NOTES ON MAGNETIC PROPERTIES OF ANTARCTIC POLYMICT EUCRITES

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Abstract: The magnetic properties of 3 newly collected Antarctic polymict eucrites, Yamato-75011, -790122 and -790266 are examined. The measured magnetic properties are characteristics of magnetic hysteresis curves and thermomagnetic curves in comparison with chemical compositions of opaque minerals contained in these polymict eucrites.

The ferromagnetic characters of Yamato-75011 are due to Ni-poor kamacite grains which are common in many other eucrites. However, the origin of magnetic characters of Yamato-790122 and -790266, represented by their Curie point at 540°C, is still unidentified, because opaque minerals in these two eucrites are only almost stoichiometric ilmenite and troilite, no metallic grain nor magnetite being detected.

1. Introduction

The magnetic properties of achondrites have been very little known, partly because rather few number of achondrite were recovered in the past and partly because precise measurements of weak magnetizations of eucrites, howardites and diogenites were experimentally difficult. In a previous paper (NAGATA, 1980), 17 Antarctic achondrites are magnetically classified into 3 groups; namely, diogenites, ureilites and another group of eucrite+howardite+shergottite. Magnetic properties of 5 Antarctic eucrites (Yamato-74159 and -74450, Allan Hills-765, -77302 and -78040) are characterized by a very small content of magnetic metal, *i.e.* 0.006–0.11 wt% which are magnetically represented by 0.012–0.22 emu/g in saturation magnetization moment (I_s), and an absolutely high relative content of Ni-poor kamacite component (80–100%) in the magnetic metal grains. All these five Antarctic eucrites are polymict eucrites (DELANEY *et al.*, 1983).

More number of polymict eucrites have been recovered from Antarctica since then. In the present work, characteristics of the magnetic hysteresis curves measured in a magnetic field range between -16 kOe and 16 kOe at room temperature and the thermomagnetic curves of saturation magnetization of Yamato-75011, -790122 and -790266 polymict eucrites will be analyzed in comparison with the microprobe analysis data of chemical compositions of opaque minerals contained in them.

2. Magnetic Properties of Eucrites

The saturation magnetization moment (I_s), saturated isothermal remanent magnetization (I_R), coercive force (H_c) and remanence coercive force (H_{RC}) at room

Table 1. Magnetic properties of Antarctic polymict eucrites.

Eucrite Sample	I_s (emu/g)	I_R (emu/g)	I_R/I_s	H_c (Oe)	H_{RC} (Oe)	Θ_c (°C)
Yamato-74159	0.061	0.0040	0.066	265	420	750
-74450	0.215	0.0044	0.020	58	70	758
-75011	0.084	0.0035	0.042	60	390	730
-790122	0.012	0.0016	0.133	45	550	538
-790266	0.0075	0.0013	0.172	24	240	538
Allan Hills-765	0.076	0.0009	0.012	15	—	750
-77302	0.017	0.0017	0.100	42	780	{740 585
-78040	0.083	0.0072	0.087	90	560	750

temperature (20–25°C) of Yamato-75011, -790122 and -790266 eucrites are summarized in Table 1 together with those of the five Antarctic eucrites which have already been reported (NAGATA, 1980). In the same table, ratio I_R/I_s for each eucrite sample is listed.

It is known (*e.g.* NAGATA, 1961) that there is an approximate relationship between I_R/I_s and H_c of natural rocks which consists of a large number of ferromagnetic grains dispersed in non-magnetic matrix as given by

$$\frac{I_R}{I_s} \simeq \frac{H_c}{NJ_s^\circ}, \tag{1}$$

where N and J_s° denote respectively the average demagnetizing factor and the average saturation magnetization moment per unit volume of the ferromagnetic grains.

In cases of terrestrial volcanic rocks ejected from a volcano at the time of its one sequence of activity, it has been observed that (I_R/I_s) is approximately proportional to H_c, because N is roughly constant owing to a randum orientation of ferromagnetic grains of irregular granular shape and J_s°, which is mostly dependent on chemical composition of the magnetic grains, also is nearly constant so that NJ_s° is approximately constant. On the other hand, H_c and I_R are generally structure-sensitive parameters of ferromagnetic materials dependent on anisotropic characteristics of stress distribution, shape and crystalline energy, so that H_c and I_R considerably widely vary even in a single large mass of igneous rocks.

It will be noted in Table 1 that $H_c/(I_R/I_s) \simeq NJ_s^\circ$ of Antarctic polymict eucrites is not roughly constant but varies in a wide range from 200 to 4000 (in unit of Oe). For reference, the $H_c/(I_R/I_s)$ values range from 930 to 2800 for the ordinary chondrites (*e.g.* NAGATA and SUGIURA, 1976) and from 600 to 3500 for diogenites and ureilites (*e.g.* NAGATA, 1980). It has been confirmed, on the other hand, that the ferromagnetic components in these ordinary chondrites, diogenites and ureilites are mostly Fe-Ni metallic alloy, J_s° of which is about 1.5×10^3 emu/cm^3. Since the median value of $H_c/(I_R/I_s)$ for these ordinary chondrites and achondrites is about 2.5×10^3 Oe, the median value of N will be about 1.7, which appears to be a reasonable value as the demagnetizing factor for the average shape of metallic grains.

For polymict eucrites listed in Table 1, the calculated values of $H_c/(I_R/I_s)$ for Yamato-74159, -74450 and -75011 and Allan Hills-765 and -78040 are larger than

1×10^3 Oe, whence the major ferromagnetic components in these eucrites can be considered to be Fe-Ni metallic alloys. However, the $H_c/(I_R/I_s)$ values of Yamato-790122 and -790266 and Allan Hills-77302 are 338, 140 and 420 respectively, which appear to be too small to be identified to NJ_s° of Fe-Ni metallic grains. It seems very likely therefore that the major ferromagnetic components in these three eucrites are some ferromagnetic or ferrimagnetic minerals, the J_s° value of which is much smaller than that of Fe-Ni metallic alloy.

The thermomagnetic curves of Yamato-75011, -790122 and -790266 polymict eucrites measured in 10^{-5} Torr and in an external magnetic field (H_{ex}) of 10 kOe are shown in Figs. 1, 2 and 3 respectively, where $\chi_p H_{ex}$ indicates the paramagnetic magnetization component in each sample. The major magnetic transition temperatures, which can be considered to be identified to Curie points of respective eucrite samples, are listed in Table 1.

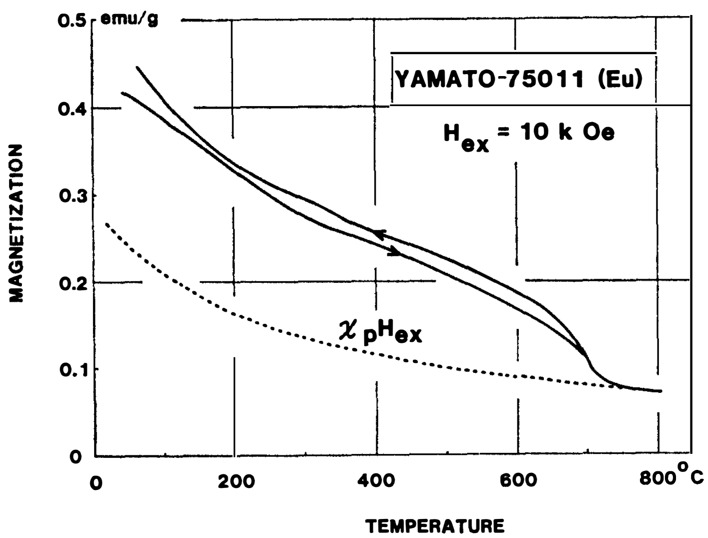

Fig. 1. First-run thermomagnetic curves of Yamato-75011 polymict eucrite.

For comparison with the present new data, the thermomagnetic curve of Yamato-74159 polymict eucrite, which has Curie point at 750°C, is shown in Fig. 4 (NAGATA, 1980). Both thermomagnetic curves of Yamato-75011 and -74159, which have Curie point at 750–760°C, indicate that their ferromagnetic components are mostly Ni-poor kamacite, in which Ni-content is less than 4 wt%. On the other hand, the thermomagnetic curves of Yamato-790122 and -790266 are thermally irreversible, the magnetization in the cooling process from 800°C becoming much larger than that in the initial heating process, though Curie point is kept at about 540°C. The second-run thermomagnetic curves of these two eucrite samples are nearly same as the first-run cooling thermomagnetic curve and approximately thermally reversible. As shown in Figs. 2 and 3, the heating thermomagnetic curves of Yamato-790122 and -790266 have the secondary magnetic transition at about 150°C and their cooling thermomagnetic curves also suggest the co-existence of a secondary magnetic component at temperatures below about 150°C.

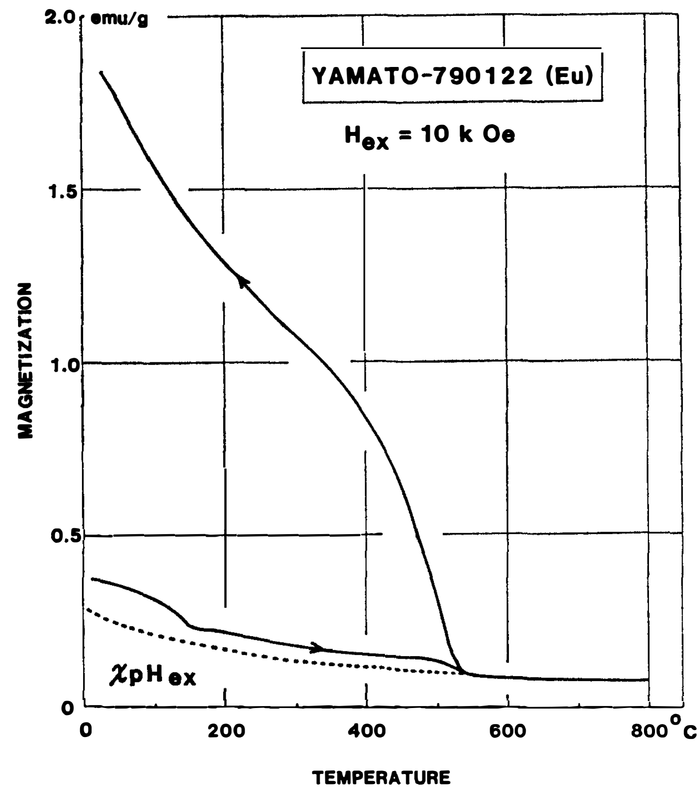

Fig. 2. First-run thermomagnetic curves of Yamato-790122 polymict eucrite.

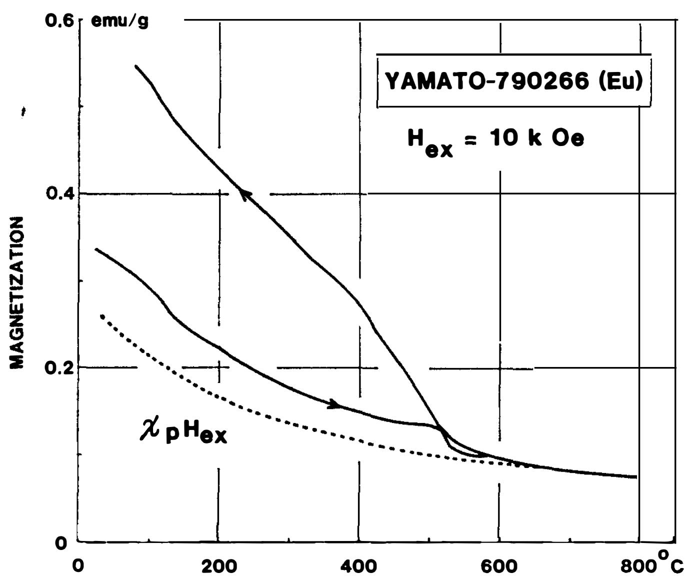

Fig. 3. First-run thermomagnetic curves of Yamato-790266 polymict eucrite.

The two magnetic phases having their magnetic transitions at about 540 and 150°C respectively are not magnetically identified to known ferromagnetic or ferrimagnetic minerals. It may be noted however that the thermomagnetic characteristics as well as

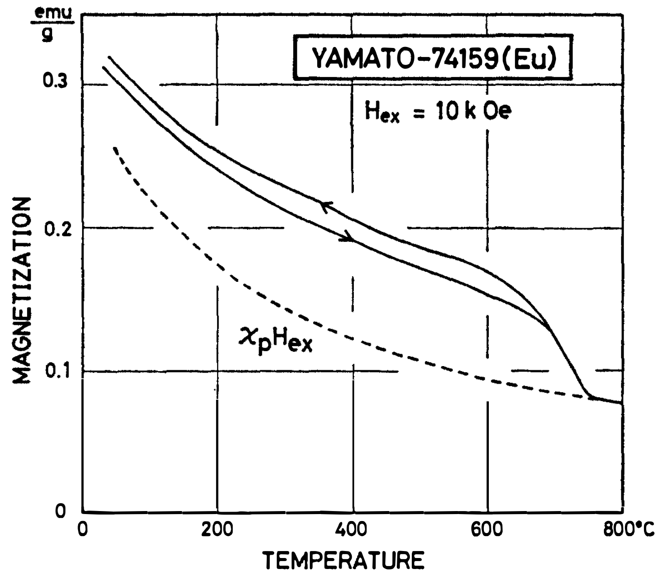

Fig. 4. First-run thermomagnetic curves of Yamato-74159 polymict eucrite for comparison with those of Yamato-75011.

the magnetic hysteresis characteristics of Yamato-790122 and -790266 are very similar to each other, but these magnetic characteristics are clearly different from the other polymict eucrites including Yamato-74159 and -75011.

3. Comparison with Chemical Compositions of Opaque Minerals

The magnetically observed magnetic phases of 730–760°C in Curie point in polymict eucrites can certainly be identified to Ni-poor kamacite containing small amounts of Co and P. However, the magnetic phases in Yamato-790122 and -790266 can not be simply identified. Then, Yamato-75011, -790122 and -790266 are examined with a reflection microscope for identifying opaque minerals contained in them and with a microprobe analyzer for determining chemical compositions of the opaque minerals. The results of measurements are summarized in Table 2.

The microprobe analysis (EPMA) is made for all oxides such as SiO_2, Al_2O_3, TiO_2, Cr_2O_3, NiO, MgO, FeO, MnO, CaO, Na_2O and K_2O and for atomic elements such as Fe, Ni, Co and S. Chemical compositions comprising selected components or elements, given in Table 2, may sufficiently well represent the chemical compositions of individual opaque minerals, as can be judged from the deviation of their sum from 100 wt%. For example, a possibility of identifying any listed opaque mineral to schreibersite, $(Fe, Ni)_3P$, can be rejected.

It will be obvious in Table 2 that the ferromagnetic properties of Yamato-75011 are due to kamacite grains of (98.7 wt%Fe, 0.5 wt%Ni and 0.5 wt%Co), which are close to pure metallic iron grains. Then, the content of the Ni-poor kamacite in Yamato-75011 is estimated to be only about 0.04 wt%. No metallic grains are detected and all examined opaque minerals are either ilmenite or troilite in Yamato-790122 and -790266. The chemical compositions of both ilmenite and troilite in Yamato-790122 are very

Table 2. Chemical composition of opaque minerals in three Yamato polymict eucrites.

Sample and mineral	Number of observed grain	TiO_2 (wt%)	FeO (wt%)	Fe (wt%)	Ni (wt%)	Co (wt%)	S (wt%)	Total (wt%)
(Y-75011)								
Ilmenite	4	54.94 (±0.45)	46.39 (±0.72)					100.33
Troilite	3			62.82 (±0.26)	0.001 (±0.00)	0.045 (±0.034)	35.97 (±0.27)	98.83
Metal	7			98.74 (±0.37)	0.49 (±0.04)	0.50 (±0.13)	0.02 (±0.01)	99.74
(Y-790122)								
Ilmenite	7	53.67 (±0.16)	45.85 (±0.63)					99.52
Troilite	8			63.64 (±0.47)	0.032 (±0.026)	0.14 (±0.10)	36.24 (±0.20)	100.06
(Y-790266)								
Ilmenite	4	53.57 (±0.23)	45.86 (±0.38)					99.42
Troilite	5			63.63 (±0.47)	0.025 (±0.014)	0.006 (±0.00)	35.53 (±0.27)	99.16

close to those in Yamato-790266, and further the chemical compositions of ilmenites in both the two eucrites are close to the stoichiometric $FeTiO_3$ and those of troilite in them are close to the stoichiometric FeS. Since the stoichiometric ilmenite is paramagnetic at room and higher temperatures, and the stoichiometric troilite is antiferromagnetic, it will be concluded that no ferromagnetic nor ferrimagnetic mineral grains can be detected in the present microscope search work, though certain ferro- or ferri-magnetic phases are cetrainly present in these two eucrites in the present magnetic analysis. Because of a limit for magnification by a reflection microscope and a limit of resolution of microprobe beam in the present study, opaque mineral grains larger than 30 μm in mean diameter only are examined, so that there is still a possibility that some ferromagnetic or ferrimagnetic mineral grains of 10 μm or less in mean diameter stand for the observed magnetic properties of the two Antarctic polymict eucrites.

A hypothesis that some portions of the observed troilite grains are deviated from stoichiometric FeS to have changed to the ferrimagnetic pyrrhotite phase may be difficult to be accepted for interpretation, because Curie point of pyrrhotite is 320°C, while the observed value of Θ_c is 540°C for the major magnetic phase. Another possible hypothesis may be that some titanomagnetite phases of TiO_2-FeO-Fe_2O_3 in chemical composition are contained as impurities in ilmenite grains, and the ferrimagnetic titanomagnetite phase becomes enriched by heating. In such a hypothesis, the chemical composition of titanomagnetite phase can not be much different from that of magnetite, Fe_3O_4, because the observed value of Θ_c is about 540°C (*e.g.* NAGATA, 1961).

If we assume that very fine grains of ferromagnetic or ferrimagnetic minerals are present in the two eucrites, even though we have not yet experimentally detected them, they could be ferrimagnetic titanomagnetites of about (95 mol%Fe_3O_4)·(5 mol%$TiFe_2O_4$) (NAGATA, 1961), or ferromagnetic taenite of about 55 wt%Ni (CRANGLE and HALLAM,

1963) because the observed value of Θ_c is about 540°C. The origin of ferro- or ferri-magnetic properties of Yamato-790122 and -790266 will have to be examined in more detail in the future by use of a high magnification electron microscope and a microprobe analyzer of high resolution power.

4. Some Discussions and Remarks

According to DELANEY *et al.* (1983), Yamato-74159, -74450 and -75011 may be fragments of a single meteorite, because their petrography and mode are very similar to one another. The Θ_c values of these three polymict eucrites also are similar to one another, indicating that their common ferromagnetic constituent is Ni-poor kamacite. Although the content of Ni-poor kamacite grains represented by I_s and the shape and inner stress distribution of kamacite grains represented by I_R, H_c and H_{RC} are considerably different in the three polymict eucrites, there is no essential difference with respect to the composition-sensitive magnetic properties of the three eucrites. Results of the present magnetic analysis show no objection so far to the suggestion given by DELANEY *et al.* (1983).

As far as the magnetic properties are concerned, Yamato-790122 and -790266 are very similar to each other, and their magnetic properties are essentially different from those of many other eucrites, the major magnetic constituent of which is Ni-poor kamacite. The opaque minerals detectable under a reflection microscope in these two polymict eucrites are only ilmenite and troilite, no metallic grains being observed, and the chemical compositions of the ilmenite and troilite grains are almost exactly same between the two eucrites. It appears very likely therefore that Yamato-790122 and -790266 are fragments of a single polymict eucrite.

In magnetic analyses of meteorites in the past, Fe-Ni metallic alloys accompanied by small amounts of Co and P, and Fe-Ni phosphide have been considered as the basic ferromagnetic components in meteorites except carbonaceous chondrites, and magnetite, pyrrhotite and Fe-Ni metallic alloys have been taken up as the basic ferrimagnetic or ferromagnetic constituents in carbonaceous chondrites. It appears that results of magnetic analyses of meteorites guided by such a basic idea are generally satisfactory in comparison with petrographical and mineralogical compositions and structures of respective meteorites. The present problem regarding the origin of ferro- or ferri-magnetism of Yamato-790122 and -790266 will be one of new problems in meteorite magnetism. As already mentioned, the observed value of $H_c/(I_R/I_s)$ of Allan Hills-77302 polymict eucrite is only 420 Oe, suggesting that its major ferromagnetic or ferrimagnetic component has a considerably smaller value of J_s° than that of Fe-Ni metallic alloy, and further the thermomagnetic curves of this eucrite consist of an additional magnetic phase having Curie point at 585°C in addition to the ordinary Fe-Ni metallic phase of 740°C in Curie point, as shown in Table 1. As Allan Hills-77302 polymict eucrite shows largely similar, though not entirely, magnetic behaviors as those of Yamato-790122 and -790266 regarding these points, it will be necessary to magnetically and mineralogically re-examine Allan Hills-77302 also in some more detail.

References

CRANGLE, J. and HALLAM, G. C. (1963): The magnetization of face-centered cubic and body-centered cubic iron-nickel alloys. Proc. R. Soc. London, Ser. A, **255**, 509–519.

DELANEY, J. S., TAKEDA, H., PRINZ, M. and NEHRU, C. E. (1983): Modal comparison of polymict eucrites from Yamato Mountains and Allan Hills, Antarctica with other basaltic achondrites (abstract). Papers presented to the Eighth Symposium on Antarctic Meteorites, 17–19 February 1983. Tokyo, Natl Inst. Polar Res., 41–43.

NAGATA, T. (1961): Rock Magnetism. Tokyo, Maruzen, 350 p.

NAGATA, T. (1980): Magnetic classification of Antarctic achondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 219–232.

NAGATA, T. and SUGIURA, N. (1976): Magnetic characteristics of some Yamato meteorites—magnetic classification of stone meteorites. Mem. Natl Inst. Polar Res., Ser. C (Earth Sci.), **10**, 30–58.

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