parameter (Å)	8.359 (8.394)	8.405	8.419	8.373 (8.470)	8.360 (8.430)
Curie temperature (° C.)	460	580	520,560	430	545

Nos. are same as those in Table 3. The lattice parameter values in parentheses are those of the titanomagnetites present in small amount. Curie temperatures are determined by the extrapolation of thermomagnetic curves for the heating process.

the degree of oxidation is recognized in the order No. 3-*b*→No. 3-*a*→ No .3.

The SiO_2 content in the specimens is due largely to pyroxene and feldspar. The presence of small amounts of such impurities obviously introduces a slight error in the calculation of the titanomaghemite compositions, but in the following calculations the silicate compositions are not subtracted from the analyses. Table 4 shows the molecular proportions and atomic ratios of the analyzed titanomaghemites. RO means the sum of FeO, MgO and MnO, and R_2O_3 that of Fe_2O_3, Al_2O_3 and V_2O_3. The difference between the ratios $FeO:Fe_2O_3:TiO_2$ and $RO:R_2O_3:TiO_2$ is small as shown in Nos. 1 and 4 of Table 4, and is insignificant for the interpretation of the relation between chemical compositions and physical properties of titanomaghemite. The value of $32(Fe+Ti)/O$ $(=32(Fe^{2+}+Fe^{3+}+Ti)/O)$ which is a measure of the degree of oxidation ranges between 24 and 23 in the titanomagnetites from volcanic rocks (Akimoto and Katsura, 1959), whereas the value for the titanomaghemites listed in Table 4 ranges from 20.6 to 21.6. Thus in the titanomaghemites there are vacancies of 2 or 3 metal ions in a unit cell with 32 oxygen atoms. The same result is obtained even when the ratio $32(RO+Ti)/O$ is used.

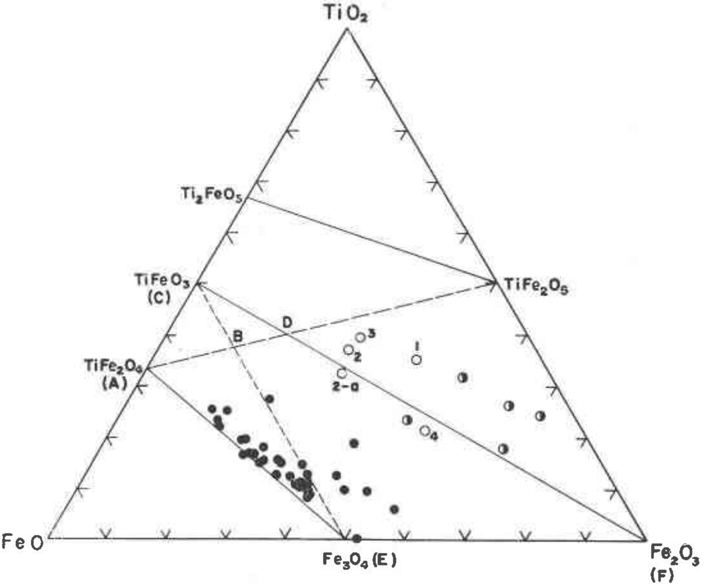
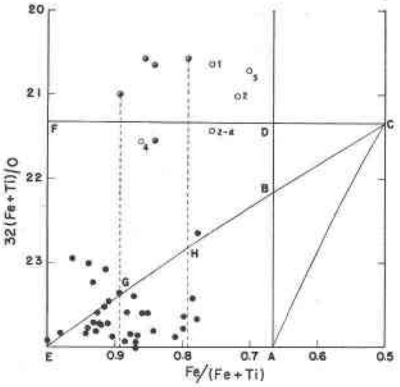


FIG. 2. Compositions of titanomagnetites and titanomaghemites in molecular per cent of FeO, Fe_2O_3 and TiO_2. Solid circles represent titanomagnetotes (data from Akimoto and Katsura, 1959). Open and half solid circles represent titanomaghemites from Japanese rocks and from South Africa respectively. (Data for latter from Basta, 1959.) The numbers refer to those in Tables 3 and 4.

Figures 2 and 3 show with open circles the chemical compositions of the titanomaghemites in the ternary system TiO_2-FeO-Fe_2O_3 and the relation between the values $Fe/(Fe+Ti)$ $(=Fe^{2+}+Fe^{3+}/(Fe^{2+}+Fe^{3+}+Ti))$ and $32(Fe+Ti)/O$ respectively. Available analyses of titanomagnetites from Japanese igneous rocks are also plotted with solid circles. The lines

EF and ABD in Fig. 3 represent the courses of oxidation of magnetite and ulvöspinel respectively. The lines AE and CBE represent the binary $TiFe_2O_4$-Fe_3O_4 and γ-$TiFeO_3$-Fe_3O_4 solid solutions assumed by Chevallier and Girard (1950) and the compositional field CAE includes the intermediate titanomagnetite of Vincent *et al.* (1957). Figure 2 shows that the Japanese titanomaghemites have compositions close to the $TiFeO_3$-Fe_2O_3 join or within the $TiFe_2O_5$-$TiFeO_3$-Fe_2O_3 triangular field. Figure 3 shows that the titanomaghemites have much more vacancies in metallic positions than the titanomagnetites.



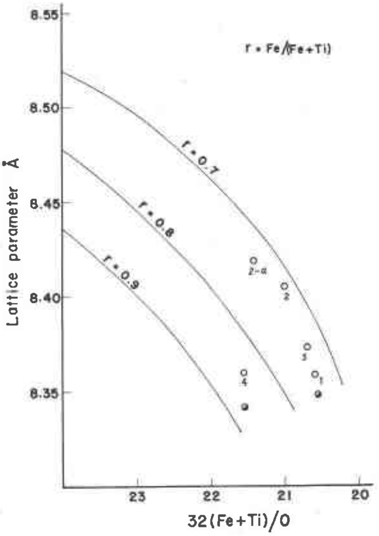


FIG. 3 (left). Relation between 32(Fe+Ti)/O and Fe/(Fe+Ti) of titanomagnetites and titanomaghemites. Symbols are same as in Fig. 2. Fe includes Fe^{2+} and Fe^{3+}.

FIG. 4. (right) Relation between lattice parameters and 32(Fe+Ti)/O of titanomaghemites. Symbols same as in Fig. 2.

Recently Basta (1959) reported titanomaghemites from South Africa and suggested that they were formed mainly by oxidation of titanomagnetite of the γ-$TiFeO_3$-Fe_3O_4 series (titanomagnetite II of Chevallier and Girard) but not of the $TiFe_2O_4$-Fe_3O_4 series. Table 5 gives recalculated Basta's data on the South African titanomaghemites. They are also plotted in Figs. 2 and 3. The South African titanomaghemites have the values of Fe/(Fe+Ti) ranging from 0.79 to 0.89 and those of 32(Fe+Ti)/O from 20.5 to 21.3. Thus, there are almost the same numbers of vacancies

TABLE 5. MOLECULAR PROPORTIONS OF OXIDES, ATOMIC RATIOS OF Fe AND Ti, AND LATTICE PARAMETERS OF TITANOMAGHEMITES FROM SOUTH AFRICA (AFTER BASTA, 1959)

	No. 1	No. 2	No. 3	No. 4	No. 5
			Mol. %		
FeO	14.41	27.83	5.45	9.64	14.81
Fe_2O_3	53.53	48.57	69.93	64.00	67.18
TiO_2	32.05	23.60	24.62	26.36	18.01
			Atomic ratio		
Fe/(Fe+Ti)	0.791	0.841	0.855	0.839	0.892
32(Fe+Ti)/O	20.55	21.54	20.56	20.63	21.20
			Mol. %		
$\left.\begin{array}{l}FeO\\MgO\\MnO\end{array}\right\}RO$	17.26	30.12	7.90	10.20	
$\left.\begin{array}{l}Fe_2O_3\\Al_2O_3\\V_2O_3\end{array}\right\}R_2O_3$	52.50	47.55	69.70	64.23	
TiO_2	30.24	22.33	22.40	25.57	
			Atomic ratio		
R/(R+Ti)	0.802	0.849	0.868	0.844	
32(R+Ti)/O	20.74	21.72	20.74	20.69	
Lattice parameter (Å)	8.3475	8.342			

in the unit cells as those in the Japanese titanomaghemites. If the South African titanomaghemites were oxidized from titanomagnetites of the γ-$TiFeO_3$-Fe_3O_4 series as postulated by Basta, the original titanomagnetites should have the values of Fe/(Fe-Ti) from 0.79 and 0.89 and 32(Fe Ti)/O from 22.9 to 23.4, in other words, they should be represented by points between H and G of Fig. 3. These titanomagnetites should have vacancies of 0.6–1.1 in the unit cells. It is clear from the experiment by Akimoto and Katsura (1959) that such titanomagnetites may be easily formed by oxidation of the titanomagnetite of the $TiFe_2O_4$-Fe_3O_4 solid solution under suitable conditions. In consideration of this, the postulation of the special solid solution series between γ-$FeTiO_3$ and Fe_3O_4 is not needed to explain the formation of titanomaghemite from normal titanomagnetite.

LATTICE PARAMETERS OF TITANOMAGHEMITES

The lattice parameters of the present titanomaghemites were determined by the measurement of diffraction angles for (440), (511, 333), (400), (311) and (220) by the "Norelco" x-ray diffractometer with FeKα radiation. Instrumental errors were calibrated by using a standard specimen of silicon. The lattice parameters are listed in Table 4. Those in parentheses are for titanomagnetites present in small amount. As reported previously (Akimoto *et al.*, 1957; Akimoto and Katsura, 1959), the change in lattice parameters of titanomagnetites depends not only on their TiO_2 content but also on the degree of oxidation. So far as we know, the relation between the lattice parameters of the Fe-Ti spinels and their TiO_2 content is not yet established. But if titanomaghemites are compared with titanomagnetites having the same Fe/(Fe+Ti) values, a certain definite relation is obtained between the lattice parameters and the degree of oxidation. Figure 4 shows the relation between lattice parameters and 32(Fe+Ti)/O for titanomaghemites and titanomagnetites with Fe/(Fe+Ti) ($=r$) equal to 0.7, 0.8 and 0.9. As will be seen in the figure, for any given values of 32(Fe+Ti)/O, the lattice parameter increases with the decrease of the r value. Basta (1953, 1959) gives a value 8.3475 Å for the cube edge of a titanomaghemite from Transvaal (No. 1 in Table 5). This value also fits the diagram.

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REFERENCES

AKIMOTO, S., KATSURA, T. AND YOSHIDA, M. (1957), Magnetic properties of $TiFe_2O_4$-Fe_3O_4 system: *Jour. Geomag. Geoelect.*, **9**, 165–178.

AKIMOTO, S. AND KATSURA, T. (1959), Magnetochemical study of the generalized titanomagnetite in volcanic rocks: *Jour. Geomag. Geoelect.*, **10**, 69–90.

AKIMOTO, S. AND KUSHIRO, I. (1960), Natural occurrence of titanomaghemite and its relevance to unstable magnetization of rocks: *Jour. Geomag. Geoelect.*, **11**, 94–110.

BASTA, E. Z. (1953), Mineralogical aspects of the system FeO-Fe_2O_3-TiO_2: Ph.D. thesis, Bristol.

——— (1959), Some mineralogical relationships in the system Fe_2O_3-Fe_3O_4 and the composition of titanomaghemite: *Econ. Geol.*, **54,** 698–719.

Chevallier, R. and Girard, J. (1950), Synthèse de titanomagnétites: *Bull. Soc. Chim. France*, **17,** 576–581.

Frenzel, G. (1953), Die Erzparagenese des Katzenbuckel im Odenwald: *Heidel. Beitr. Min. Petrogr.*, **3,** 409–444.

Iwasaki, I., Katsura, T., Yoshida, M. and Tarutani, T. (1957), Rapid chemical analysis of magnetite and ilmenite: *Jap. Analyst*, **6,** 211 (in Japanese).

Kushiro, I. (1959), Preliminary note on alkali-dolerite of Atumi District, northern Japan: *Jap. Jour. Geol. Geogr.*, **30,** 259–272.

Schwellnus, C. M. and Willemse, J. (1943), Titanium and vanadium in the magnetic iron ores of the Bushveld complex: *Geol. Soc. South Africa Trans.*, **46,** 23–38.

Vincent, E. A. and Phillips, R. (1954), Iron-titanium oxide minerals in layered gabbros of the Skaergaard intrusion, East Greenland: *Geoch. Cosmoch. Acta*, **6,** 1–26.

Vincent, E. A., Wright, J. B., Chevallier, R. and Mathieu, S. (1957), Heating experiments on some natural titaniferous magnetites: *Min. Mag.*, **31,** 624–655.

Wagner, P. A. (1928), The iron ore deposits of the Union of South Africa: *Mem. Geol. Surv. South Africa*, **26,** 29–34.

Walker, T. L. (1930), Lodestone from Bon Accord, Transvaal: *Toronto Univ. Studies, Geol. Ser.*, **29,** 17–19.

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