MAGNETIC PROPERTIES OF YAMATO-791197 IN COMPARISON WITH THOSE OF LUNAR HIGHLAND ANORTHOSITIC BRECCIAS

Takesi NAGATA and Minoru FUNAKI

National Institute of Polar Research, 9–10, Kaga 1-chome,
Itabashi-ku, Tokyo 173

Abstract: Magnetic properties of Yamato-791197 anorthositic breccia meteorite are compared with those of lunar highland anorthositic breccias and rocks such as Apollo 15418, 66055, 68815, 60016 and others.

Thermomagnetic curve characteristics of Y-791197 and all lunar anorthositic breccias and rocks show the coexistence of almost pure metallic iron and kamacite of about 5% Ni, associated with a small amount of taenite. The coexistence of almost pure metallic iron, which are primary lunar components and/or a product of the breakdown of Fe-bearing minerals such as fayalite caused by impact metamorphism, together with kamacite is very common in lunar surface materials. The coexistence of iron and kamacite has never been observed in achondrites and other stony meteorites. It is therefore highly plausible that Y-791197 is a fragment of lunar highland anorthositic material, which was explosively ejected from the lunar surface.

The specific paramagnetic susceptibility (χ_P) of Y-791197 ($\chi_P=(0.85\text{–}1.2)\times 10^{-5}$ emu/g/Oe at 300 K) is much smaller than that of ordinary achondrites, but very common for lunar anorthositic rocks and breccias. Ferromagnetic hysteresis behavior of Y-791197 has typical characteristics of lunar surface materials, which indicate the coexistence of superparamagnetically fine metallic iron particles. The NRM characteristics of Y-791197 also are in harmony with those of lunar highland anorthositic breccias and rocks.

1. Introduction

As pointed out by YANAI and KOJIMA (1984), chemical and mineralogical compositions of Yamato-791197 meteorite are considerably different from those of many other achondrites, but they are very similar to those of lunar highland anorthositic breccias. In Table 1, bulk chemical compositions of Y-791197 (YANAI and KOJIMA, 1984), Apollo 15418 (APOLLO 15 PRELIMINARY EXAMINATION TEAM, 1972), Apollo 66055 (MACKAY *et al.*, 1973), and Apollo 68815 (APOLLO 16 PRELIMINARY EXAMINATION TEAM, 1973) are summarized for intercomparison, where Apollo 15418 is a blocky, angular anorthositic breccia including white clast, Apollo 66055 is an anorthositic breccia with white matrix, and Apollo 68815 is a tough, medium dark gray anorthositic breccia including plagioclase-rich (90%) clasts.

In the consortium studies of Y-791197, comparisons of its chemical, petrological and mineralogical properties with those of lunar highland anothositic breccias will be undertaken by other workers. In the present study, ferromagnetic and paramagnetic characteristics of Y-791197 are examined in comparison with those of lunar highland

Table 1. Bulk chemical composition of Y-791197 and Apollo lunar highland anorthositic breccias (wt %).

	Y-791197(1)	ALHA-81005(2)	Apollo			Apollo 16 Breccias and soils(6)	
			15418(3)	66055(4)	68815(5)	(Max)	(Min)
SiO_2	43.14	46.46	44.97	45.1	45.10	45.38	44.14
TiO_2	0.35	0.23	0.27	0.9	0.49	0.67	0.09
Al_2O_3	26.01	25.32	26.73	23.2	27.15	33.19	26.22
Fe_2O_3	0.04	—	—	—	—	—	—
FeO	7.02	5.40	5.37	5.76	4.75	6.08	1.40
MnO	0.08	0.076	0.08	—	0.06	0.08	0.02
MgO	6.22	7.98	5.38	9.05	5.88	7.69	2.42
CaO	15.33	15.11	16.10	13.0	15.45	18.30	15.28
Na_2O	0.33	0.31	0.31	0.53	0.42	0.57	0.26
K_2O	0.02	0.29	0.03	0.27	0.14	0.14	0.01
P_2O_5	0.31	—	0.03	0.12	0.18	0.18	0.0
Cr_2O_5	0.13	0.12	0.11	0.16	—	—	—
S	0.41	—	0.03	—	—	0.09	0.01
Total	99.39*	101.04	99.41	98.2**	99.62		

(1) Yanai and Kojima (1984), (2) Palme *et al.* (1983), (3) Apollo 15 Preliminary Examination Team (1972), (4) MacKay *et al.* (1973), (5),(6) Apollo 16 Preliminary Examination Team (1973).

* In addition H_2O (−) 0.10, H_2O (+) 0.48, Ni 0.018, Co 0.003. Hence, total is 99.99,

** Average of crystalline matrices of 8 schreibersite-bearing clast.

anorthositic breccias. Apollo 15418, 66055 and 68815 are selected as being typical lunar highland anorthositic breccias, the bulk chemical compositions of which are approximately identical to the bulk chemical composition of Y-791197. In addition, two Apollo 16 lunar breccias, Apollo 60016 and 60255, whose bulk chemical compositions are roughly similar to those of Apollo 66055 and 68815, are magnetically examined for the purpose of additional intercomparison.

As described with maps and photographs *in situ* in the Apollo 15 Preliminary Science Report (1972), Apollo 15418 was collected from the summit of the subdued rim crest of the Spur Crater near Station 7 at the Apollo 15 landing site (03°39′20″E, 26°26′00″N). Although Apollo 15418 is described as a blocky, angular anorthositic breccia, it appears to be a shock-melted rock, probably derived from a high-Al and low-Fe basalt. This shock-melted anorthositic breccia is unique in texture as well as in chemical composition at the Apollo 15 landing site, where more basaltic rocks are dominant. Apollo 15418 is specifically selected for comparison with Y-791197, because it has been reported (*e.g.* Verkouteren *et al.*, 1983; Laul *et al.*, 1983) that petrological and chemical characteristics of Apollo 15418 are very similar to those of Allan Hills A81005 meteorite which also has been considered to be a lunar meteorite.

As described with maps and photographs *in situ* in the Apollo 16 Preliminary Science Report (1973), Apollo 66055 and 68815 were collected from Stations 6 and 8, respectively, both in the South Ray Crater which is about 2.8 km south of the Apollo 16 landing site (15°30′47″E, 8°59′34″S), while Apollo 60016 and 60255 were collected from the Apollo 16 lunar module landing site in the Descartes Highlands. It has been reported (APOLLO 16 PRELIMINARY EXAMINATION TEAM, 1973) that the bulk chemimal compositions of all chemically analyzed breccias (6 samples) and soils (11 samples) collected from the Apollo 16 landing site are approximately constant, as expressed by the maximam and minimum values of their chemical components in Table 1, and that there are good positive correlations between CaO and Al_2O_3 and between MnO and FeO, and negative correlations between MgO and Al_2O_3, between FeO and Al_2O_3, between TiO_2 and Al_2O_3, and between K_2O and Al_2O_3. The bulk chemical compositions of both Y-791197 and ALHA81005 are within the ranges of chemical components of these lunar highland anorthositic materials.

As for the ferromagnetic metal component of ALHA81005, the content of metallic iron was evaluated by ferromagnetic resonance and magnetic hysteresis methods to be 0.11 wt%, which is within the range of metallic iron content in Apollo 16 rocks and soils (MORRIS, 1983). Results of magnetic studies of lunar highland anorthositic breccias have given that metallic iron contents (m) in Apollo 15418, 60016, 60255, 66055 and 68815 are 0.067, 0.33, 0.47, 0.38 and 0.51 wt%, respectively (NAGATA *et al.*, 1973, 1974). In the present study, ferromagnetic and paramagnetic characteristics of both Y-791197 and Apollo lunar samples are comparatively studied with the aid of magnetic hysteresis and thermomagnetic analyses.

2. Ferromagnetic Composition

It has been reported (NAGATA, 1980) that the coexistence of apparently pure metallic iron (Fe° phase) and kamacite of several percent in Ni content (α phase) is fairly common in lunar surface materials, but such a coexistence of Fe° and α phases has never been observed in stony meteorites. The apparently pure metallic iron phase coexisting with kamacite in several lunar materials has been identified as the product of the breakdown of fayalite and other Fe-bearing minerals by subsolidus reduction caused by severe impacts upon the lunar surface (*e.g.* EL GORESY *et al.*, 1972). In Table 2, magnetically analyzed compositions of metallic component in lunar materials

Table 2. Ferromagnetic compositions of lunar materials and stony meteorites.

Fe-Ni phase	Lunar materials			Meteorites					
	Rock	Breccia	Soil	Chondrite			Achondrite*		
				H	L	LL	Ur	Di	Eu+Ho
Fe° alone	7	2	6	0	0	0	0	0	0
α alone	0	2	1	0	0	0	0	0	7
$\alpha+\mathrm{Fe}^{\circ}$	3	11	0	0	0	0	0	0	0
$\alpha+\alpha_2$	2	2	0	0	1	0	0	0	0
$\mathrm{Fe}^{\circ}+(\alpha+\gamma)$	0	0	0	0	0	0	0	3	0
$\alpha+(\alpha+\gamma)$	0	0	0	8	9	2	3	0	3
$\mathrm{Fe}^{\circ}+\gamma$	0	0	0	1	0	0	0	3	0
$\alpha+\gamma$	0	0	0	0	2	4	0	0	0
$\alpha+(\alpha+\gamma)+\gamma$	0	0	0	0	3	2	0	0	0
Total	12	17	7	9	15	8	3	6	10

* Ur: Ureilite, Di: Diogenite. Eu+Ho: Eucrite plus howardite.

(igneous rocks, breccias and soils separately), and in stony meteorites (H, L and LL chondrites and an achondrite group of ureilite, diogenite and eucrite plus howardite, separately) are statistically summarized, where α, $(\alpha+\gamma)$ and γ denote kamacite, plessite and taenite, respectively, and α_2 denotes the unequilibrated Ni-rich α_2 phase of b.c.c. structure. The symbol (+) means coexistence of the components of both sides of (+) symbol, namely $\alpha+\mathrm{Fe}^\circ$ indicates the coexistence of α and Fe° phases, for example.

As shown in Table 2, the coexistence of α and Fe° phases is common in lunar materials, particularly in lunar breccias, but it has never been observed in 51 stony meteorites containing Fe-Ni metallic grains, which have been magnetically examined by the authors to date. It may be further noted in Table 2 that the presence of Fe°, either Fe° alone or Fe° coexisting with α, is very common in lunar materials, suggesting that the original native iron in lunar materials is poor in Ni. On the contrary, the presence of Fe° is rare in stony meteorites, while the presence of kamacite, either α alone or α coexisting with $(\alpha+\gamma)$ and/or γ, is common in stony meteorites. As it is extremely difficult (*i.e.* almost impossible) to magnetically distinguish kamacite of less than 2 wt% in Ni content from pure Fe° metal, we cannot determine whether the Fe°

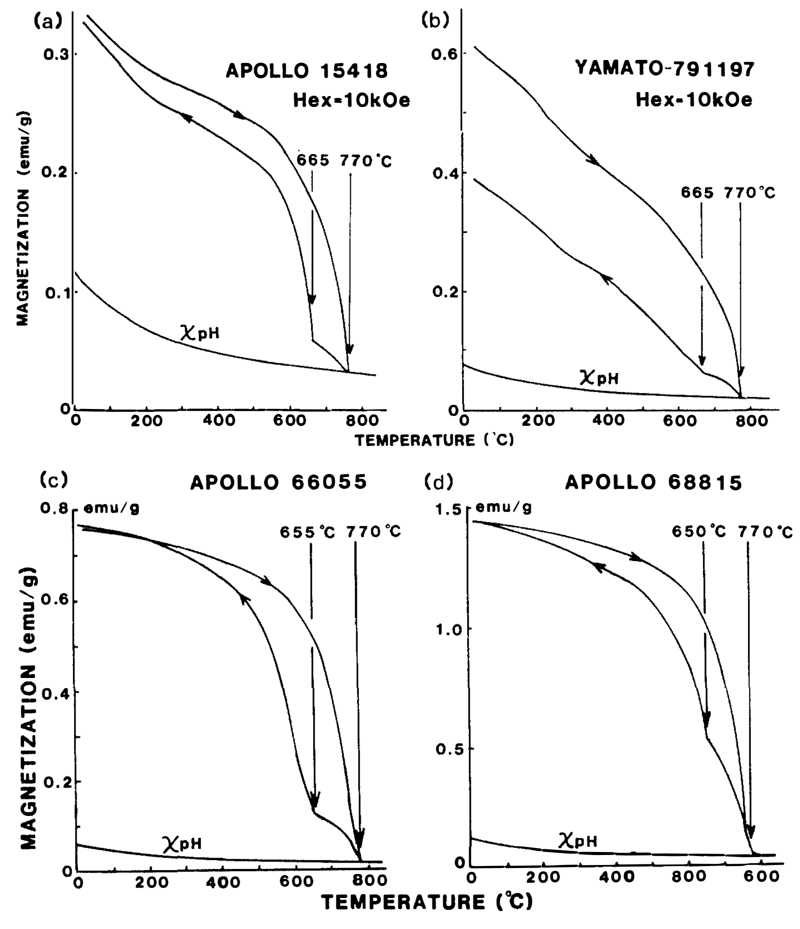

Fig. 1. Thermomagnetic curves of Yamato-791197 meteorite and Apollo lunar highland anorthositic breccias. (a) Apollo 15418 breccia, (b) Yamato-791197, (c) Apollo 66055 breccia and (d) Apollo 68815 breccia.

phase coexisting with plessite or taenite in some achondrites is pure Fe° metal or Ni-poor kamacite.

On the basis of the statistical result in regard to the coexistence of Fe° and α phases, as given in Table 2, ferromagnetic properties of Y-791197 are critically examined in comparison with Apollo 15418, 66055, 68815, 60016 and 60255 lunar breccias. Figures 1a–1d show the first-run thermomagnetic curves of Y-791197 and Apollo 15418, 66055, and 68815, respectively. All these heating-cooling cycles of thermomagnetic curve indicate that their ferromagnetic component consists of Fe° phase of around 770°C in Curie point (Θ_c) and α-phase of about 770°C in $\alpha\to\gamma$ transition temperature ($\Theta^*_{\alpha\to\gamma}$) in the heating process and 645–665°C in $\gamma\to\alpha$ transition temperature ($\Theta^*_{\gamma\to\alpha}$) in the cooling process, in addition to the paramagnetic component. General features of thermomagnetic curves of Apollo 60016 and 60255 are the same as those of Apollo 15418, 66055 and 68815 except for magnetization intensity and relative ratio of Fe°

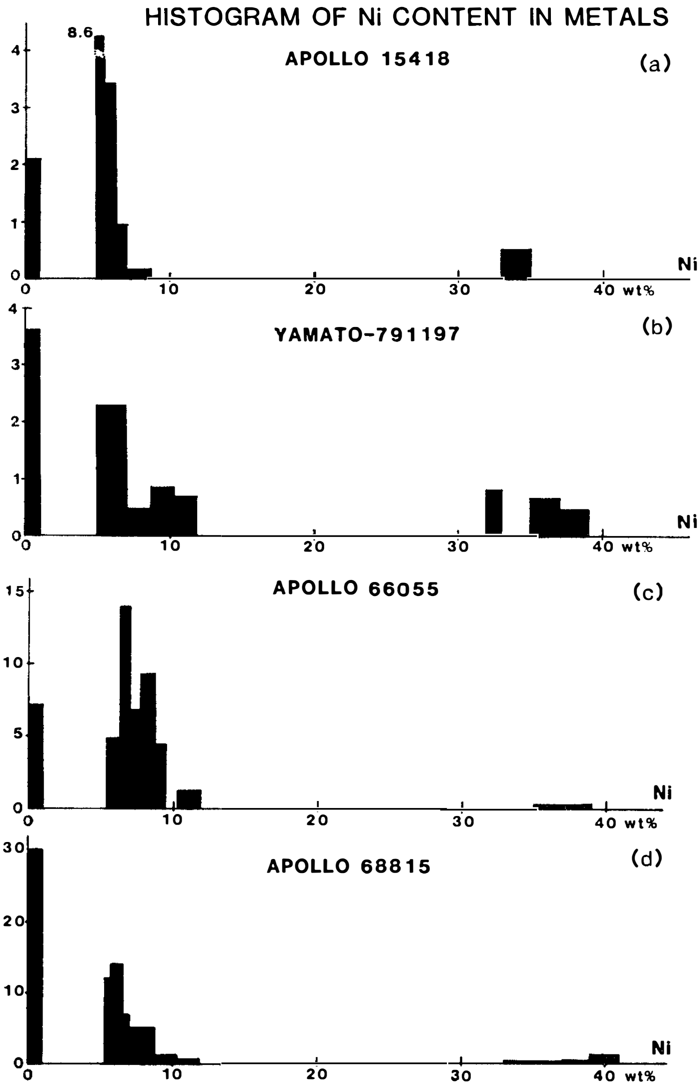

Fig. 2. Ni content spectra of metallic component in (a) Apollo 15418, (b) Yamato-791197, (c) Apollo 66055 and (d) Apollo 68815.

phase intensity to α phase intensity. The thermomagnetic curve characteristics of all these six samples are reproducible in the second-run measurement so that the observed Fe° and α phases are thermally stable.

With the aid of a numerical thermomagnetic analysis method (NAGATA *et al.*, 1974) using the standard cooling thermomagnetic curve of kamacite of given Ni content and the reversible thermomagnetic curves of taenite phase of given Ni content and Fe° phase, the spectrum of Ni content in kamacite and taenite phases in lunar materials and meteorites can be evaluated. Figures 2a–2d are obtained Ni content spectra in metals of Y-791197, Apollo 15418, 66055 and 68815, respectively. General features of the Ni content spectra of Apollo 60016 and 60255 are approximately similar to those of Apollo 66055. The Ni content spectra of the six examined samples comprise a sharp spectral line of Fe°, a spectral band extending from 5 to 8% Ni as the main component with a decreasing tail extension up to the α_2 region of more than 8%Ni, and a small amount of taenite around 35 wt% in Ni content. Table 3 summarizes the observed values of Θ_c of Fe°-phase, $\Theta^*_{\alpha\rightarrow\gamma}$ and $\Theta^*_{\gamma\rightarrow\alpha}$ of α-phase, weight content of metallic component (m), and percentages of Fe° ($m_{Fe°}$), kamacite (m_K) and taenite phases (m_T), in the metallic component for the six examined samples. In addition, the basic magnetic properties at room temperature (300 K) and liquid He temperature (4.2 K), where I_S, I_R, H_C, H_{RC} and χ_P denote respectively saturation magnetization, saturated isothermal remanent magnetization, coercive force, remanence coercive force and paramagnetic susceptibility, are also indicated in Table 3. As shown in Table 3, magnitudes of the basic magnetic parameters, I_S, I_R, H_C, H_{RC} and χ_P, of the lunar anorthositic breccias are somewhat different from the corresponding parameters of the two examined pieces of Y-791197 meteorite. However, the observed values of

Table 3. Magnetic properties of Y-791197 and five Apollo lunar breccias.

	Y-791197		Apollo lunar breccia				
	(a)	(b)	15418	60016	60255	66055	68815
I_s (300 K) (emu/g)	0.46	0.46	0.15	0.73	1.02	0.82	1.34
I_s (4.2 K) (〃)	0.88	0.80	0.47	0.99	1.40	1.05	1.30
I_R (300 K) (emu/g)	0.030	0.035	0.0013	0.0037	0.057	0.0064	0.0030
I_R (4.2 K) (〃)	0.158	0.148	0.018	0.010	0.210	0.010	0.032
H_C (300 K) (Oe)	49	62	11	19	47	20	12
H_C (4.2 K) (〃)	178	183	45	54	187	—	—
H_{RC} (300 K) (Oe)	450	680	—	—	670	400	350
H_{RC} (4.2 K) (〃)	460	570	—	—	—	—	—
χ_P (300 K) (emu/g/Oe)	1.2×10^{-5}	0.85×10^{-5}	1.4×10^{-5}	0.83×10^{-5}	1.7×10^{-5}	0.4×10^{-5}	1.4×10^{-5}
Θ_c (°C)	770		770	770	770	770	770
$\Theta_{\alpha\rightarrow\gamma}$ (〃)	770		770	770	780	770	770
$\Theta_{\gamma\rightarrow\alpha}$ (〃)	665		665	660	640	650	650
m (wt %)	0.21		0.07	0.33	0.47	0.38	0.61
$m_{Fe°}/m$ (〃)	25		20	30	47	18	48
m_K/m (〃)	54		71	70	53	81	42
m_T/m (〃)	21		9	(0–2)	(0–2)	2	10

these magnetic parameters of Y-791197 are within the respective ranges corresponding to the parameters of lunar anorthositic breccias.

A significant key point in the observed results is that almost pure metallic iron (Fe°) with a 770°C Curie point coexists with kamacite having $\Theta^*_{\gamma\to\alpha}$ values within a temperature range between 640 and 665°C which correspond to 5.8 and 5.0 wt% in Ni content. The coexistence of Fe° and α phases has never been observed in meteorites, as summarized in Table 2. Therefore it seems very likely that such a coexistence of Fe° and α phases can take place in lunar materials which have been strongly and repeatedly impact-metamorphosed at the lunar surface. The observed coexistence of Fe° and α phases in Y-791197 is a strong supporting evidence for its lunar surface origin. Various investigations have provided direct or indirect evidence for the production of metallic iron by subsolidus reduction of lunar surface materials, caused by severe meteorite impacts, such as for Apollo 61156 metaclastic rock (ALBEE *et al.*, 1973), 66095 metaclastic rock (EL GORESY *et al.*, 1973) and 68415 igneous rock (HELZ and APPLEMAN,

Table 4. Bulk chemical composition and basic magnetic properties of Apollo 61156, 66095 and 68415.

		61156	66095	68415
Chemical composition in wt %				
SiO_2		44.65	44.47	45.40
TiO_2		0.64	0.71	0.32
Al_2O_3		22.94	23.55	28.63
FeO		7.75	7.16	4.25
MnO		0.12	0.08	0.06
MgO		9.60	8.75	4.38
CaO		13.34	13.69	16.39
Na_2O		0.39	0.42	0.41
K_2O		0.11	0.15	0.06
P_2O_5		0.22	2.24	0.07
S		0.12	0.12	0.04
Total		99.88	99.34	100.01
Magnetic properties				
I_S (300 K)	(emu/g)	1.51	2.63	0.50
I_S (4.2 K)	(〃)	1.71	2.89	0.75
I_R (300 K)	(〃)	0.0030	0.0063	0.0030
I_R (4.2 K)	(〃)	0.015	0.011	0.0113
H_C (300 K)	(Oe)	7.5	7.5	16
H_C (4.2 K)	(〃)	32	12	49
H_{RC} (300 K)	(〃)	450	250	420
χ_P (300 K)	(emu/g/Oe)	1.7×10^{-5}	1.6×10^{-5}	1.0×10^{-5}
Θ_C	(°C)	770	770	770
$\Theta^*_{\alpha\to\gamma}$	(〃)	770	770	780, 700
$\Theta^*_{\gamma\to\alpha}$	(〃)	660	645	680, 395
Composition of metal				
m	(wt %)	0.69	1.21	0.30
m_{Fe°/m	(〃)	10	20	21
m_K/m	(〃)	90	80	38, 41
m_T/m	(〃)	(0–2)	(0–2)	(~0)

1973; Walker *et al.*, 1973). Bulk chemical compositions (Apollo 16 Preliminary Examination Team, 1973) and basic magnetic properties (Nagata *et al.*, 1973, 1974) of these three lunar anorthositic rocks are summarized in Table 4. The bulk chemical compositions of these igneous and metaclastic lunar rocks are close to those of Y-791197 and Apollo 16 breccias and soils (given in Table 1), and the magnetic properties of the former group are substantially the same as those of the latter group, Fe° phase and α phase coexisting in the metallic component. The kamacite phase of Apollo 68415 consists of α phase represented by $\Theta^*_{\alpha\to\gamma}=780°\text{C}$ and $\Theta^*_{\gamma\to\alpha}=680°\text{C}$ (4 wt%Ni kamacite) and α_2 phase represented by $\Theta^*_{\alpha\to\gamma}=700°\text{C}$ and $\Theta^*_{\gamma\to\alpha}=395°\text{C}$ (12 wt%Ni unstable kamacite) (see Nagata *et al.*, 1973 for details). It may thus be confirmed that the Fe° metal phase coexisting with kamacite is generally common on the lunar surface. It is, therefore, plausible that Y-791197 is a fragment of breccias which were produced in the lunar highland region where high-Al and low-Fe rocks, breccias and soils are very dominant.

3. Paramagnetic Susceptibility

The paramagnetic susceptibility (χ_P) of natural rocks is proportionally dependent on the contents of FeO, Fe_2O_3 and MnO in olivine, pyroxene, and other Fe-bearing silicate minerals (*e.g.* Nagata, 1961). The χ_P value of Y-791197 (given in Table 3) is unusually smaller than that of any other stony meteorite, but it is of the same order of magnitude as the χ_P values of lunar anorthositic rocks and breccias (given in Tables 3 and 4). As relative contents of Fe_2O_3 and MnO are much smaller than the FeO content in lunar materials, ordinary chondrites and achondrites, their paramagnetic susceptibility at room temperature can be theoretically approximated (Nagata, 1961; Nagata *et al.*, 1972) by

$$\chi_P(300\text{ K})=1.67\times10^{-4}\ m(\text{FeO})\quad \text{emu/g/Oe}\,, \tag{1}$$

where m(FeO) is the weight content of FeO. It has been reported (Nagata *et al.*, 1973) that the observed values of χ_P(300 K) of the Apollo lunar materials are in an approximate agreement with the theoretical estimate expressed by eq. (1) for a range of FeO from 3 to 25 wt%, but the observed values of χ_P(300 K) at room temperature are a little larger than their theoretical estimates in most cases, because of the coexistence of superparamagnetically fine grains of metallic iron. A similar test on the positive correlation between χ_P(300 K) and m(FeO) is carried out for 10 Antarctic achondrites, m(FeO) values of which range from 7.02 to 20.7 wt%. An empirical relationship between χ_P(300 K) and m(FeO) for the Antractic achondrites is evaluated as

$$\chi_P(300\text{ K})=(1.67\pm0.16)\times10^{-4}\ m(\text{FeO})\,, \tag{2}$$

which is in a good agreement with the theoretical estimate. The paramagnetic susceptibility, χ_P, can therefore represent the FeO content in the Antarctic achondrite meteorites.

In Fig. 3, histograms of the paramagnetic susceptibility at room temperature, χ_P(300 K), of 33 samples of the Apollo lunar materials and 19 samples of Antarctic achondrites are shown, where the darker shading on the lunar material histogram indicates the χ_P(300 K) values of lunar anorthositic igneous rocks, breccias, and soils,

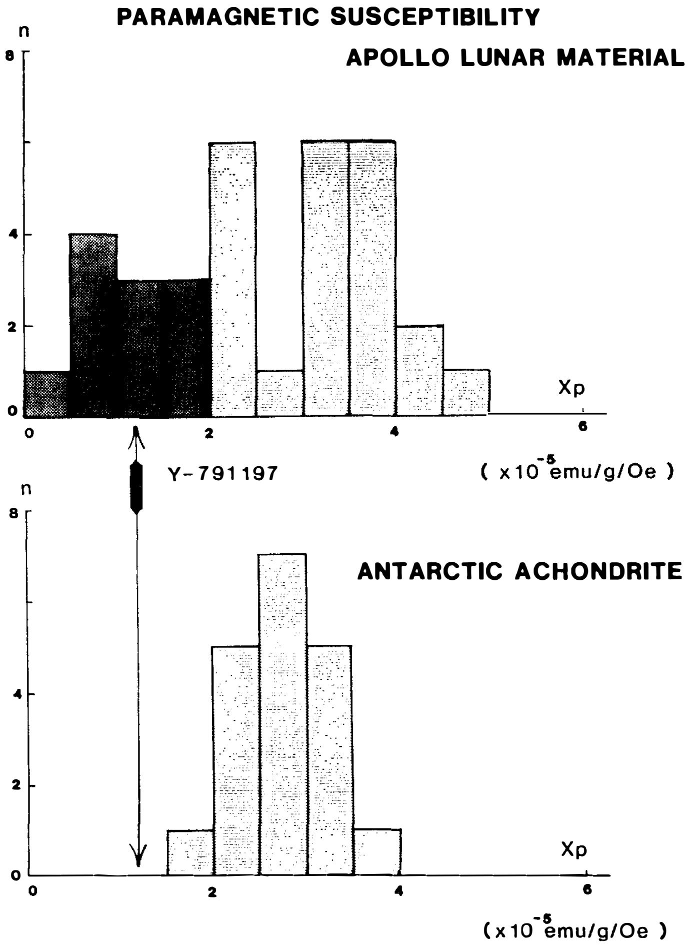

Fig. 3. Histograms of paramagnetic susceptibility at room temperature of Apollo lunar materials (top) and Antarctic achondrites (bottom).

while the examined Antarctic achondrite group covers eucrite, diogenite, howardite and ureilite. As indicated in Fig. 3, it is obvious that the paramagnetic characteristic of Y-791197 is similar to the lunar anorthositic materials and is distinctly different from the ordinary achondrites.

It must be noted here, however, that the Serra de Magé eucrite is an unusually high-Al and low-Fe achondrite, whose chemical composition is given by Al_2O_3 27.20%, Fe_2O_3 2.07%, FeO 4.79% and MnO 0.58% (MASON, 1962). The theoretical estimate of χ_P(300 K) of the Serra de Magé based on the chemical composition amounts to 1.22×10^{-5} emu/g/Oe, which is approximately same as the χ_P(300 K) value of Y-791197. Since the m(MnO)/m(FeO) ratio of the Serra de Magé is much different from the unique lunar material value (about 1/80), the Serra de Magé eucrite has not been considered as a lunar meteorite. Therefore, the observed fact that the χ_P(300 K) value of Y-791197 is different from the χ_P(300 K) range for ordinary achondrites but is within the range for lunar highland anorthositic materials may not be regarded as a very strong evidence for Y-791197 being a fragment of the lunar highland anorthositic materials. However, the χ_P(300) contrast lends support to the idea that Y-791197 may originate from lunar highland type materials.

4. Other Magnetic Properties

In addition to the thermomagnetic characteristics and the paramagnetic susceptibility, we considered additional magnetic properties to characterize the materials by the basic magnetic parameters, I_S, I_R, H_C and H_{RC}, which specify the ferromagnetic hysteresis character, and natural remanent magnetization (NRM) is also considered.

4.1. Ferromagnetic hysteresis characteristics

As summarized in Tables 3 and 4, the basic ferromagnetic hysteresis parameters, I_S, I_R, H_C and H_{RC}, of Y-791197 measured at room temperature (300 K) and at liquid helium temperature (4.2 K) are compared with those of several lunar anorthositic breccias and rocks. Both I_R and H_C increase considerably with a decrease in temperature from 300 to 4.2 K in Y-791197 as well as in the Apollo anorthositic breccias and rocks, and I_S also increases with a decrease in temperature from 300 to 4.2 K. The origin of the considerably large increase of I_S, H_C, I_R and I_R/I_S of lunar igneous rocks, breccias and soils associated with a decrease in temperature (in the cryogenic temperature range) has been studied in fair detail (Schwerer and Nagata, 1974, 1976). Results of these studies have shown that the observed increase of the magnetic parameters during the temperature decrease from 300 to 4.2 K is attributable to transitions from a superparamagnetic type behavior to a single domain type behavior in metallic iron phases, where the size distribution of the metallic particles is in an approximate range from 30 to 150 Å in mean diameter. Several possible processes have been proposed to account for a considerable amount of fine metallic particles in the lunar surface materials (Schwerer and Nagata, 1976, and the literature therein). All these plausible processes are caused, directly or indirectly, by repeated severe meteoritic impacts on the lunar surface.

Observed ratios $I_R(4.2\text{ K})/I_R(300\text{ K})=5.27$ and 4.23, $H_C(4.2\text{ K})/H_C(300\text{ K})=3.63$ and 2.95, and $[I_R(4.2\text{ K})/I_S(4.2\text{ K}]/[I_R(300\text{ K})/I_S(300\text{ K})]=2.75$ and 2.43 for Y-791197 samples (a) and (b) respectively are typical median values within the ranges of these ratios for the Apollo lunar surface materials. Ratios $I_S(4.2\text{ K})/I_S(300\text{ K})=1.91$ and 1.74 for Y-791197 are also within the range for the lunar surface materials.

Studies of the low temperature characteristics of meteorite magnetism have been started recently, so that only very little is known about the magnetic properties of stony meteorites at low temperatures. The ratios of magnetic parameters for 7 stony meteorites (L and LL chondrites) examined so far are

$$1.15 \leqq I_R(4.2\text{ K})/I_R(300\text{ K}) \leqq 3.43\,,$$
$$1.00 \leqq H_C(4.2\text{ K})/H_C(300\text{ K}) \leqq 2.20\,,$$
$$1.10 \leqq I_S(4.2\text{ K})/I_S(300\text{ K}) \leqq 2.04 \quad \text{and}$$
$$0.90 \leqq [I_R(4.2\text{ K})/I_S(4.2\text{ K})]/[I_S(300\text{ K})/I_S(300\text{ K})] \leqq 3.12\,.$$

It seems likely, therefore, that stony meteorites also contain fine metallic particles which behave superparamagnetically at room temperature. It could be provisionally stated at the present stage that the content of superparamagnetically fine metallic particles relative to ferromagnetic metals of larger grain size in Y-791197 is in a reasonable agreement with the lunar surface meterials, but it is not clear yet whether the content of fine metallic particles in Y-791197 exceeds the possible upper limit for ordinary stony meteorites, particulary achondrites.

4.2. *Natural remanent magnetization* (*NRM*)

The NRM of lunar igneous rocks and breccias are not stable during the AF-demagnetization, except a few special samples, mostly because of the presence of pseudo-superparamagnetically fine particles of metallic iron (*e.g.* NAGATA and CARLETON, 1970). If Y-791197 is a fragment of consolidated lunar surface material, it appears that for some reason the NRM has become magnetically harder than the NRM of the lunar surface breccias and rocks. Perhaps this is due to the additional large scale impact given at the time when the lunar meteorite was explosively ejected from the lunar surface. If there were a magnetic field when the impact took place on the lunar surface, ejected fragments might have acquired additional remanent magnetization either as a thermoremanent magnetization (TRM) or as a piezo-remanent magnetization (PRM). If there were no magnetic field, the NRM of the impacted lunar surface region might have been more or less shock-demagnetized (*e.g.* NAGATA, 1974). In any case, it seems likely that the NRM of Y-791197 is expected to be not magnetically softer than the lunar highland anorthositic rocks and breccias.

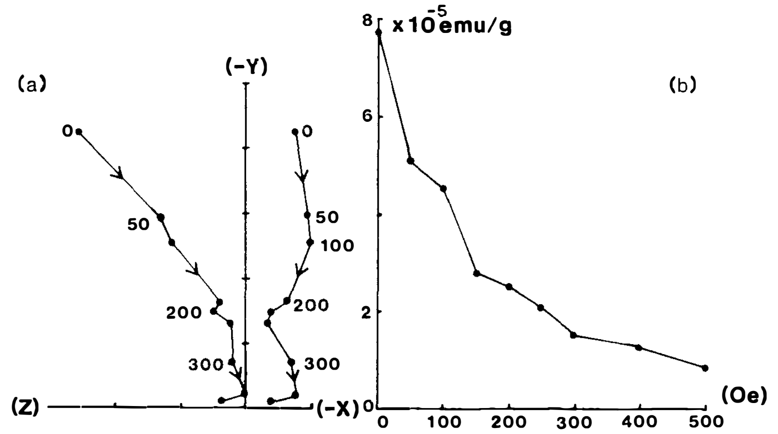

Fig. 4. AF-demagnetization characteristics of natural remanent magnetization of Y-791197. (a) X vs. Y, and Y vs. Z changes during AF-demagnetization. Numerals denote peak intensity of AF field in Oe. (b) AF-demagnetization curve of NRM intensity.

Figure 4 shows the AF-demagnetization characteristics of the NRM of Y-791197; *X* component *vs.* *Y* component and *Y* component *vs.* *Z* component to represent changes in the residual NRM direction on the left and the residual NRM intensity on the right. Parameters to represent the AF-demagnetization characteristics of the NRM of Y-791197 in comparison with those of 5 lunar anorthositic breccias and 3 lunar anorthositic rocks are summarized in Table 5, where I_n°, $I_n(100)$, $\tilde{H}(e^{-1})$ and $\tilde{H}^*$ denote respectively the initial intensity of NRM, NRM intensity after AF-demagnetizing up to 100 Oe peak, AF-magnetic field to demagnetize NRM to I_n°/e and the maximum AF-magnetic field to keep the direction of the NRM within 10° in angle from the initial orientation. Comparing the observed values of I_n°, $I_n(100)$, I_n°/I_s, $\tilde{H}(e^{-1})$ and $\tilde{H}^*$ of Y-791197 with those of 8 lunar anorthositic surface materials, it may be concluded that the NRM of Y-791197 is considerably harder than that of any lunar surface

Table 5. Characteristics of natural remanent magnetization of Y-791197 and Apollo lunar anorthositic breccias and rocks.

Sample		I_n° ($\times 10^{-6}$emu/g)	$I_n(100)$ ($\times 10^{-6}$emu/g)	I_n°/I_s ($\times 10^{-5}$)	$\tilde{H}(e^{-1})$ (Oe)	$\tilde{H}^*$ (Oe)
Y-791197		76.9	45.3	16.7	140	250
Apollo	15418	6.4	1.0	4.3	50	60
〃	60016	29.9	1.0	4.1	12	200
〃	60255	54.9	15.3	5.4	45	200
〃	66055	58.6	2.7	7.1	13	60
〃	68815	17.9	2.2	1.3	13	125
〃	61156	6.0	1.1	0.40	60	80
〃	66095	129.7	1.1	4.9	25	60
〃	68415	3.5	0.6	0.7	22	20

Remarks I_n°: Initial intensity of NRM.
$I_n(100)$: NRM intensity after AF-demagnetization by $H=100$ Oe peak.
$\tilde{H}(e^{-1})$: AF-magnetic field to demagnetize NRM down to I_n°/e.
$\tilde{H}^*$: Maximum AF-magnetic field to keep the direction of residual NRM within 10° in angle from the initial orientation.

materials having similar petrological and chemical compositions. Although it is not decisive, this conclusion is in favor of the idea that Y-791197 came from the lunar surface when a cratering event on the lunar surface took place by a meteorite impact.

5. Concluding Remarks

In addition to various lines of petrological and chemical composition evidence, the magnetic properties also support an interpretation that Y-791197 meteorite originated from the lunar anorthositic highland materials. In particular, the coexistence of pure metallic iron phase (Fe°) with kamacite phase (α) of 5–8 wt%Ni in Y-791197 may be regarded as a fairly decisive fact to support the idea of the lunar surface origin of this unique meteorite. Other magnetic properties of Y-791197, such as its paramagnetic susceptibility, ferromagnetic hysteresis behaviors and the NRM characteristics also present a similarity to the respective characteristics of lunar highland anorthositic rocks and breccias.

Although it is believed certain that Y-791197 originated from the lunar highlands, there still remains a problem as to where in the lunar highlnd religions Y-791197 came from. As far as the basic magnetic properties and the NRM characteristics are concerned, it seems that Apollo 60255 is closest to Y-791197.

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