NOTES ON MAGNETIC PROPERTIES OF THE YAMATO METEORITES

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Abstract: The magnetic properties of four typical samples of the Yamato meteorites, which were collected near the Yamato Mountains in Antarctica in 1969, have been examined. These meteorites are (a) enstatite chondrite, (b) Ca-poor achondrite, (c) carbonaceous chondrite (C3), and (d) olivine-bronzite chondrite.

The basic magnetic properties of these samples have been determined on the basis of the magnetic hysteresis curves at room temperature and the thermomagnetic curves in a strong magnetic field ($H = 5.53$ k.Oe), with additional data of the electron microprobe analysis.

The main magnetic constituents in the Yamato meteorites thus evaluated are 3 wt % Ni kamacite and 25 wt % Ni kamacite in (a), almost pure metallic iron and probably maghemite in (b), magnetite in (c), and 6 wt % Ni kamacite and 50 wt % Ni taenite in (d).

The natural remanent magnetization (NRM) and its AF-demagnetization characteristics also have been studied for these meteorites. The coercivity of NRM against the AF-demagnetization is in a good positive correlation with the cosmic-ray exposure age of these meteorites. This result seems to support the Butler-Cox hypothesis that the cosmic-ray exposure is capable of converting the soft isothermal remanent magnetization in meteorites to remanence with a higher coercive force.

1. Introduction

Nine pieces of meteorite were found and collected by the Yamato mountain field party of the 10th Japanese Antarctic Research Expedition in a very limited area near the southern foot of the Yamato Mountains in December 1969 (YOSHIDA *et al.*, 1973). The locations where these meteorite pieces were collected on the surface of ice sheet are shown by full circles in Fig. 1. The full circles designated by I (A) and II (B) in the figure represent respectively the locations where Yamato meteorite (a) and (b) were collected. Unfortunately, however, the identification of numbering of the other seven meteorite pieces has been lossed.

Among the nine meteorite pieces, four are comparatively large and they have been named Yamato meteorite (a) (715 gm in weight), (b) (138 gm), (c) (150 gm) and (d) (62 gm). These four Yamato meteorites have been chemically analyzed

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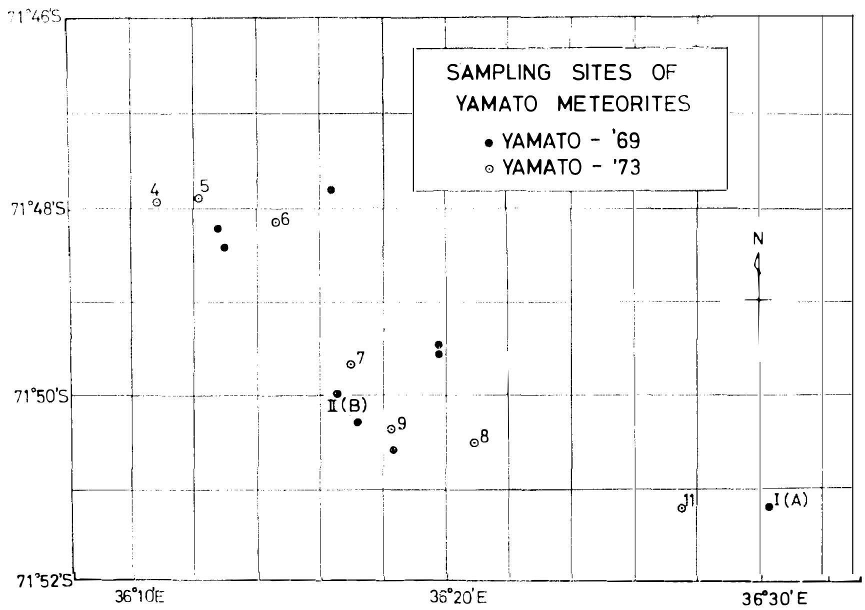

Fig. 1. A map showing Yamato meteorite sampling sites.
Yamato-'69: Yamato meteorites collected in 1969.
Yamato-'73: Yamato meteorites collected in 1973.
I (A): Site where Yamato (a) meteorite was found.
II (B): Site where Yamato (b) meteorite was found.

Table 1. Chemical composition of Yamato meteorites (in wt %).

	Yamato (a)	Yamato (b)	Yamato (c)	Yamato (d)
SiO_2	37.98	55.17	33.26	38.90
MgO	19.28	26.22	24.42	24.08
$FeO+Fe_2O_3$	0.48	12.58	27.84	12.02
Al_2O_3	1.55	0.70	2.44	1.93
CaO	0.45	1.21	2.37	1.68
Na_2O	0.86	0.012	0.46	0.92
K_2O	0.085	0.006	0.039	0.104
Cr_2O_3	0.42	1.38	0.56	0.65
MnO	0.25	0.52	0.17	0.30
TiO_2	0.075	0.072	0.133	0.082
P_2O_5	0.46	0.009	0.22	0.25
(Metals)				
Fe	22.18	0.66	0.15	12.69
Ni	1.86	≦0.004	1.32	1.52
Co	0.089	0.003	0.075	0.081
(Sulfides)				
Fe	7.20	0.85	2.30	3.38
S	4.71	0.49	1.32	1.94
Ca	0.72	—	—	—
Total	98.65	99.88	97.08	100.52

(After SHIMA *et al.*, 1973)

by SHIMA *et al.* (1973), and petrologically studied by OKADA (1975). The bulk chemical compositions of these meteorites obtained by SHIMA *et al.* are reproduced in Table 1. The results of petrographical studies and the X-ray powder pattern studies of these samples by OKADA have shown that the main constituents of the opaque phase are nickel-iron metal and troilite in (a), probably chromite in (b), mostly magnetite in (c), and mostly nickel-iron metal in (d). According to the results of these studies, the four meteorites are classified as follows:

Yamato (a): enstatite chondrite (Metal=24.13 wt %, Ilmenite=0.15 wt %, Troilite=11.34 wt %, Oldhomite=1.30 wt % in Norm; Opaque mineral=35.6 vol. % in Mode).

Yamato (b): Ca-poor achondrite (Metal=0.66 wt %, Ilmenite=0.15 wt %, Troilite=1.34 wt %, Chromite=2.01 wt % in Norm; Opaque mineral=5.8 vol. % in Mode).

Yamato (c): Type III carbonaceous chondrite (Metal=1.55 wt %, Ilmenite =0.30 wt %, Magnetite=14.82 wt %, FeO=13.02 wt %, Troilite=3.62 wt %, Chromite=0.90 wt % in Norm; Opaque mineral=22.9 vol. % in Mode).

Yamato (d): Olivine-bronzite chondrite (Metal=14.29 wt %, Ilmenite=0.15 wt %, Troilite=5.32 wt %, Chromite=0.90 wt % in Norm; Opaque mineral= 16.3 vol. % in Mode).

The observed relationship between oxidized iron and Fe in metal and troilite for three chondritic meteorites, Yamato (a), (c) and (d), is in good agreement with the diagram of the relationship for chondrites of various different types (MASON, 1962).

Yamato meteorites (a), (c) and (d) have been indentified to the respective meteorites by the presence of characteristic chondrules. In addition, all four samples including Yamato (b) which has been identified to an achondrite, have been confirmed to be meteorites by the rare gas isotope analyses of these samples such as (^{3}He, ^{4}He), (^{20}Ne, ^{21}Ne, ^{22}Ne) and (^{36}Ar, ^{38}Ar, ^{40}Ar) (SHIMA *et al.*, 1973). The exposure ages of these samples have been estimated in two different ways; the Ne exposure ages amount to 1.7, 31, 25 and 4.3 m. y., while the He exposure ages are 1.3, 35, 23 and 5.5 m. y. for Yamato meteorites (a), (b), (c) and (d), respectively. Compared with the approximate mutual agreement between the exposure ages of individual meteorites estimated by two different rare gas element isotopes, the observed discrepancies among the exposure ages of the four meteorites are considerably large. This suggests that the parent bodies of the four meteorite pieces were entirely different from one another. It is very likely, therefore, that the observed concentration of meteorite pieces within a very limited area is not attributable to an occurrence of a meteorite shower over the locality, but probably to a result of transportation of individual meteorite pieces by ice sheet movements to a possible convergence point near the Yamato Mountains. Since all meteorite pieces were found on the surface of ice sheet, it might also be necessary to consider a certain upwell mechanism which kept the meteorites on the ice surface in spite of the regelation of ice for heavy meteorite pieces.

2. Basic Magnetic Properties at Room Temperature

The magnetic hysteresis curves of the meteorite samples have been determined at room temperature (295°K), an example of the measurements being shown in Fig. 2. The observed basic magnetic parameters, such as initial magnetic susceptibility (χ_o), paramagnetic susceptibility (χ_a), saturation magnetization (I_s), saturation remanent magnetization (I_R) and coercive force (H_c), are summarized in Table 2, where several fragments of some samples are separately measured in order to estimate the magnetic inhomogeneity within individual meteorite samples. The differences of magnetic parameters among different fragments of same samples are sufficiently small compared with their discrepancies among different samples.

Table 2. Basic magnetic properties of Yamato meteorites at room temperature.

Magnetic parameters	Yamato meteorites				Unit
	(a)	(b)	(c)	(d)	
Susceptibility (χ_o)	2141	9.0	477. 556. 547. — } 536.	1355	$\times 10^{-5}$emu/gm/Oe
Apparent paramagnetic susceptibility (χ_a)	2.5	0.295 0.29 0.27 } 0.28	0.61 0.53 0.55 0.48 0.50 } 0.53	1.94 2.06 } 2.0	$\times 10^{-4}$emu/gm/Oe
Saturation magnetization (I_s)	48.0	0.18 0.18 0.21 } 0.19	10.7 11.2 10.2 11.1 10.5 } 10.8	32.0 32.6 } 32.3	emu/gm
Saturation remanence magnetization (I_R)	0.35	0.0035 — —	1.7 1.6 1.65 1.75 1.76 } 1.69	0.60 —	emu/gm
Coercive force (H_c)	12	42 — —	175 167 152 160 133 } 157	23 —	Oersteds
Curie point (Θ)	769	780 567	540	759	°C
$\gamma \rightarrow \alpha$ transition temperature (●*)	40	None	None	690	°C
I_R/I_s	0.007	0.018	0.156	0.019	
χ_a(FeO)	8.6×10^{-7}	2.3×10^{-5}	2.4×10^{-5}	2.2×10^{-5}	emu/gm/Oe
I_R/χ_o	16	39	315	44	Oersteds
m_k/m	0.22	—	—	0.93	

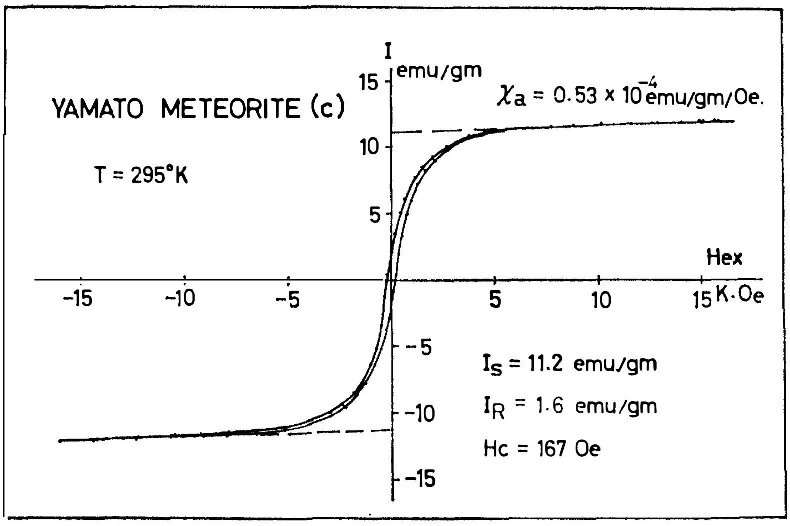

Fig. 2. Example of magnetic hysteresis curve at room temperature.

2.1. *Saturation magnetization* (I_s)

From the petrographical observations, it is expected that the main ferromagnetic constituents in (a) and (d) are FeNi alloys of kamacite composition and those in (c) are magnetite, while those in (b) may probably be kamacite plus ferromagnetic chromite.

As the first approximation, it is assumed that only kamacite and magnetite are responsible for the ferromagnetism of these samples. Then, the I_s values can be theoretically estimated from the weight contents of FeNi alloy, $m(Fe^0)$, and magnetite, $m(Mt)$, in the samples, where $I_s(Fe^0)=218$ emu/gm and $I_s(Mt)=92$ emu/gm at 295°K; namely,

$$I_s=218\ m\ (Fe^0)+92\ m(Mt)\ \text{emu/gm}. \tag{1}$$

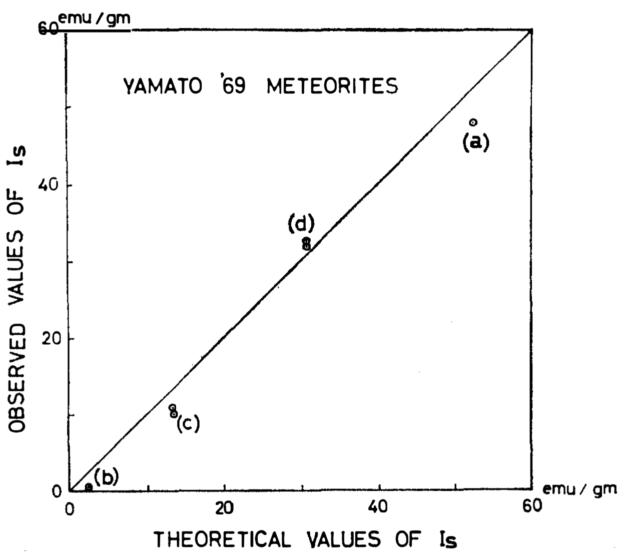

Fig. 3. Correlation between the observed value of saturation magnetization (I_s) and the theoretically estimated value of I_s based on the abundance of NiFe metal or magnetite in Yamato meteorites.

The theoretically estimated values of I_s are plotted against the observed I_s values of the respective samples in Fig. 3, where the agreement between the theoretical and observed values of I_s is reasonably good except for (b) sample. Ferromagnetism of Yamato (b) meteorite will be discussed again in Section 3 together with its thermomagnetic characteristics.

2.2. *Initial magnetic susceptibility* (χ_0)

The observed values of χ_0 given in Table 2 range widely from 9×10^{-5} to 2×10^{-2} emu/gm/Oe, but they are approximately proportional to the I_s values. As already discussed (NAGATA *et al.*, 1974), the ratio of χ_0 to I_s is theoretically represented by

$$\chi_0/I_s \simeq (\bar{N}\ J_s^0)^{-1}, \tag{2}$$

where $\bar{N}$ and J_s^0 denote respectively the average demagnetization factor of ferromagnetic particles and the saturation magnetization of the ferromagnetic constituent per unit volume. The observed relationship between χ_0 and I_s for the Yamato meteorites is illustrated in Fig. 4, where $(\chi_0/I_s)\simeq4.5\times10^{-4}$ is obtained as the linear relation coefficient. Although the numerical value of coefficient is reasonable for magnetites in Yamato (c) sample, it is too large for metallic FeNi alloys in chondritic meteorite, Yamato (a) and (d), for which the theoretical value should be about 2×10^{-4} in order of magnitude.

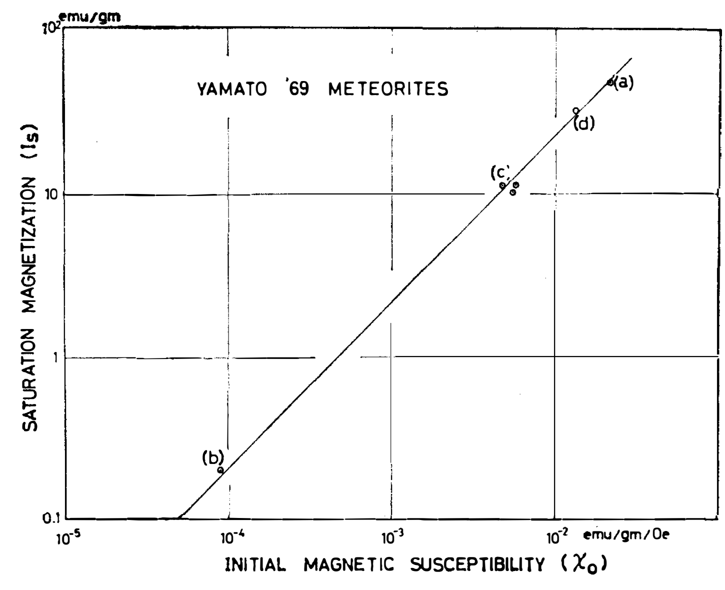

Fig. 4. Correlation between saturation magnetization (I_s) and initial magnetic susceptibility (χ_0) in Yamato meteorites.

2.3. *Saturation remanent magnetization* (I_R) *and coercive force* (H_c)

The observed I_R and H_c values also are markedly different for different samples, and ratio I_R/I_s ranges from 0.007 to 0.156. It can be observed in Table

2 that the larger value of I_R/I_s corresponds to the larger value of H_c. It has been suggested (*e.g.* NAGATA, 1961) that I_R/I_s of natural rocks is theoretically represented by

$$I_R/I_s \simeq H_c/N\ J_s^0. \qquad (3)$$

Then, combining (3) with (2), we get

$$I_R/\chi_0 \simeq H_c. \qquad (4)$$

In Table 2, I_R/χ_0 values are given for a comparison with the directly observed values of H_c. As far as the order of magnitude is concerned, I_R/χ_0 values are in approximate agreement with H_c.

2.4. *Paramagnetic susceptibility* (χ_a)

The paramagnetic susceptibility (χ_a) was determined from the linear relation between the magnetization intensity (I) and a high magnetic field (H) in a range of 10 k.Oe$\leqq H \leqq$16 k.Oe. Hence, the observed χ_a values include the paramagnetic susceptibility of Fe^{2+} in olivine, pyroxene and others and the antiferromagnetic susceptibility of $FeTiO_3$ and FeS.

The contribution of Fe^{2+} to the paramagnetic susceptibility at 295°K is theoretically given by

$$\chi_a(\mathrm{FeO}) = 1.65\times10^{-4}\ \mathrm{C(FeO)emu/gm/Oe}, \qquad (5)$$

where C(FeO) denotes the weight content of FeO (*e. g.* NAGATA, 1961). In the case of lunar materials, this theoretical expression by (5), which takes into account only the contribution of Fe^{2+}, is in reasonably good agreement with the observed relation between χ_a and FeO content (NAGATA *et al.*, 1973). The theoretical values of χ_a(FeO) for Yamato meteorites are given in Table 2, where the observed values of χ_a are considerably larger than the theoretical value of χ_a(FeO) except for Yamato (b) meteorite. A large difference between χ_a(FeO) and χ_a(observed) is observed particularly in Yamato (a) meteorite whose FeO content is of a very small value. However, a cotribution of antiferromagnetic troilite (FeS) to the apparent paramagnetization may not be ignored in these Yamato meteorites, particularly in (a) and (d). The antiferromagnetic susceptibility at 295°K contributed from FeS is estimated from its abundance to be 2.5×10^{-6}, 0.29×10^{-6}, 0.79×10^{-6}, and 1.2×10^{-6} emu/gm/Oe respectively for Yamato (a), (b), (c) and (d) meteorites. These estimated values of χ_a(FeS) are still negligibly small compared with the respective observed values of χ_a. Since the difference of χ_a(observed) from χ_a(FeO)+χ_a(FeS) is particularly large in Yamato (a) and (d) meteorites, whose I_s value is markedly large and whose magnetic constituents are iron and FeNi alloy, there might be a possibility that the observed apparent paramagnetic susceptibility includes a small part of the ferromagnetic rotational susceptibility in Yamato (a) and (d) meteorites in particular.

3. Thermomagnetic Properties and Electron Microprobe Analysis

Observed thermomagnetic curves of Yamato meteorites (a), (b), (c) and (d) are illustrated in Figs. 5(a)-(d), and $\gamma\rightarrow\alpha$ transition temperature (Θ^*) of kamacite phase as well as Curie point (Θ) determined from these magnetic curves are summarized in Table 2.

3.1. Yamato (a) meteorite

Figure 5(a) indicates that the main ferromagnetic component in Yamato (a) meteorite is Ni-poor kamacite whose Curie point is about 760°C. Results of the electron microprobe (XMA) analyses have shown that the Ni content in the Ni-poor kamacite grains is 2.5–3.0 wt %.

The irreversibility of magnetization between the heating and cooling processes is reproducible so that a sharp change in I at about 40°C in the cooling curve may represent a $\gamma \rightarrow \alpha$ transition temperature of Ni-rich kamacite, which corresponds to about 25 wt % Ni kamacite. The XMA analysis has shown that the Ni-content in the Ni-rich kamacite grains is more than 15 wt % in most cases.

As I_s of kamacite decreases sharply with an increase in the Ni-content in a range over 20 wt % of Ni-content, it is difficult to determine the exact abundance of Ni-rich kamacite in the metal phase only from the thermomagnetic curve. However, with m_{k_1} and m_{k_2} denoting the abundance of 3% Ni kamacite and that of 25% Ni kamacite respectively, we have observed data such as

$$m_{k_1}+m_{k_2}=24.04 \text{ wt } \%, \quad 0.03m_{k_1}+0.25m_{k_2}=1.86 \text{ wt } \%,$$

which give $m_{k_1}=18.86$ wt % and $m_{k_2}=5.18$ wt %.

The magnetic data given in Table 2 and Fig. 5 (a) indicate

$$I_s(k_1)=41.86 \text{ emu/gm}, \quad I_s(k_2)=6.14 \text{ emu/gm},$$

where $I_s(k_1)$ and (k_2) represent respectively the saturation magnetizations of 3% Ni and 25% Ni kamacite components in this meteorite at 295°K. Then the specific intensities, $I_s^0(k_1)$ and $I_s^0(k_2)$, of saturation magnetization of 3 % Ni and 25% Ni kamacite must be expressed as

$$m_{k_1}I_s^0(k_1)=I_s(k_1), \quad m_{k_2}I_s^0(k_2)=I_s(k_2). \tag{6}$$

Putting the numerical values of m_{k_1}, m_{k_2}, $I_s(k_1)$ and $I_s(k_2)$ into (6), one gets

$$I_s^0(k_1)=220 \text{ emu/gm}, \quad I_s(k_2)=120 \text{ emu/gm},$$

which are quite reasonable values as the saturation magnetization of 3% Ni and 25% Ni kamacites (*e. g.* BOZORTH, 1951).

3.2. Yamato (b) meteorite

Figure 5 (b) shows that Yamato (b) meteorite has the second Curie point at 567°C in addition to the main Curie point at 780°C. The magnetization of this meteorite is irreversibly increased by the initial heating up to 810°C in 10^{-5} torr atmosphere, amounting to about 2.7 times as large as the initial value.

The main ferromagnetic component can be identified to the almost pure metallic iron which contains very small amounts of Ni and Co. The XMA analysis has shown that the metallic grains in this sample consist of Ni of 0.5 vol. %, Co of 0.8 vol. % and the remaining parts of Fe. This result is in approximate agreement with ratios Ni/Fe and Co/Fe in chemical data in Table 1. As already discussed in the previous section, however, the observed values of I_s of three different fragments of this meteorite, given in Table 2, are very small compared with the theoretically estimated value (*i. e.* 1.44 emu/gm) of the almost pure metallic iron derived from the chemical data in Table 1.

Because Ni content in metal is particularly small in this sample, it seems impossible to assume the presence of Ni-rich γ-NiFe alloy. As shown in Fig. 5 (b), however, the intensity of magnetization of another fragment of this meteorite in a magnetic field of 5.53 k.Oe, (which is approximately 4/5 of I_s value) amounts to about 0.5 emu/gm at 295°K. Since the chemical analysis was made on a different part of this meteorite, only a possible interpretation of the considerable discrepancies of I_s-value among the two magnetic measurements and the theoretical estimate based on the chemical data would be such that the distribution of metallic component is inhomogeneous within a certain limit in this meteorite, (probably between 0.1 and 0.7 wt %). Then, a qualitative conclusion in regard to the metallic component in this meteorite will be the following: Both magnetic and chemical analyses have shown that the metallic abundance is very small ($<$0.7 wt %), considerably deviating from the standard relationship between ($FeO+Fe_2O_3$) and Fe in metal and troilite for chondrites (MASON, 1962). This result also may indicate that this meteorite is not a chondrite.

The second ferromagnetic component having Curie point at 567°C could be identified to a solid solution between magnetite and chromite, *i.e.* $xFeCr_2O_4 \cdot (1-x)\ Fe_3O_4$, because the opaque mineral grains separated under a microscope have the spinel structure and are weakly magnetic (OKADA, 1975), and chemically the abundance of Cr_2O_3 in this meteorites is considerably large, Norm of chromite being estimated to be 2.01 wt %. However, the magnetic study on a large chromite crystal in this meteorite by TAKEDA *et al.* (1975) has shown that it is an almost pure $FeCr_2O_4$ which is antiferromagnetic.

The magnetization intensity of this second ferromagnetic component is extremely increased by the initial heat treatment, amounting to about 11 times as large as the initial value; the saturation magnetization of this component at 295°K after the heat treatment amounts to about 1.0 emu/gm. This kind of irreversible change of magnetic property by the heat treatment has been often observed, particulary in submarine basatls (*e.g.* COX and DOELL, 1962; OZIMA *et al.*, 1968). The ferrimagnetic constituents in these basalts are identified to maghemite or titanomaghemite which may have an unstable ironic configuration in the oxidized spinel crystal. Similar magnetic characteristics have been observed for synthesized titanomaghemite which is artificially oxidized by the wet griding technique (SAKAMOTO *et al.*, 1968). In the present Yamato (b) meteorite, a possible candidate for the second ferromagnetic component might therefore be maghemite.

It seems to be hardly possible, however, that metallic iron and strongly oxidized maghemite have been co-produced in the original meteorite. It seems likely, therefore, that the presumed presence of maghemite is a result of high oxidization in the later stage. It is true in microscopic observations that this meteorite has been considerably oxidized compared with the other three meteorites.

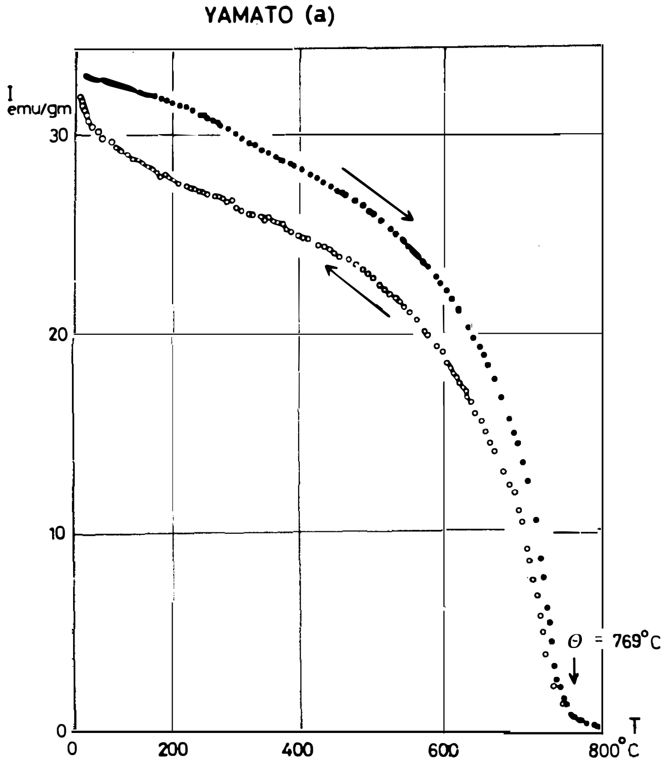

Fig. 5(a). Thermomagnetic curve of Yamato (a) meteorite.

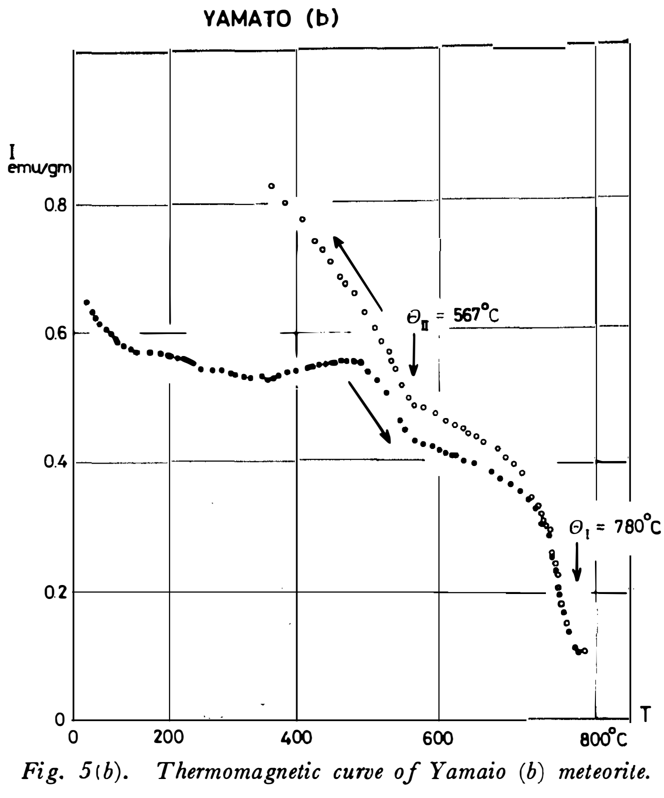

Fig. 5(b). Thermomagnetic curve of Yamaio (b) meteorite.

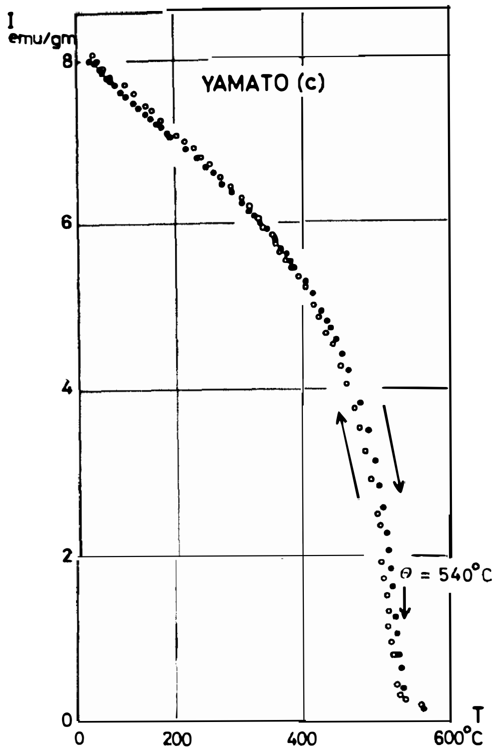

Fig. 5(c). Thermomagnetic curve of Yamato (c) meteorite.

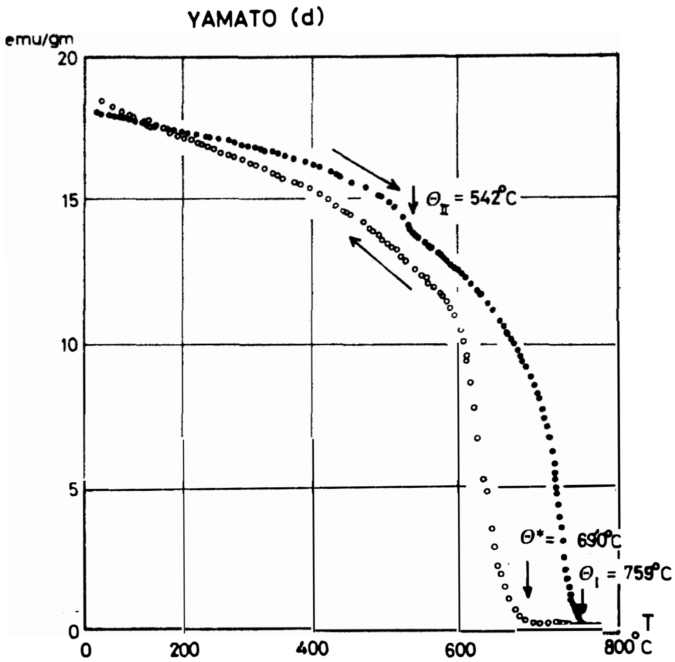

Fig. 5(d). Thermomagnetic curve of Yamato (d) meteorite.

3.3. Yamato (c) meteorite

Figure 5 (c) indicates that Yamato (c) meteorite contains only a very small amount of metallic iron, namely about 0.05 wt %, and almost all parts of its ferromagnetism are due to the ferrimagnetism of magnetite. It has been petrologically observed that opaque mineral grains in this meteorite are mostly magnetites (OKADA, 1975).

However, Curie point at 540°C of this meteorite suggests that the magnetite is not stoichiometric, but Fe^{3+} in its spinel crystal is replaced by either Cr^{3+} or Al^{3+} or alternatively and/or additionally $2Fe^{3+}$ are substituted by $Fe^{2+}+Ti^{4+}$. The observed Curie point corresponds to either one of $0.05\ TiFe_2O_4 \cdot 0.95Fe_3O_4$, $0.15FeCr_2O_4 \cdot 0.85Fe_3O_4$ and $0.25FeAl_2O_4 \cdot 0.75Fe_3O_4$. Since the chemically obtained abundances of TiO_2 and Cr_2O_3 are not sufficient to produce the magnetic solid solution of spinel structure by themselves, it appears that $xFeAl_2O_4 \cdot (1-x)Fe_3O_4$ also is included in the substituted magnetites. In any case, the saturation magnetization (I_s) is theoretically estimated from the amount of Fe_3O_4 to be about 12 emu/gm at 295°C, which is in approximate agreement with the observed value.

A problem in this meteorite is an unusually large abundance of Ni in comparison with Fe and Co in metal. No magnetic evidence has been available for the presence of expected Ni rich-NiFe alloy. In the XMA analysis of this meteorite, on the other hand, a number of grains of $(Fe_{0.5}, Ni_{0.5})S$ are observed.

3.4. Yamato (d) meteorite

Figure 5 (d) shows that Yamato (d) meteorite contains kamacite, whose Curie point is 759°C and whose $\gamma \rightarrow \alpha$ transition temperature is 690°C, as the main ferromagnetic component. Ni-content in this kamacite phase is estimated to be about 6 wt %. Debye-Sherrer X-ray photographs also have shown the presence of α-NiFe metal in this meteorite (OKADA, 1975). In addition, the second ferromagnetic component of a small amount, whose Curie point is 542°C, is observed. The XMA analysis has indicated the presence of a number of taenite grains, in which Ni-content is about 29% in the center and 37% at edges. Hence, the second ferromagnetic component can be identified to taenite.

From the observed Curie point value, however, Ni-content in taenite is estimated to be about 40 wt %. From ratio of magnetization of taenite component to that of kamacite one derived from the thermomagnetic curve (*i. e.* I (taenite)/I (kamacite)=0.049), ratio of taenite abundance (m_{tae}) to kamacite one (m_k) is estimated to be 0.071, because I_s (6% Ni kamacite)=218 emu/gm and I_s (40% Ni taenite)=150 emu/gm. Namely, $m_{tae}=0.071\ m_k$. On the other hand, I_s of this meteorite must be expressed by

$$I_s=218\ m_k+150\ m_{tae}=32.3 \text{ in unit of emu/gm.}$$

From these equations, we get

$$m_k=14.13 \text{ wt \%}, \quad m_{tae}=0.10 \text{ wt \%},$$

which give m(Fe)=13.9 wt % and m(Ni)=1.4 wt %.

These values of m(Fe) and m(Ni), which are estimated entirely from the magnetic data, are in reasonably good agreement with the respective values obtained by the chemical analysis in Table 1.

3.5. Mutual comparison of Yamato (a), (b), (c) and (d) meteorites

Generally speaking, the magnetic data of Yamato (a) and (d) meteorites are in reasonably good agreement with their chemical and petrological data. In these chondritic meteorites, NiFe alloys, either kamacite or taenite, are the main ferromagnetic constituents. Yamato (c) meteorite is a carbonaceous chondrite, in which magnetite is mostly responsible for the magnetic properties. Plotting the observed chemical data of these three chondrites given in Table 1 into the well known diagram of the weight per cent of iron in metal and troilite versus that of oxidized iron (MASON, 1962), it is clearly observed that Yamato (a), (c) and (d) meteorites belong to the groups of enstatite, carbonaceous and olivine-bronzite-chondrites respectively. As far as the major characteristics are concerned, the magnetic properties of these three chondritic meteorites well represent their chemical and petrological characteristics.

However, Yamato (b) meteorite can be identified to a hypersthene achondrite from its chemical and petrological compositions. This meteorite contains only a small amount of ferromagnetic metal, as observed in its weak ferromagnetism of almost pure metallic iron. This is one of general characteristics of hypersthene achondrites. In addition, a thermally unstable ferromagnetic component also has been observed in this achondrite. Although this second magnetic component is provisionally identified to maghemite, the identification is quantitatively uncertain. Futher studies on this component in detail may be necessary.

4. Natural Remanent Magnetization and Its Stability

The natural remanent magnetization (NRM) of meteorites has been examined by several workers (*e.g.* STACEY *et al.*, 1961; WEAVING, 1962; GUS'KOVA, 1963; BANERJEE and HARGRAVES, 1972; SUGIURA and NAGATA, 1974). These workers have been inclined to consider that NRM of meteorites is mostly due to the thermoremanent magnetization (TRM) which was acquired by the meteorites when they were cooled in an ambient magnetic field in the extraterrestrial space. With the aid of the so called Thellier-Thellier method, these workers have estimated the paleointensity of ambient magnetic field based on experimental data of the thermal demagnetization of NRM and the acquisition of partial TRM of ordinary and carbonaceous chondrites, the results being summarized as a histogram of the paleointensity in Fig. 6. It is observed in the figure that the paleointensity of 0.1–0.3 Oersteds is the most predominant, though five meteorites (two ordinary chondrites and three carbonaceous chondrites) have the paleointensity larger than 0.6 Oe. and smaller than 1.1 Oe.

Unfortunately, sufficient volumes of Yamato (a)–(d) meteorites have not been reserved for the purpose of Thellier-Thellier method study. Since a large number of other meteorites have been found in the same area where Yamato (a)–(d) meteorites were colleted, the Thellier-Thellier method studies on Yamato meteorites will be carried out in detail with these new meteorite samples which have been specifically reserved with specical precautions against a possible magnetic contamination.

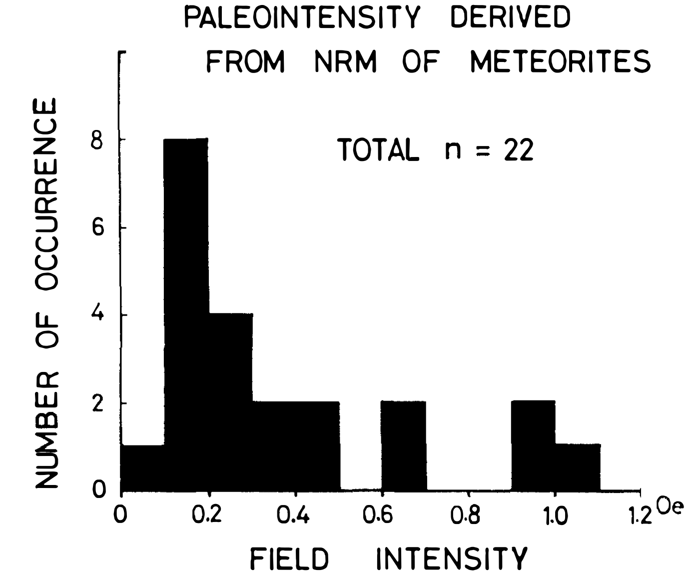

Fig. 6. Histogram af paleointensities of meteorites which have been reported to date.

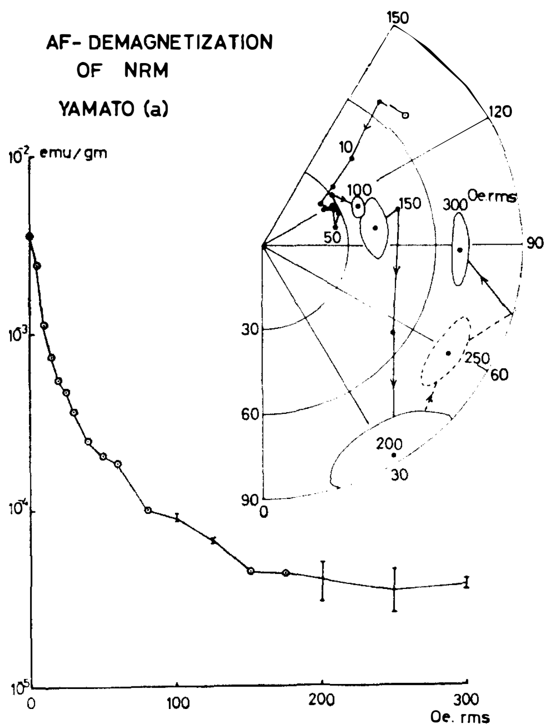

Fig. 7(a). AF-demagnetization characteristics of NRM of Yamato (a) meteorite. Lower left: change in intensity. Upper right: change in direction.

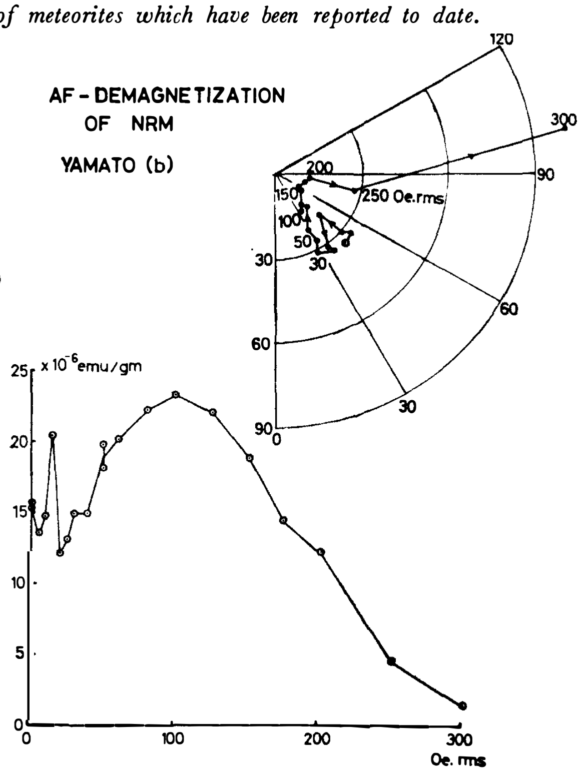

Fig. 7(b). AF-demagnetization characteristics of NRM of Yamato (b) meteorite.

AF - DEMAGNETIZATION OF NRM

YAMATO (c) - 1

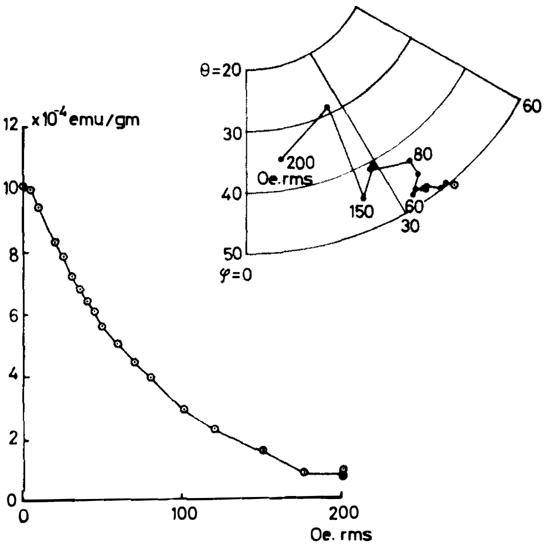

Fig. 7(c-1): AF-demagnetization characteristics of NRM of Yamato (c) meteorite (one of divided specimens).

AF - DEMAGNETIZATION OF NRM

YAMATO (c) - 3

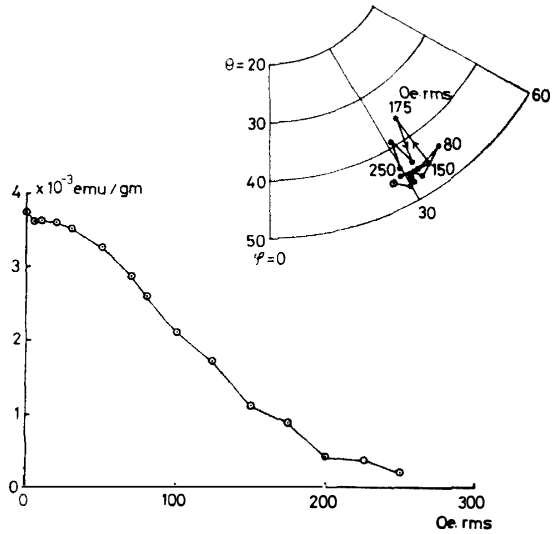

Fig. 7(c-3). AF-demagnetization characteristics of NRM of Yamato (c) meteorite (a divided specimen different from c-1 specimen).

AF - DEMAGNETIZATION OF NRM

YAMATO (d)

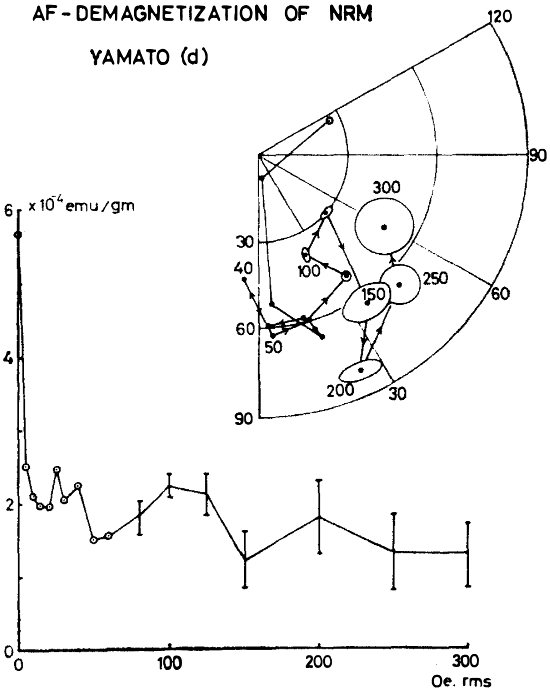

Fig. 7(d). AF-demagnetization characteristics of NRM of Yamato(d) meteorite.

With respect to NRM of Yamato (a)-(d) meteorites, their NRM and its AF-demagnetization characteristics have been examined in comparison with their isothermal remanent magnetization (IRM) and its AF-demagnetization characteristics. The AF-demagnetization characteristics of NRM of 40 meteorites have been studied by LARSON *et al.* (1973). They have concluded that almost all of carbonaceous chondrites possess an NRM which is stable with respect to both intensity and direction during the AF-demagnetization up to 400 Oe., whereas some ordinary chondrites are associated with the low-stability magnetization in addition to a stable component of NRM.

In Figs. 7(a)-(d), the AF-demagnetization characteristics of Yamato (a)-(d) meteorites are illustrated for both intensity and direction. Of Yamato (c) meteorite, two different specimens were separately examined. As for parameters to represent the stability of NRM against the AF-demagnetization and the capability of acquisition of remanent magnetization of these meteorite samples, the following quantities are specifically determined.

I_n: the intensity of NRM of the sample as received,

I_n^0: the intensity of NRM after the AF-demagnetization up to $\tilde{H}=100$ Oe. rms,

$\tilde{H}_0$: AF-demagnetization field to reduce I_n to e^{-1} of its initial value.

$\tilde{H}^*$: AF-demagnetization field which has almost completely demagnetized the directionally stable component of NRM.

b: IRM acquisition rate which is defined by $b=(\text{IRM})/H_{ex}^2$.

h: a stationary magnetic field which produces IRM whose intensity is equal to I_n.

$\tilde{H}_0'$: AF-demagnetization field to reduce IRM acquired by h to e^{-1} of its initial value.

These parameters are summarized in Table 3. As shown in Figs. 7 (a)-(d), the

Table 3. Characteristics of NRM of Yamato (a)-(d) meteorites.

Parameter	Yamato meteorites					Unit
	(a)	(b)	(c-1)	(c-3)	(d)	
I_n	3535	15.4	1005	3764	567	$\times 10^{-6}$emu/gm
I_n^0	92	23.4	290	2124	224	$\times 10^{-6}$emu/gm
$\tilde{H}_0$	6	240	82	140	41	Oe. rms
$\tilde{H}^*$	150	250	150	250	125	Oe. rms
b	4.8×10^{-5}	2.0×10^{-8}	1.5×10^{-6}	1.6×10^{-6}	5.2×10^{-5}	emu/gm/Oe^2
h	9.3	26.5	23.5	44.0	3.1	Oersteds
$\tilde{H}_0'$	2.2	13.0	7.0	11.5	1.1	Oe. rms
I_V/I_O	0.03	0	0.15	0.12	$<10^{-3}$	
Average exposure age	1.5 ± 0.2	33 ± 2	24 ± 1		4.9 ± 0.6	m. y.

intensity of NRM of Yamato (a) and (d) meteorites decreases sharply and its direction changes considerably with an increase of the AF-demagnetization field from zero to several tens of Oersteds, rms. This soft component of NRM, which can be easily demagnetized by the weak AF-demagnetization field, may be considered an IRM which has been acquired in the geomagnetic field. For these two samples, therefore, $\tilde{H}^*$ is so defined that the observed direction of NRM is kept approximately invariant for the AF-demagnetization field from 15 Oe. rms to $\tilde{H}^*$.

As observed in Figs. 7 (a)-(d) and in Table 3, NRM of Yamato (a) and (d) meteorites is less stable than that of Yamato (b) and (c) meteorites. The instability of NRM of the two meteorites could be justified by their considerably small values of magnetic coercive fore (H_c) given in Table 2, and also by their very small values of h and $\tilde{H}_o'$ given in Table 3. These observed data of H_c, h and $\tilde{H}_o'$ of the two meteorites may suggest that the observed values of their NRM are considerably contaminated by IRM acquired in the geomagnetic and artificial magnetic fields before received by our magnetic laboratories. Actually, the principal ferromagnetic constituents in these two meteorites are metallic iron and kamacite which have negligibly small magnetic viscosity, as represented by the ratio of the viscos component (ΔI_v) to the stable component of IRM acquired in h in magntic field, given in Table 3. These experimental results may indicate that the largest parts of ferromagnetics in these meteorites are multidomain metallic grains.

Compared with Yamato (a) and (d) meteorites, Yamato (b) and (c) meteorites have a reasonably stable NRM. As shown in Fig. 7 (b), the AF-demagnetization curve of Yamato (b) meteorite shows a little complicated change for the AF-demagnetization field less than 100 Oe. rms. This anomalous change might be interpreted as due to the magnetic interaction between the two ferromagnetic phases, which are clearly indicated in Fig. 5 (b).

As given in Table 3, the observed intensity of RNM of Yamato (b) and (c) meteorites could be acquired as IRM in a magnetic field of several tens of Oersted. However, the stability of their NRM is extremely higher than that of their IRM of the same intensity as NRM, as indicated in comparison of $\tilde{H}_o$ with $\tilde{H}_o'$ in Table 3. On the other hand, Fig. 8 illustrates a relationship between the intensity of a steady magnetic field (H_{ex}) to produce an IRM and the average (root-mean-square) intensity of the AF-demagnetization field ($\tilde{H}_o$) to reduce the IRM to 1/50 of its initial value, for Yamato (a)-(d) meteorites. The approximately linear relation between $\tilde{H}_o$(Oe. rms) and H_{ex} (Oersteds) in Fig. 8 is represented by $\tilde{H}_o = \sqrt{2} H_{ex}$, which indicates that IRM acquired in a magnetic field of H_{ex} can be almost completely demagnetized by the AF-demagnetization process only when the peak intensity of alternating magnetic field ($\tilde{H}$) exceeds H_{ex}. Then, the observed stable NRM of Yamato (b) and (c) meteorites could be acquired as IRM only if H_{ex} exceeds about 400 and 350 Oersteds respectively. As represented by h-values in Table 3, however, their NRM intensities are equivalent to IRM values acquired in 20~40 Oersteds of H_{ex}. Further, the viscous component of IRM acquired by h, which is represented by ΔI_v in Table 3, is very small in

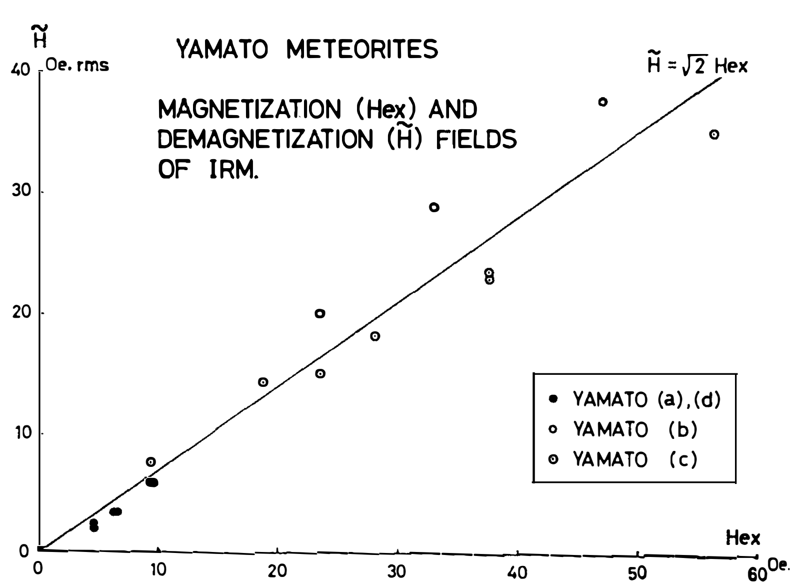

Fig. 8. Correlation between the magnetization field to produce IRM (H_{ex}) and the AF-demagnetization field to reduce the IRM intensity to 1/50 of the initial value.

comparison with its stable component (I_0), so that the observed NRM may not be attributable to the stable component of IRM acquired in a strong magnetic field of several hundreds of Oersted in intensity.

As Yamato meteorite samples have never been exposed to such a strong magnetic field since the time when they were collected on the surface of Antarctic ice sheet, and as the AF-demagnetization curves of Yamato (b) and (c) meteorites well resemble that of TRM of chondritic meteorites (*e. g.* WEAVING, 1962), it seems most likely that the observed stable NRM of Yamato (b) and (c) meteorites is of the TRM origin. At present, however, no further experimental study of this problem is possible for Yamato (a)-(d) meteorites.

The coercivity of NRM of Yamato (a)-(d) meteorites could be considered from a completely different viewpoint. The average values of Ne- and He-exposure ages of these four meteorites are summarized in Table 3, where $\tilde{H}_0$ values to represent the stability of NRM against the AF-demagnetization are in a good positive correlation with the exposure ages. BUTLER and COX (1971) have suggested on the basis of the results of laboratory experiments of neutron irradiation of metallic iron and kamacite, that the cosmic-ray exposure may be capable of converting soft IRM in meteorites and lunar samples to remanence with a higher coercive force. For three meteorites, Yamato (a), (b) and (d), in which metallic iron and/or kamacite are the main ferromagnetic constituents, the relationship between $\tilde{H}_0$ and the exposure age is almost linear, whereas $\tilde{H}_0$-value of Yamato (c) meteorite whose magnetization is due to magnetite is a little deviated from the linear relationship. As far as those magnetic and exposure age data of the four Yamato meteorites are concerned, therefore, it seems very likely that the suggestion made by BURLER and COX can be reasonably well supported.

5. Concluding Remarks

This note gives results of a preliminary study on the magnetic properties of a large number of meteorites which have been collected on the surface of ice sheet within a very limited area near the Yamato mountain range in East Antarctica. In the area, nine pieces of meteorite were collected in 1969. Then, a special program to find meteorites in the particular area started in 1973, collecting eleven pieces of meteorite. In 1974, more than 600 pieces have been collected. These meteorites have been named "Yamato meteorites".

Only four typical pieces of Yamato meteorites, which were collected in 1969, have been studied for their petrological, chemical and magnetic properties. They are two ordinary chondrites, a carbonaceous chondrite and an achondrite. As far as the petrological and chemical characteristics of these four meteorites are concerned, they are nothing particular compared with those of many other meteorites which have been reported to date.

In regard to their magnetic properties, the main ferromagnetic constituents of two ordinary chondrites, Yamato (a) and (d) meteorites, and an achondrite are NiFe alloys, whereas a carbonaceous chondrite contains only magnetite as the main ferrimagnetic constituent. These results of magnetic studies are in approximate agreement with those of the petrological and chemical analyses of these meteorites.

An interesting result is concerned with the coercivity of NRM of these four meteorites. Namely, the coercivity of their NRM is approximately proportional to their cosmic-ray exposure age. This result seems to support the idea of BUTLER and COX (1971) that IRM of a meteorite acquired in a temporary interplanetary magnetic field of several tens of Oersted in intensity could be converted to remanence of higher coercive force by the production of lattice damage in ferromagnetic or ferrimagnetic minerals caused by the cosmic-ray exposure for a certain long time.

Since a large number of meteorite have been collected in a limited area in Antarctica where no or very little artificial disturbance has ever existed, the problem of a possible relationship between the coercivity of NRM and the exposure age can be examined with a much larger number of meteorites.

In the course of the present magnetic studies of Yamato meteorites, the authors are much indebted to Dr. M. SHIMA for chemical data and to Dr. K. YAGI and Dr. H. TAKEDA for petrological data of these meteorite samples. The authors' thanks are due to them.

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