Magnetic Properties of Submarine Basalts from Site 443 of DSDP Leg 58, the Shikoku Basin

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Thermomagnetic properties, lattice constants and optical properties of Fe–Ti oxide minerals contained in 31 submarine basalt samples from the Shikoku basin (Site 443 of DSDP Leg 58) were studied. It seems to be clarified by this work that the magnetic properties are not dependent on depth from sub-bottom at the drilling site but on their lithological facies. As the result of the thermomagnetic analysis of the magnetic minerals separated magnetically from these samples, they were classified in four types (i.e. 1. reversible 2. semi-irreversible 3. irreversible 4. high Curie temperature). Specimens in the irreversible type seems to be reconstituted by a certain heat treatment. This fact shows us the necessity of reconsideration of the mechanism of a thermo-chemical change in low temperature-oxidized (non-stoichiometric) minerals.

1. Introduction

The magnetic properties of Fe–Ti oxide minerals have been precisely studied over several decades and many studies of magnetic properties of these minerals in submarine basalts have been reported.

OZIMA and LARSON (1967) reported that titanomagnetites (β -phase) were transformed into ilmenite-hematite phase (α -phase) by heating. O'REILLY (1968) reported that low temperature oxidation of titanomagnetites increased their Curie temperature. Using synthesized magnetites, OZIMA and SAKAMOTO (1971) reported that low temperature oxidation of titanomagnetites decreased their lattice constants in addition to the increasing of the Curie temperatures. OZIMA and OZIMA (1971) reported the chemical changes such that one phase of titanomagnetite was transformed into two phases (less-titaniferous magnetite phase and Ti-rich Fe–Ti oxide phase), with which the irreversible changes of J_s - T curve in natural submarine basalts could be plausibly interpreted. MARSHALL and COX (1972) concluded that low temperature oxidation accompanied by weathering had some effect on the changes in the lattice constant and Curie temperature of the samples. The chemical composition of oceanic tholeiites are different from the continental ones (MIYASHIRO, 1976). The X -value [$X\text{Fe}_2\text{TiO}_4$ ($1 - X$) Fe_3O_4] of titanomagnetites in the submarine basalts are reported to be about 0.6 (e.g. JOHNSON and HALL, 1978; Hamano *et al.*, 1979).

FURUTA *et al.* (1980) studied magnetic properties of submarine basalts from Site 443 of Leg 58. Using 27 samples from the drill core, an optical and electron microprobe analyses of opaque minerals was made and these results were compared with the shipboard magnetic data, i.e. magnetic polarities, J_n , MDF etc. In their results, they reported the existence of 2 types, 1) thermally reversible and 2) thermally irreversible, which were classified by the shape of their J_s - T curves; They also reported various features of titanomagnetites, of ilmenites and of the other opaque minerals by microscopic observation, and an ulvospinel content of $X = 0.6$ from electron microprobe analysis. Since their results were obtained from only about half of the drilling core samples of basalts from Site 443 of DSDP Leg 58, it is necessary to examine the rest of the samples in order to discuss the characteristics in detail.

KLEIN *et al.* (1980) reported that five units were identified in the basalt sequence in Hole 443:

- Unit 1 (457.0–457.1 m sub-bottom)
- Unit 2 (457.1–500.2 m sub-bottom)
plagioclase olivine pyritic basalt
- Unit 3 (500.2–538.5 m sub-bottom)
aphyric basalt (pillow lavas)
- Unit 4 (538.5–552.8 m sub-bottom)
plagioclase olivine pyritic basalt
- Unit 5 (552.8–576.5 m sub-bottom)
plagioclase (sparsely) pyritic basalt
- Unit 6 (576.5–581.5 m sub-bottom)
olivine plagioclase pyritic basalt

According to KLEIN *et al.* (1980), pillow basalts occur at Site 443, while the basalts overlying and intercalated with the pillows are massive basalts. A detailed description of the stratigraphy of these basalts was reported by DICK *et al.* (1980). Some massive basalts were identified as sills or sheets intruding into sediments.

The purpose of this study is as follows:

- (1) To supplement the study of FURUTA *et al.* (1980).
- (2) To obtain the differences of magnetic properties between submarine samples and continental samples or synthesized ones.
- (3) Consideration of the mechanism of the mode of thermo-chemical changes related to the "low temperature oxidation" and the "high temperature oxidation".

It is important for us to study magnetic properties of submarine basalts in company with their mineralogical and petrological properties.

2. Thermomagnetic Measurements of Virgin Samples

Thermal changes of saturation magnetization, J_s , were measured on 31 virgin samples from Site 443. The magnetic minerals, separated from the basalts with a magnet, were heated at the approximate rate of 10°C a minute in a magnetic field of about 3,000 Oe. After attaining 620°C , they were cooled to room temperature at the same rate in the same field. The heating and cooling were done in a vacuum of

Fig. 1. J_s - T curves of four typical types of virgin specimens. Closed circles show the heating process; open circles show the cooling process. (a) J_s - T curve of reversible type in low temperature type. (b) J_s - T curve of semi-irreversible type in low temperature type. (c) J_s - T curve of irreversible type in low temperature type. (d) J_s - T curve of irreversible type in high temperature type.

10^{-3} torr. All Curie temperature values were determined using the graphic method of GROMME *et al.* (1969).

As a result, four types of thermomagnetic curves were recognized: thermally reversible (Fig. 1-a), thermally semi-irreversible (Fig. 1-b), and thermally irreversible (Fig. 1-c) in low Curie temperature type, and thermally irreversible in high Curie temperature (Fig. 1-d). These are temporarily called Type I, II, III and IV, respectively. Type I, II and III are common in many submarine basalts (e.g. OZIMA and OZIMA, 1971; HAMANO *et al.*, 1979), but Type IV is not.

In the reversible type, the Curie temperature (T_{c1}) is easily determined, as shown in Fig. 1-a. In semi-irreversible and irreversible curves, more than two Curie temperatures, (T_{c1} , T_{c2} , . . . , T_{cn}) are recognized. T_{cn} , the Curie temperature after heating process up to 620°C , is nearly the same or slightly higher than the highest T_{c1} seen in the heating process. The multiple Curie temperatures seem to be due rather to the stepwise transformation of titanomagnetite into less-titaniferous magnetite and a certain Ti-rich Fe-Ti oxide mineral at approximate temperatures (e.g. OZIMA *et al.*, 1968; OZIMA and LARSON, 1970) than to the coexistence of multiple magnetic phases in the virgin specimens.

There is only a single example (58-2, 67 ~ 69) of high Curie temperature type (Type IV) in this study; the Curie temperature of it is about 550°C , nearly equal to the Curie temperature of pure magnetite.

The intensity ratio of saturation magnetizations at room temperature before and after heating at 620°C , Jh_0/J_0 , were calculated from the results of the thermomagnetic measurements and are listed in Table 1 with the Curie temperature. Their ratios are in the range from 0.95 to 4.50.

3. Thermomagnetic Measurements after Heat Treatment

The specimens after the thermomagnetic measurements were enclosed in quartz glass at vacuum of 10^{-3} torr and were heated by an electric furnace. Higher heat treatments than before were done successively, using the same specimen, to examine the thermal contribution to the chemical change of the mixing.

Thermal changes of saturation magnetization, J_s , of the heated specimens were measured under the same thermomagnetic conditions as the virgin specimens.

In the case of 61-4, 106 ~ 108 (Figs. 2-a, b and c), the thermomagnetic curves of specimens heated directly from the virgin state to 100°C for 48 hours and to 150°C for 100 hours (2-b, 2-c) are almost same as the curve of the virgin specimen (2-a). This result suggests that the titanomagnetites have not yet been destroyed at 150°C .

In the case of 59-1, 12 ~ 14 (Figs. 3-a, b and c), the specimens of the curves were heated after the first run at 680°C for 3 hours and 900°C for 5 hours. These curves obviously differ from the curve of the virgin specimen. Comparing Fig. 3-a with 3-b and 3-c, it is clear that T_{c1} of 3-b and 3-c are lower than T_{cn} of 3-a; therefore the chemical changes that occurred might be as follows: The titanomagnetites unmixed into a less-titaniferous magnetite phase and a non-magnetic phase as the result of the

Fig. 2. J_s - T curves of a specimen heated at high temperatures. Closed circles show the heating process; open circles show the cooling process. Figures 2-(b) and 2-(c) are after successive heat treatment of the virgin specimen in Fig. 2-(a).

Fig. 3. J_s - T curves of a specimen heated at high temperatures. Closed circles show the heating process; open circles show the cooling process. Figure 3-(b) is for the heated specimen after the measurement shown in Fig. 3-(a). The measurement for the heated specimen in Fig. 3-(c) was taken after that one shown in Fig. 3-(b).

Fig. 4. J_s - T curves of a heated specimen of Type IV. Closed circles show the heating process ; open circles show the cooling process. The curves in Figs. 4-(b) and (c) are after successive heat treatments of the same specimens.

heating to 620°C in the first run and, subsequently, a new titanomagnetite was synthesized from these two phases in the higher heat treatment processes mentioned above.

Figure 4 shows thermomagnetic curves of the Type IV specimen (58-2, 67 ~ 69) heated at various temperatures. It is seen in this figure that the Curie temperatures of the heated specimens are lower than the Curie temperature of the virgin specimen. From the result, we can conclude the following: If the chemical composition of the magnetic grains in specimen 58-2, 67 ~ 69 is the same as the others, the high Curie temperature of the thermomagnetic curve of the virgin specimen may be interpreted by assuming that these grains are a comparison of two phases, one being a low titanium magnetite and the other being a particular Ti-rich Fe-Ti oxide which is non-magnetic above room temperature; these two phases were then synthesized into a new titaniferous magnetite through heat treatment, the Curie temperature of which is lower than that of the virgin specimen. And, progressively, higher heat treatments caused more and more Ti to enter the titanomagnetite lattice.

It is reported that the Curie temperature of the cooling process appear at a lower point than that of the heating process in some J_s - T curves because of re-mixing of the unmixed phases which is accompanied with reduction, when the oxygen fugacities during heating is very low (MARSHALL, 1978; STAINER, 1982). Heat treatment in higher temperature may have caused a further reduction of the magnetic grains, as well as the lower oxygen fugacities during heating.

From the result of the thermomagnetic measurements of the heated specimen, it is recognized that the magnetic minerals of Type III and Type IV specimens do not seem to be mixed back perfectly into the chemically stable magnetic minerals as contained in Type I specimens.

4. Microscopy of Opaque Minerals

Opaque minerals were examined in polished sections with the reflected light microscope. Titanomagnetite was distinguished from ilmenite by its color and optical anisotropy, and from iron-sulfides by its color. As for iron-sulfides, pyrrhotite was distinguished from pyrite by its optical anisotropy. The majority of titanomagnetite and titanomaghemite grains were optical uniform as seen in Plate 1. In general, as to the shapes of titanomagnetites, the majority of them belong to skeletal (Plate 2) type or herring-bone type (Plate 3). But a few of the platy type (Plate 4), which are euhedral, were also observed in each section. Some titanomagnetites have well developed cracks (Plate 4), which were also reported by HALL *et al.* (1976), JOHNSON and HALL (1978), KOBAYASHI *et al.* (1979), and GURUTA *et al.* (1980). Plate 5 shows titanomagnetite containing ilmenite evolution lamellae along (111) planes. Plate 6 shows herring-bone type ilmenite which is judged from optical anisotropy and Ti/Fe ratio analyzed by the electron microprobe. Since this is not the crystal habit of ilmenite, it could be titanomagnetite that have been replaced by ilmenite. Many grains of pyrrhotite and pyrite were observed in each polished section. And a few grains of goethite and chromian spinel were also observed in some polished sections.

63-5 137~139

Plate 1. The titanomagnetite which is optically uniform.

49-3 101~103

Plate 2. The skeletal type titanomagnetite.

52-2 120~123

Plate 3. The herring-bone type titanomagnetite.

59-4 142~144

Plate 4. The platy type titanomagnetite, which have well developed cracks.

60-4 4~6

165 μ m

x400

Plate 5. The titanomagnetite containing ilmenite exsolution lamellae along (111) planes.

63-5 137~139

70 μ m

x400

Plate 6. The herring-bone type grain which have optical anisotropy.

Table 1

Sample number (unit)	Type ^a	T_{c1} (°C)	T_{c2} (°C)	T_{c3} (°C)	T_{c4} (°C)	Jh_0/J_0	Lattice const. (Å)	x-value II-Ti/Fe ^b (based on EPMA) ^c	Al ₂ O ₃ (wt %)	Grain size (μm)
49-3	I	120			120	1.06	8.4737			104
49-4	II	250	360		465	1.06	8.4621			336
50-1	II	190	230		260	1.09	8.4634			344
50-4	I	300			300	1.06	8.4614			165
52-2	I	105			105	0.99	(8.4803)			158
53-1	I	120			120	0.99				59
53-3	II	165			275	1.26	8.4552			128
54-1	III	315	420	578	578	3.0+ ^d	(8.4027) ^e			25
54-2	I	110			110	1.00	(8.4871)	0.696	1.715	187
54-4	I	140			140	1.00	(8.4851)			270
54-6	II	170			380	1.23	8.4552			48
54-7	III	300	540		570	4.5+	8.4463			10
56-2	III	350			575	3.97				51
57-2	III	340	535		580	3.81	8.4545			22
58-2	IV	550			550	1.25	8.3973			26
58-3	II	255	370	490	560	1.03	8.4573			46
58-3	II	260	330		405	1.22		*0.540 ^f	1.877	118
58-4	III	350	580		580	4.15				11
59-1	III	225	545		565	1.62	8.4628	0.717	1.311	108
59-2	II	155			210	1.10	8.4497			25
59-4	III	265	510		530	2.0+	8.3939			106
60-1	II	170			220	1.05	8.4710			147
60-3	I	165			165	0.97	8.4779			475
60-3	I	140			140	1.02	8.4848			415
61-1	I	150			145	0.96	8.4772			204
61-4	III	235	480		520	2.10	(8.4147)			40
63-1	III	280	575		575	3.0+	8.3919	0.681	1.981	89
63-4	II	215	480		480	1.02	8.4606			69
63-5	II	140	330		385	1.09	8.4621			143
64-2	I	155			155	0.95	8.4690			264
64-3	I	155			155	0.94	8.4780			257

^aThe Type from the shape of J_s - T curve.^bThe molecular ratio of Ti to Fe of ilmenite grain.^cEPMA is the abbreviation of electron probe micro analyzer.^d+ implies that the net value is more than the measured one.^e() imply that the peak which determine the lattice constant is broad.^fSince some analyzed grains were almost pure magnetites ($X < 0.1$), the value of each grain was averaged except for the grains which were $X < 0.1$.

A determination of the grain size of titanomagnetite was applied to about ten of the largest grains in order to obtain the correction between grain size and thermomagnetic properties, as the thermomagnetic measurements are influenced by larger grains of titanomagnetite contained in the specimen. This grain size of titanomagnetite is listed in Table 1.

5. Relation between Lattice Constant and Curie Temperature of Titanomagnetite

Lattice constant of titanomagnetite was measured by use of Geiger Flex, RDA-III A X-ray deflection analyzer. Silicon was used as a standard. The peaks of Cu $K\alpha_1$ ray, deflected from (440), (511), (422), (400), (222) and (311), were measured. The lattice constants of their peaks were determined from the Miller index, respectively, and they were averaged. The results are listed in Table 1. The lattice constant was not determined for some samples because only a small amount of titanomagnetite was contained in them. Figure 5 shows distribution of lattice constant of titanomagnetite or titanomaghemite is related to its titanium content and to the degree of low temperature oxidation (e.g. OZIMA and LARSON, 1970; OZIMA and SAKAMOTO, 1971; MARSHALL and COX, 1972).

Figure 6 shows the mutual relation between lattice constant and Curie temperature within the $\text{FeO}-\text{TiO}_2-\text{Fe}_2\text{O}_3$ ternary diagram. As seen in Fig. 6, the chemical compositions of the titanomagnetite of each type are different from each other. The X -value of Type I and Type II are concentrated between 0.6 to 0.7. Four samples of Type III is too small a number to emphasize the $X = 0.7$ value, however, the X -value of Type III seems greater than 0.7 and its chemical composition is rich in Fe_2O_3 . The X -value of Type IV is nearly equal to 0.2 and this value implies that the titanomagnetite phase is poor in titanium.

Fig. 5. The distributions of lattice constants in four types.

Fig. 6. The chemical compositions of titanomagnetites on the FeO-TiO₂-Fe₂O₃ ternary diagram, which are determined by their Tc contours (solid lines) and lattice constant contours (dashed lines) are those of NISHITANI (1979).

6. Electron-Microprobe Analysis of Opaque Minerals

Specimens were analyzed for Al, Ti, Fe and Si. Content of SiO₂ was monitored as a check against contamination, under the assumption that Si is extremely limited or absent in the Fe-Ti oxide minerals.

If the grain size was larger than 10 μ m, the Ti/Fe ratio in titanomagnetite and ilmenite was determined by use of a JAX-5 electron-probe microanalyser in the University of Tokyo. The following selected minerals were used as standard materials: Si: synthetic quartz; Al: synthetic corundum; Ti: synthetic rutile; Fe: natural hematite (Sennin Mine, Iwate, Japan). The correction of NAKAMURA and KUSHIRO (1970) was used for this analyses. Ulvospinel contents were calculated by first converting weight percentages into cations, normalized to three cations (i.e., under an assumption of stoichiometry). The cations of Ti and Fe were directly used to determine the Ti/Fe ratio and hence the ulvospinel content (X) for each grain. Since, unfortunately, most of the grains in the specimens have well developed cracks and scratches, only four specimens, which were suitable for microprobe and which

Fig. 7. Al₂O₃ weight percentage versus Ti/Fe ratios in titanomagnetites. Closed circles are skeletal titanomagnetites; open circles are herring-bone titanomagnetites; crosses are platy titanomagnetites. The skeletal and the herring-bone are subhedral titanomagnetites as seen in Plate 2 and Plate 3. The platy type are euhedral titanomagnetites as seen in Plate 4. Squares indicate those which can not grouped into the above three type titanomagnetite. They are not euhedral and their shapes are not similar to the skeletal or the herring-bone titanomagnetites but are shapes such as nuts or beans.

Fig. 7

represented each type (except for Type IV), were selected for analysis. The chemical composition was determined by this method in more than 20 grains in each specimen and the results were averaged. The molecular ratio of Ti to Fe of ilmenite and X -value of titanomagnetite based on electron-microprobe analysis are shown in Table 1.

The Al_2O_3 content ranges from 1.3 to 2.0 (weight percentage) as seen in Table 1. The existence of Al_2O_3 would slightly modify the X -value of the titanomagnetite if it is in a solid solution of magnetite-ulvöspinel (GROMME *et al.*, 1979; FURUTA *et al.*, 1980).

The correlation between the molecular ratio of Ti to Fe, Ti/Fe, and weight percentage of Al_2O_3 is shown in Fig. 7. As seen in Fig. 7, the weight percentage of Al_2O_3 seems to increase when the molecular ratio of Ti to Fe decrease except for the case of grains of the platy type, although the scatter is relatively large. This may be a petrologic (differentiation) trend.

7. Discussion

Magnetic properties, drilling depth and lithology had already been determined on board and they were reported in the Initial Report of DSDP (KLEIN *et al.*, 1980). The grain sizes of the titanomagnetites, Tc_1 , Tc_h and Jh_0/J_0 have been measured in this study. As seen in Fig. 8, it is clear that there is no obvious correlation between the magnetic properties and drilling depth, but there seems, however, to be a correlation between the magnetic properties and lithology. The grain sizes of titanomagnetites in aphyric basalts or pillow basalts are generally smaller than those in phyrlic basalts and the values of Tc_1 , Tc_h and Jh_0/J_0 in aphyric basalts or pillow basalts are generally larger than those in phyrlic basalts (e.g. JOHNSON and HALL, 1978; KOBAYASHI *et al.*, 1979; DAY *et al.*, 1979; STAINER, 1982). Figures 9-a and b show that Tc_1 and Jh_0/J_0 depend on the grain sizes of titanomagnetites.

The major magnetic minerals in the samples of this study are titanomagnetites and their oxidized products, titanomaghemites. The iron-sulfides were observed in the polished sections under the reflected light microscope. Their quantities are not greater than those of titanomagnetites, but still considerable. They do not influence the J_s - T curves because their saturation magnetization is much weaker than that of the titanomagnetites. In the case of Type I, the J_s - T curves are reversible (Fig. 1-a) and it means that the magnetic minerals are chemically stable in the thermomagnetic measurements. On the other hand, in case of Type II, Type III and Type IV, the J_s - T curves are semi-irreversible or irreversible (Figs. 1-b, c and d) and this means that they are chemically meta-stable or unstable in thermomagnetic measurements.

Ilmenite lamellae were not found in the polished section of Type IV (58-2, 67 ~ 69) under the reflected light microscope. If its chemical composition is not much different from that of titanomagnetites which are contained in ordinary submarine basalts ($X = 0.6$ – 0.7 ; e.g. HAMANO *et al.*, 1979), it is reasonable to consider that the ilmenite-hematite phases are not contained in the form of lamellae which are chemically stable, but in the form of "immature" (FURUTA, 1981) ilmenite-hematite phases which are chemically unstable. If the magnetic grains of Type II and Type III

Fig. 8. Magnetic properties with magnetic polarity sequence, drilling depth and lithology.

Fig. 9. (a) T_{c1} versus grain size. (b) J_{h0}/J_0 ratio versus grain size. (c) J_{h0}/J_0 ratio versus T_{c1} J_{h0}/J_0 : The intensity ratio of saturation magnetizations at room temperature before and after heating at 620°C .

include titanomaghemite which is due to low temperature oxidation and the magnetic grains of Type IV include the "immature" ilmenite, both the magnetic grains of Type II and III and Type IV are thought of as non-stoichiometric titanomagnetites which have excess oxygen.

The J_s - T curves of the heated specimen of Type IV (Fig. 4) are irreversible and it is thought that the two phases, into which the virgin titanomagnetites unmixed in thermomagnetic measurements, were re-mixed and were synthesized into non-stoichiometric titanomagnetites. This seems to be true because it has a lower T_{c1} than T_{c_h} , T_{c_h} being almost the same temperature in every specimen, as will be mentioned later. The Curie temperature (T_{c1}) of the synthesized products are different from each other as seen in Fig. 4. This fact makes us suppose that the synthesized product may depend on two conditions, the heating temperature and the length of heating. Although the conditions of heating are different in each case, in the J_s - T curves which indicate irreversible changes, the T_{c_h} of the heated specimen is nearly equal to the T_{c_h} of the virgin specimen. Thus, apparently, the spinels synthesized by heat treatment are also unstable in the heating process of thermomagnetic measurements, and they unmix into a ilmenite-hematite phase and a less titaniferous magnetite. The curves of heated specimens of Type III (Fig. 3) are also explained by the same chemical procedure as above-mentioned (Type IV).

If we regard the irreversible change in the J_s - T curves of the heated specimen as oxidation-reduction reaction, it should be considered that oxidation occurs on the thermomagnetic measurement and that reduction occurs on the heat treatment. Since both experiments were carried out in vacuum of 10^{-3} torr, which is generally regarded as atmosphere of oxidation below $1,000^\circ\text{C}$, it is reasonable to understand that the reduction on the heat treatment was induced by buffers such as sulfides and silica, which could not be separated completely from the magnetic minerals as the specimen.

There are, however, a few doubtful points mentioned as follows:

- 1) Whether or not the buffers such as sulfides and silica are stable to the repetition of reduction in the heat treatment?
- 2) Why is the magnetic produced by unmixing so stable to the repetition of the oxidation in the thermomagnetic measurements?

It is therefore, also supposed that the so-called mixing and unmixing mentioned above may constitute a closed system in terms of the chemical changes and that oxidation-reduction reaction may occur inside the magnetic grains (partly oxidized and partly reduced). However, the mechanism of irreversible changes as seen in the J_s - T curves in this study is not made clear. Clearing up uncertainties with regard to the mechanism, it is desirable that the quantitative analyses of oxygen in the magnetic minerals is done.

Summaries of the nature of the four types classified by J_s - T curves are as follows:

- 1) The samples of Type I contain titanomagnetites which are chemically stable in heat. The magnetic grains retain the original condition at the time when submarine basalts were generated.
- 2) The samples of Type II and Type III contain titanomaghemites which are

Fig. 10. The distributions of T_c , J_{h0}/J_0 ratio and grain size of four types. (J_{h0}/J_0 = the intensity ratio of saturation magnetizations at room temperature before and after heating at 620°C).

Fig. 11. The histogram of grain size distribution in Type III.

oxidized titanomagnetites and chemically meta-stable to heat. It has a tendency that the grain sizes of the magnetic grains of Type II and Type III are smaller than those of Type I, as seen in Fig. 10. The magnetic grains suffered low temperature oxidation after they had been generated. The grade of low temperature oxidation of Type III is higher than that of Type II.

3) The sample of Type IV is only one of 31 samples and it is observed that the grain sizes of the magnetic grains of this sample are very small. The J_s - T curve of the virgin specimen of this type resembles one of the J_s - T curves of the heated specimens of Type III (Fig. 3-b), and it is supposed that the magnetic grains of Type IV consist of two phases, ilmenite-hematite phase and less-titaniferous magnetite phase. The magnetic grains, which already suffered low temperature oxidation on the sea floor, were heated by some heat source.

If the chemical composition of the titanomagnetites in submarine basalts is almost the same ($X = 0.6, 0.7$), it seems possible that relatively high T_{c1} is due to low temperature oxidation. Jh_0/J_0 of the magnetic grains is proportional to its T_{c1} , as seen in Fig. 9-c. Therefore, Jh_0/J_0 , T_c can be used as factors to estimate low temperature oxidation. From the dependence of T_{c1} and Jh_0/J_0 on grain sizes in Figs. 9-a and b, it is considered that small grains of magnetic minerals suffer low temperature oxidation more easily than larger grains. This consideration seems to be supported by Fig. 11 for the number of Type III samples grouped in the range of small grain sizes.

Most of the Fe-Ti oxide minerals in natural samples seem to contain trace components such as Al_2O_3 , judging from the results of the microprobe analyses. Nevertheless all the considerations in this paper have been done without regard to any trace components, for the sake of convenience. It is significant, however, to consider the influences of the trace components for the studies of rock magnetism in order to establish more complete concepts on magnetic properties.

8. Conclusion

Most of the results in this study seem to support the results of FURUTA *et al.* (1980).

1) The X -values of titanomagnetites in this study concentrate between 0.6 to 0.7 and resemble the X -values of submarine basalts.

2) Four types of J_s - T curves of virgin samples are found in this study, and each type shows a different character.

3) The magnetic properties and mineralogical properties of the samples are correlative to the grain size of the titanomagnetites and lithological facies of the rocks.

From the above we can conclude the following: Non-stoichiometric titanomagnetites such as titanomaghemites are unmixed by heat, however, unmixed phases are not mixed back perfectly into the chemically stable (stoichiometric) titanomagnetites, so as to indicate a reversible change in the J_s - T curve, by the heat treatment in this study.

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