VISCOUS MAGNETIZATION AND FERROMAGNETIC COMPOSITION OF STONY METEORITES AND LUNAR MATERIALS

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***Abstract*:** Effects of the shock metamorphism on stony meteorites are compared with those on lunar materials with respect to (a) the viscous magnetization which represents a relative abundance of superparamagnetically fine metallic grains produced by the explosive shock metamorphism and (b) the magnetic phase composition of metallic nickel-irons which represents effects of their remelting (or reheating up to about 1000°C) followed by rapid cooling caused by the shock metamorphism.

Experimental results show that the Type (II) viscous magnetization, which gives the presence of superparamagnetic metallic grains more than 1/4 of total metal, is observed in almost all lunar fines and breccias but none of stony meteorites possesses the Type (II) viscous magnetization, and that almost all stony meteorites are still maintaining a magnetic phase composition resulted from a slow cooling of a metallic melt, approximately keeping the phase equilibrium condition, whereas the majority of lunar materials, particularly lunar breccias, contain the secondary products of a remelting (or a reheating) followed by a rapid cooling such as α_2-phase of metallic nickel-iron, schereibersite, and pure metallic iron exsolved from Fe-bearing silicate minerals by the subsolidus reduction process.

These experimental results may lead to a conclusion that the lunar surface materials were seriously shock metamorphased probably owing to repeated meteorite impacts, whereas most stony meteorites have been subjected to much less shock effects than in the case of lunar materials.

1. Introduction

One of characteristic properties of lunar surface materials is the presence of a considerable amount of superparamagnetic and/or pseudo-superparamagnetic fine metallic grains, particularly in lunar fines and low-grade metamorphosed breccias (NAGATA and CARLETON, 1970; NAGATA *et al.*, 1972a,b, 1974a,b; SCHWERER and NAGATA, 1976). The abundant presence of the very fine metallic grains relative to the amount of larger metallic grains behaving ferromagnetic results in characteristic magnetic properties such as (a) a relatively large viscous magnetization component in the process of magnetization in a small or moderate magnetic field (say, $\lesssim$20 Oe), or a relatively large viscous remanent magnetization (VRM) in comparison with the steady isothermal remanent magnetization (IRM) acquired in a small or moderate magnetic field ($\lesssim$20 Oe), (b) a relatively large ratio of the initial magnetic susceptibility (χ_0) to the saturation magnetization (I_s) because of an addition of relatively large superparamagnetic susceptibility, and (c) a marked increase of saturation remanent magnetization (I_R) at temperatures below a critical temperature, at which the superparamagnetic character is blocked and consequently superparamagnetism is transfered to ferromagnetism. It has been proposed by NAGATA *et al.* (1972b, 1974b) that lunar materials can be classified into two groups, *i.e.* a group of igneous rocks and largely recrystallized breccias whose magnetic properties are mostly due to multidomain irons, having a weak magnetic viscosity (Type I), and the other group of lunar soils and low metamorphic grade breccias, which contain a significant fraction of metallic iron of single domain and superparamagnetic or pseudo-superparamagnetic size and therefore can acquire an anomalously large VRM (Type II). These very fine metallic grains in lunar soils and breccias are most likely to have been produced by explosive fragmentations by repeated meteoritic impacts on the lunar surface. On the other hand, the coexistence of kamacite and pure metallic iron in a number of lunar igneous rocks and breccias has been interpreted as due to the metallic iron produced by a subsolidus reduction of fayalite and other Fe-bearing silicate minerals owing to the shock metamorphism caused by meteoritic impacts in addition to the existing kamacite (HAGGERTY *et al.*, 1971; PEARCE *et al.*, 1972; ELGORSY *et al.*, 1972, 1973; ALBEE *et al.*, 1973; HAGGERTY, 1973; HARZ and APPLEMAN, 1973; WALKER *et al.*, 1973; HEWINS and GOLDSTEIN, 1974; BENCE *et al.*, 1973; TAYLOR *et al.*, 1973; NAGATA *et al.*, 1975; GIBBONS *et al.*, 1975). Kamacite can be clearly distinguished from pure or almost pure metallic iron by a thermomagnetic analysis, in which the thermally irreversible thermomagnetic curve of kamacite is characterized by an α–γ phase transition in the heating process and a γ–α phase transition in the cooling process, whereas the thermally reversible thermomagnetic curve of pure metallic iron has only Curie point as its magnetic transition. In a number of lunar breccias and some lunar igneous rocks, the coexistence of kamacite and almost pure metallic iron has been magnetically discovered (NAGATA *et al.*, 1975). Schreibersite, $(FeNi)_3P$, also is a ferromagnetic material of about 760°C of Curie point, magnetic properties of which are very similar to those of pure metallic iron. In a number of lunar material, schreibersites coexist with kamacites and the coexistence of schreibersite and kamacite has been experimentally demonstrated by rapidly cooling a melt of Fe-Ni-P system from 1350° to 900°C and keeping it at 900°C for 10^2 hours, then quenching to 550°C in a reduction atmosphere (MCKAY *et al.*, 1973).

It seems thus that the viscous magnetization in comparison with the stable ferromagnetic magnetization and the ferromagnetic composition, particularly the coexistence of ferromagnetizations of kamacite and almost pure metallic iron or schreibersite, of lunar materials can be reasonable measures for estimating the grade of their shock metamorphism in the past.

Since meteorites also should have been subjected to the shock metamorphism to a certain extent, the same approaches to examine the viscous magnetization and the ferromagnetic composition could be applied on stony meteorites for estimating the grade of their shock metamorphism.

2. Viscous Magnetization

Typical examples of the viscous decay with time (t) of lunar breccias of Type (II) VRM are shown in Fig. 1. In the figure, the remanent magnetization was acquired during 3×10^2 s in a magnetic field of 5 Oe and the ordinate value presents the total remanent magnetization, *i.e.* VRM plus IRM, normalized by the total remanent magnetization at $t=120$ s. In these lunar breccias possessing Type (II) VRM characteristics, IRM is extremely smaller than VRM for a small magnetizing field of less than 10 Oe in intensity. Noting then the intensities of VRM and IRM acquired by applying an external magnetic field (H_{ex}) during Δt in time and then putting in non-magnetic space during t in time by $I_v(\Delta t,\ t,\ H_{ex})$ and $I_0(H_{ex})$ respectively, a typical Type (II) VRM characteristic can be represented by

$$I_v(\Delta t,\ 0,\ H_{ex})\gg I_0(H_{ex}) \quad \text{for } H_{ex}\lesssim 10 \text{ Oe}, \tag{1}$$

where $I_0(H_{ex})$ assumes to be independent of Δt and t. However, eq. (1) does not directly represent that the total mass (m_v) of superparamagnetic or pseudo-superparamagnetic single-domain metallic grains is much larger than the total mass (m_I)

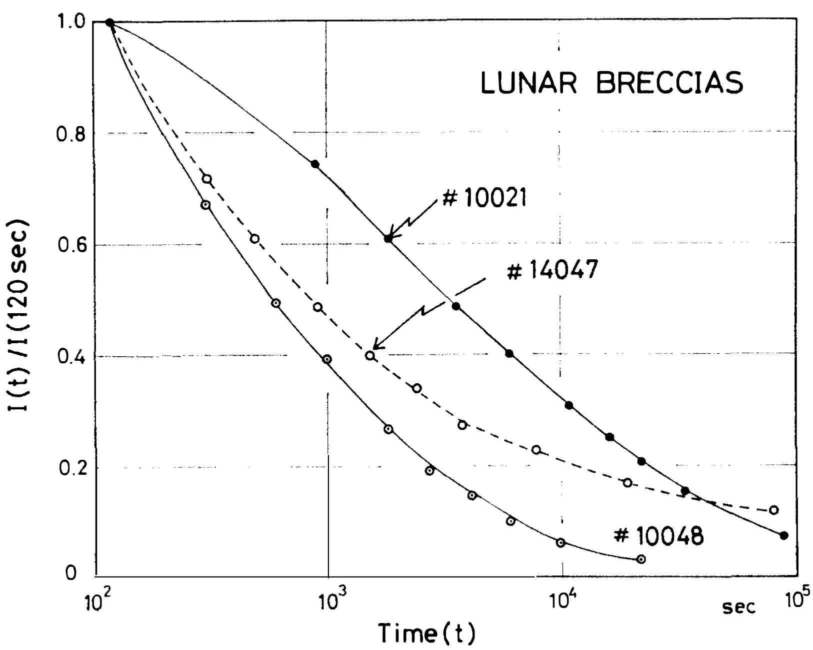

Fig. 1. Typical examples of Type (II) viscous remanent magnetization of lunar materials.

of multi-domain metallic grains which are mainly responsible for the stable IRM. It is because a ratio of $I_o(H_{ex})$ of multi-domain metallic grains to their saturation magnetization is much smaller than a ratio of $I_v(\Delta t,\ 0,\ H_{ex})$ of fine single-domain metallic grains to their saturation magnetization.

NAGATA *et al.* (1974b) have shown that the initial magnetic susceptibility (χ_0) of a mixture of multidomain grains and superparamagnetic single-domain grains can be approximately given by

$$\chi_0/J_s \simeq \frac{(1-\beta)}{\bar{N}J_s^\circ} + \frac{\beta}{3}\frac{\bar{v}J_s^\circ}{kT}, \tag{2}$$

where k, T, J_s, J_s°, $\bar{N}$ and $\bar{v}$ denote respectively Boltzmann constant, absolute temperature, the saturation magnetization of a sample per unit volume, the spontaneous magnetization of ferromagnetic grains, the mean demagnetizing factor of multi-domain grains and the mean volume of superparamagnetic grains, and β is a fraction of the superparamagnetic grains and $(1-\beta)$ is the remaining fraction of the multi-domain grains. The first and second terms of the right-hand side of eq. (2) represent the contribution of χ_0/J_s of the multi-domain component and the superparamagnetic one respectively. From the observed values of χ_0, J_s, $\bar{N}$ and $\bar{v}$, β-values of Apollo lunar breccias, 10021, 10048 and 14047, have been determined as 0.57, 0.26 and 0.28 respectively (NAGATA *et al.*, 1974a, b). Since, $(NJ_s^\circ)^{-1}\sim 1.7\times 10^{-7}$ and $(\bar{v}J_s^\circ/3kT)\sim 2\times 10^{-2}$ in c.g.s. emu in these cases, the contribution to χ_0/J_s of the superparamagnetic magnetization is much larger than that of the ferromagnetization of multi-domain component when $\beta\simeq 0.3$–0.6.

The superparamagnetic magnetization (J) of an assemblage of fine ferromagnetic grains of randam orientation of $\bar{v}$ in average volume and J_s° in spontaneous magnetization in a magnetic field (H) is theoretically given by

$$J(H,\ T) = \frac{n\bar{v}J_s^\circ}{2}\ \tanh\ (vJ_s^\circ\ H/kT), \tag{3}$$

where n denotes the number density of ferromagnetic fine grains in a unit volume. It has been demonstrated that the magnetization of lunar soils at various values of T can be well represented by eq. (3) for $H\leq 10^3$ Oe (NAGATA and CARLETON, 1970). However, the analysis with the aid of eq. (2) of three lunar soils have shown $\beta=0.35$, 0.28 and 0.33 for Apollo lunar fines 10084, 12071 and 14259 respectively (NAGATA *et al.*, 1974). These experimental results on lunar soils and breccias suggest that the magnetization characteristics of lunar materials possessing Type (II) VRM behave almost superparamagnetically if $\beta\geq 1/4$.

On the other hand, most lunar igneous rocks and largely recrystallized breccias have Type (I) VRM characteristics, which are defined by

$$I_v(\Delta t,\ 0,\ H_{ex}) < I_o(H_{ex}) \quad \text{for } H_{ex}\lesssim 10\ \text{Oe}, \tag{4}$$

and $\beta\ll 0.1$.

Table 1. VRM characteristics of stony meteorites and lunar materials.

VRM Type	Meteorites (n=14)				Lunar materials (n=21)		
	E	H	L	Achondrites	Rocks	Fines	Breccia
(I)	1	2	6	5	5	0	2
(II)	0	0	0	0	1	5	8
Total	1	2	6	5	6	5	10

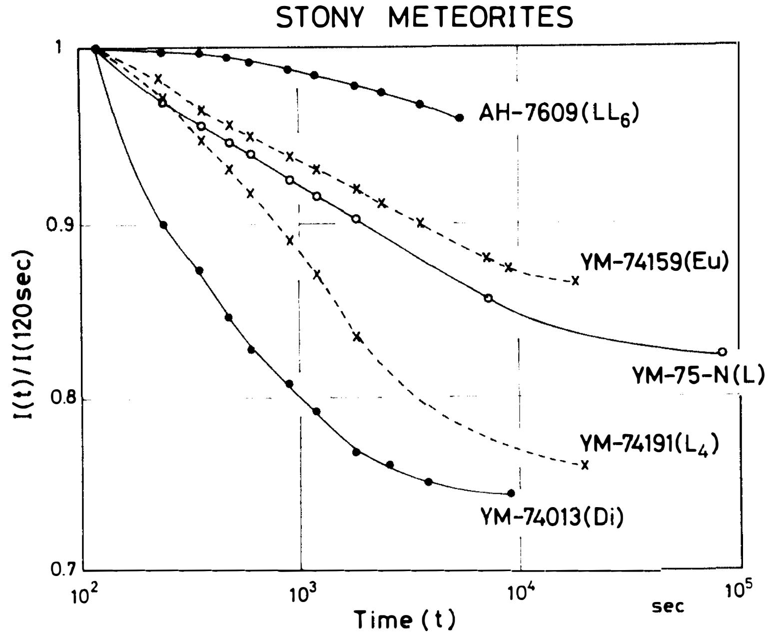

Fig. 2. Typical examples of Type (I) viscous remanent magnetization of stony meteorites.

In Table 1, VRM characteristics of 21 lunar materials are summarized. It will be obvious in the table that all lunar fines and most lunar breccias possess Type (II) viscous magnetization.

Fig. 2 shows 5 examples of VRM characteristics of Antarctic stony meteorites. In these examples, $I_v(\Delta t, 0, H_{ex})$ is always smaller than $I_0(H_{ex})$. VRM characteristics of 14 Antarctic stony meteorites summarized in Table 1 show that no stony meteorite possesses Type (II) VRM characteristics. χ_0/I_s values of 7 samples (1 E-chondrite, 2 H-chondrites, 2 L-chondrites, 1 howardite, 1 diogenite) among the 14 Antarctic meteorites have been examined to evaluate this β-value. The observed β-values range from 0 to 0.015, which suggest that they should be classified into Type (I) in terms of VRM characteristics. It may thus be concluded that no stony meteorite having Type (II) VRM characteristics has yet been detected.

In regard to the relatively abundant presence of superparamagnetically fine metallic grains in lunar soils and breccias, various possible processes to account for their production have been proposed. These possible processes are such as the subsolidus reduction by annealing in thermal blankets (PEARCE *et al.*, 1972), the reduction during impact heating of soils previously saturated with solar-wind implanted hydrogen (HOUSLEY *et al.*, 1973), the precipitation of metallic iron during meteoritic shock events (CISOWSKI *et al.*, 1973; SCLAR *et al.*, 1973), the dissemination of meteoritic metal as fine particles during impact (GIBBONS *et al.*, 1975; MORRIS *et al.*, 1975) and a solar-wind sputtering and vapor deposition following meteoritic impact vaporization (HAPKE *et al.*, 1975). Each possible process suggested above is a result of meteoritic impacts on the lunar surface on the physical and chemical conditions of interplanetary space.

Then, the observed fact that no stony meteorite possessing Type (II) VRM characteristics has yet been found may suggest that stony meteorites, chondrites and achondrites, have never been subjected to a strong explosive shock metamorphism in their history.

3. Ferromagnetic Composition

The ferromagnetic composition and structure of metallic phase in lunar rocks and stony meteorites can be approximately determined by the thermomagnetic analysis of these extraterrestrial materials. A large number of lunar rocks have already been thermomagnetically annalyzed for such a purpose (NAGATA *et al.*, 1970, 1971, 1972a, b, 1973, 1974a, b, 1975). Figs. 3 and 4 are examples of the thermomagnetic curves (the first and second runs for each) of two lunar materials, Apollo 66055 (anorthositic breccia) and 77017 (anorthositic gabbro). In both cases, the thermally irreversible thermomagnetic curves are reproducible in laboratory time-scale. The thermomagnetic curve (TM-curve) of Apollo 66055 consists of a thermally reversible paramagnetic component ($\chi_p H$), a thermally reversible ferromagnetic component having Curie point (Θ_C) at 772°C and a thermally irreversible ferromagnetic component which is identified to a kamacite (α-phase) of 6% Ni. Similarly, the TM-curve of Apollo 77017 consists of a $\chi_p H$ component, a small amount of thermally reversible ferromagnetic phase of $\Theta_C=770$°C, and a group of α-phases having a broad spectrum of Ni-content. The highest value of $\alpha\rightarrow\gamma$ transition temperature in the heating curve is 735°C, and the highest value of $\gamma\rightarrow\alpha$ transition temperature in the cooling curve is 590°C, which correspond to a kamacite phase of about 8% in Ni-content. However, both $\alpha\rightarrow\gamma$ and $\gamma\rightarrow\alpha$ transitions are extended toward a lower temperature range in this sample. On the assumption that a thermomagnetic curve of such a lunar materials is an integration of elementary thermomagnetic curves of stoichiometric nickel-iron metals of various Ni-contents, the bulk spectrum of Ni-content in metallic nickel-iron can be estimated (NAGATA *et al.*, 1974a). The distribution spectra of Ni-content thus estimated for 66055

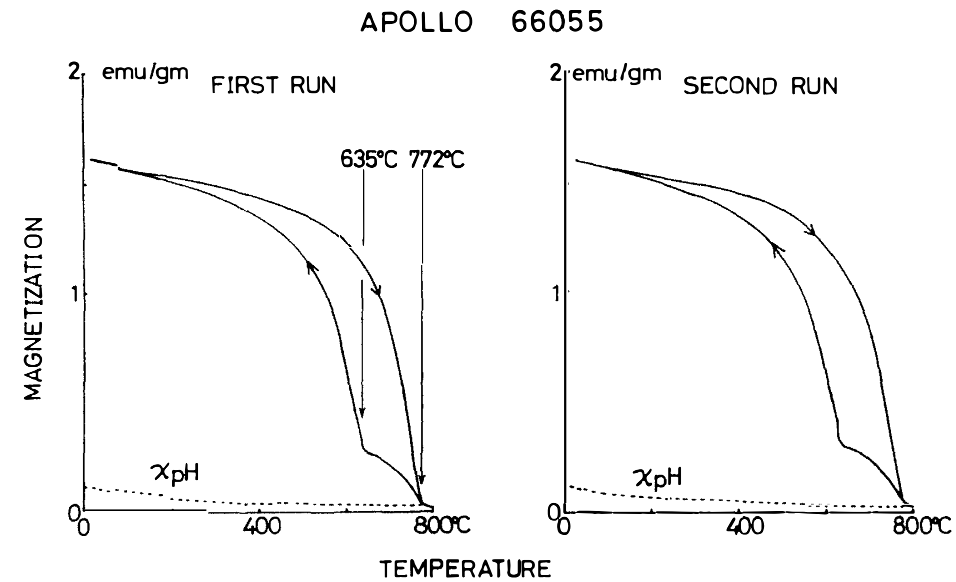

Fig. 3. *Thermomagnetic curves of a lunar anorthositic breccia (66055) which contains kamacite and schreibersite grains.*

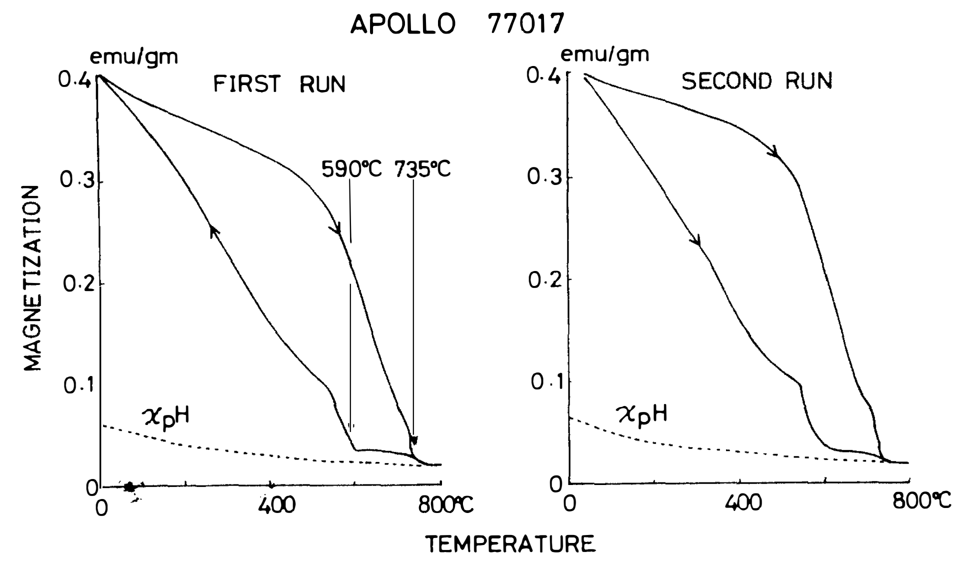

Fig. 4. *Thermomagnetic curves of a lunar anorthositic gabbro (77017) which contains both Ni-poor and Ni-rich metallic nickel-iron grains.*

and 77017 are illustrated in Fig. 5, together with those of two other lunar samples, 68415 (anorthositic gabbro) and 70017 (coarse basalt). In Figs. 6 and 7, the Ni-content spectra thus magnetically obtained are compared with the results of electron-microprobe analysis of Ni- and Co-contents in metallic grains (Taylor and Williams, 1974) for 77017 and 70017. Taking into consideration that the Ni-content spectrum

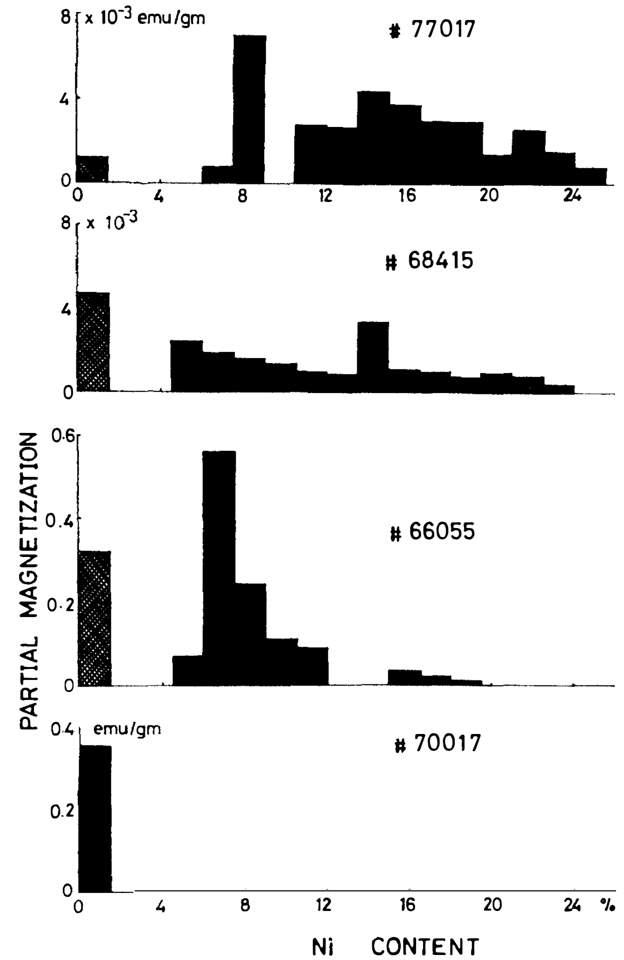

Fig. 5. Spectra of Ni-content in metallic nickel-iron in lunar materials, estimated from analyses of thermomagnetic curves.

derived magnetically is presented in terms of the saturation magnetization while the electron-microprobe analysis results are given in volume per cent, it may be concluded that results of the magnetic and electron-microprobe analyses are in reasonably good agreement with each other. In Figs. 5 through 7, kamacites of 3–7 wt% in Ni-content have the thermally irreversible thermomagnetic curves which show the $\alpha \rightarrow \gamma$ transition in the heating process and the $\gamma \rightarrow \alpha$ transition in the cooling process where the $\alpha \rightarrow \gamma$ transition temperature is definitely higher than the $\gamma \rightarrow \alpha$ transition temperature. This is the most characteristic behavior of α-phase of metallic nickel-iron whose Ni-content is less than 7 wt%. For Ni-poor kamacites whose Ni-content is less than 3 wt%, however, their thermomagnetic curves are thermally almost reversible and their Curie point is 760–770°C so that they can not be clearly distinguished from the pure metallic iron and from iron phosphide, Fe_3P, which has Curie point at 760°C in the present experimental technique. As shown

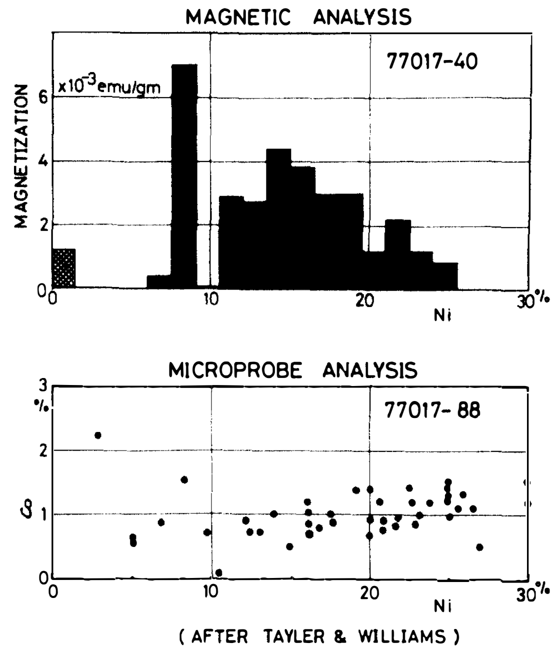

Fig. 6. Example of a comparison of Ni-content spectrun estimated from magnetic analysis with that obtained by electron-microprobe analysis (Sample: lunar anorthositic breccia 77017).

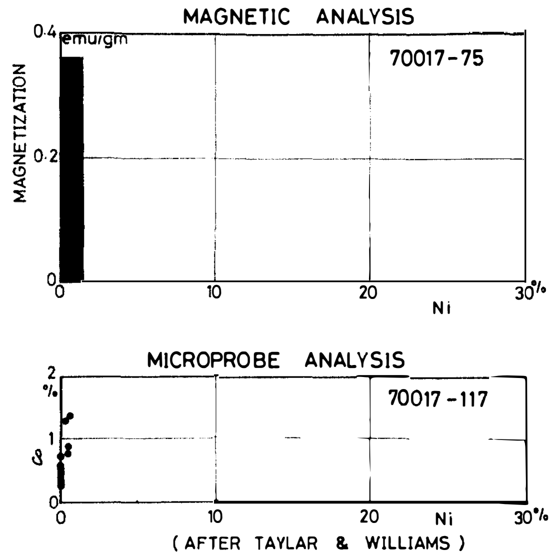

Fig. 7. Example of a comparison of Ni-content spectrun estimated from magnetic analysis with that obtained by electron-microprobe analysis (Sample: lunar basalt 70017).

in Fig. 5, this ferromagnetic phase whose magnetization is thermally reversible and whose Curie point is 760–770°C often coexists with a kamacite (α-phase) of 3–7 wt% in Ni-content in lunar materials. In order to distinguish the former ferromagnetic phase from α-phase, the former will be named *α_0-phase* in the present study.

Another ferromagnetic phase in lunar materials, whose thermomagnetic curves are thermally irreversible but their $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ transition temperatures are considerably lower than the corresponding values of their lower limits of α-phase can be identified to *α_2-phase*, which has the crystal structure of kamacite but Ni-content is beyond the upper limit for α-phase, and which can be formed by a diffusionless transformation from γ-state to α_2-state caused by a rapid cooling. In Fig. 5, both 77017 and 68415 have broad spectra of α_2-phase extending to about 20% in Ni-content in addition to α- and α_0-phases, whereas 66055 contains α_0- and α-phases and 70017 does only α_0-phase.

On the basis of petrological studies, McCallum *et al.* (1974) have concluded that 77017 is a metaclastic rock formed by subsolidus recrystallization of a breccia in a thick ejecta blanket and that all vestages of the original texture have been destroyed by repeated cycles of fragmentation, melting and recrystallization. Taylor and WILLIAMS (1974) also concluded that the metals in 77017 are somewhat similar to those in 68415 and may indicate a similar origin, *i.e.* impact-induced melted soil. WALKER *et al.* (1973) have suggested that 68415 is a crystallization product of a highly aluminous melt and its compositions were produced by partial or complete melting of lunar crustal materials. HARZ and APPLEMAN (1973) also reported that 68415 is very likely to have been produced by impact melting of soils and breccias containing more than one lunar rock types, followed by very rapid cooling. All these petrological and geochemical studies suggest that both 77017 and 68415 were reheated and then rapidly cooled down near the lunar surface. The magnetic result that the two lunar materials contain a large amount of α_2-phase may give the same conclusion, namely, that these two lunar gabbros were reheated up to about 1000°C and then rapidly cooled down, resulting in a diffusionless transformation from γ-state to α_2-state of their metallic nickel-irons.

Another problem is concerned with a possible origin of α_0-phase. Among 36 lunar materials whose thermomagnetic characteristics were examined, 16 samples contain a single ferromagnetic component of α_0-phase. Sample 70017, shown in Figs. 5 and 7, belongs to this group. The α_0-phase in some lunar materials has been identified to the pure metallic iron which was produced by a subsolidus reduction of fayalite and other Fe-bearing silicate minerals by severe meteorite impacts. Lunar sample 14053 is a typical example of such a case, containing a number of almost pure iron grains of breakdown product (ELGORESY *et al.*, 1972).

On the other hand, some lunar materials contain a considerable amount of schreibersite in addition to kamacite. 66055 is a typical example of such a case. According to MCKAY *et al.* (1973), 66055 contains spherical particles of kamacite up to 500 μm in diameter, which contain rounded inclusions of schreibersite reaching 20 μm in diameter, where Ni-content in kamacite phase is larger than 4% and Ni- and P-contents on average in schreibersite phase are 12 and 13% respectively. α_0- and α-phases of 66055, shown in Fig. 5, then correspond to the schreibersite and kamacite respectively. An exsolution of the schreibersite phase from a Fe-Ni-P system can take place at temperatures above 1000°C. There is a high possibility, therefore, that 66055 was reheated up to over 1000°C and then rapidly cooled, probably because of the impact metamorphism.

As shown in Table 2, among the magnetically examined 36 lunar materials, 18 samples contain α_0- or α_2-phases in addition to α-phase, and only 3 lunar samples contain α-phase metals alone. It is certain that most lunar breccias are products of the impact metamorphism caused by meteorite impacts on the lunar surface associated with the reheating effect. Then, the magnetically detected α_0-phase which coexists with α-phase metals in lunar breccias is attributable to either almost pure metallic irons produced by the subsolidus reduction or schreibersites exsolved from a P-rich FeNi system, both caused by the reheating effect due to the shock metamorphism. Those lunar surface materials, in which α_0-phase and/or α_2-phase coexists

Table 2. Ferromagnetic phases of metallic component in stony meteorites and lunar materials.

Metal phase	Meteorites (n=38)					Lunar materials (n=36)		
	Chondrites			Achondrites				
	H	L	LL	Di	Eu+Ho	Rocks	Fines	Breccia
α-phase								
α only	8	10	4	0	0	0	1	2
α_0 only	0	0	0	8	7	7	6	2
$\alpha+\alpha_0$	0	0	0	0	0	3	0	11
$\alpha+\alpha_2$	0	1	0	0	0	2	0	2
$(\alpha+\gamma)$-phase	8	9	4	4	0	0	0	0
γ-phase	0	1	2	4	0	0	0	0
Total	8	11	4	8	7	12	7	17

with α-phase, may have been subjected to the effect of reheating and rapid cooling caused by the shock metamorphism.

On the other hand, the thermomagnetic characteristics of stony meteorites, chondrites and achondrites, are considerably different from those of the lunar surface materials. A typical example of thermomagnetic curves of a chondrite for the first and second run measurements is shown in Fig. 8 (The thermomagnetic curves of a number of other chondrites and achondrites have already been reported, *e.g.* NAGATA and SUGIURA, 1976). As shown in Fig. 8 the thermomagnetic charac-

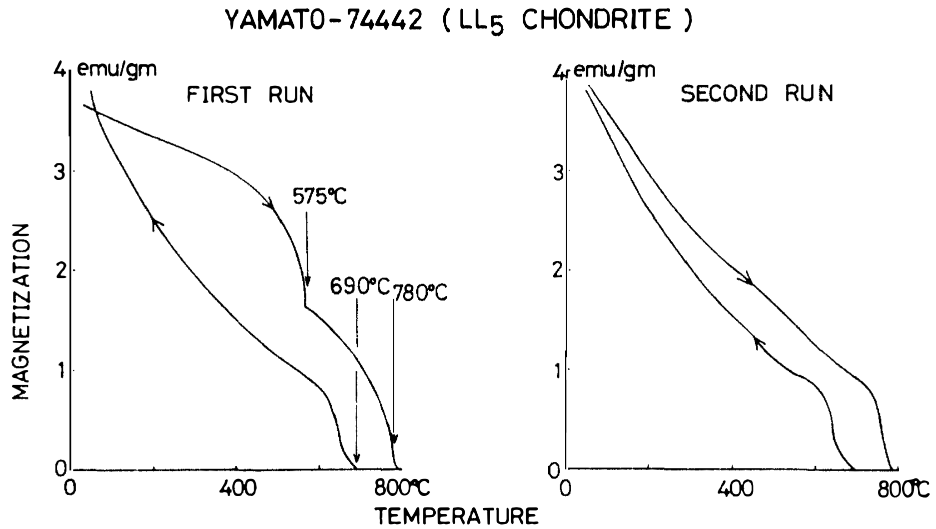

Fig. 8. Thermomagnetic curves of an LL-chondrite (Yamato-74442) which contains kamacite and plessite before a heating and kamacite and taenite after a heating up to 850°C.

teristics obtained in the first run measurements are not reproducible in the second run experiment. In the first run measurements, a ferromagnetic phase having a transition at 575°C in the heating curve represents an $(\alpha+\gamma)$-phase (plessite), which has been transformed to a γ-phase (taenite) in the cooling curve, while the other ferromagnetic phase having an $\alpha\rightarrow\gamma$ transition (or Curie point) at 780°C in the heating curve and a $\gamma\rightarrow\alpha$ transition at 690°C in the cooling curve can be identified to kamacite phase of about 4.5 wt% in Ni-content and about 1 wt% in Co-content. The second run thermomagnetic curves comprise a thermally irreversible magnetization of the kamacite phase and a thermally reversible magnetization of the taenite phase. The third run thermomagnetic curves are almost identical to the second run ones. It will mean that only a drastic change in the magnetic constituents in this chondrite is a transformation of a martensitic plessite phase to a taenite phase in the first heating process, and after this transformation of $(\alpha+\gamma)\rightarrow\gamma$, both the kamacite and taenite phases are thermally stable in laboratory time scale. As summarized in Table 2, all H- and LL-chondrites and the majority of L-chondrites contain the thermally unstable $(\alpha+\gamma)$-phase, whereas none of lunar surface materials contain $(\alpha+\gamma)$-phase of metallic nickel-iron. This would be one of remarkable contrasts between the lunar materials and the stony meteorites. The $(\alpha+\gamma)\rightarrow\gamma$ transition temperature of examined chondrites and achondrites ranges between 540°C and 580°C, which indicate that the average value of Ni-content in the plessite phase is about 30 wt% or a little more. This result suggests that these chondrites and achondrites were very slowly cooled down to about 450°C associated with the phase equilibrium between α- and γ-phases, and then the γ-phase was transformed to the $(\alpha+\gamma)$-phase at temperatures lower than 450°C with the diffusionless transformation mechanism. On the contrary, the observed fact that no $(\alpha+\gamma)$-phase has been detected in the lunar surface materials may suggest their thermal history that their $(\alpha+\gamma)$-phase or γ-phase metallic nickel-irons were reheated and quenched to result in α_2-phase by repeated effects of shock metamorphism. It must be noted here that no coexistence of α- and α_2-phases has been detected in chondrites, diogenites, eucrites and howardites except for a special case (Yamato-7307 L-chondrite) which has clear evidence of a severe shock metamorphism (YAGI *et al.*, 1978). This result may suggest that these stony meteorites have never been reheated and then rapidly cooled to result in a transformation of Ni-rich metallic nickel-iron from γ-phase to α_2-phase.

4. Concluding Remarks and Summary

In the present study, the magnetic properties of stony meteorites are compared with those of the lunar surface rocks from two main viewpoints, *i.e.* the magnetic viscosity characteristics and the composition of metallic nickel-iron.

In results of the measurements of viscous magnetization characteristics, all lunar fines and 8 among 10 samples of lunar breccias possess Type (II) VRM, whereas none of 14 stony meteorites has Type (II) VRM. The Type (II) VRM can take place when more than 1/4 of ferromagnetic metallic grains are superparamagnetically fine, and the production of such superparamagnetically fine grains of metallic nickel-iron in lunar fines and breccias have been interpreted as due to severe meteorite impacts on the lunar surface. Then, the observed fact that no stony meteorite possesses Type (II) VRM characteristics may suggest that stony meteorites have never been subjected to the explosive shock metamorphism such as most lunar breccias and fines experienced in the past.

The metallic grains in lunar rocks and stony meteorites are composed of Fe and Ni and small amounts of Co and P. In accordance with their chemical compositions and thermal histories, the metallic grains consist of one or several of ferromagnetic phases such as α-, α_2-, $(\alpha+\gamma)$-, and γ-phases of metallic nickel-iron with small amounts of impurity of Co and P. The α_0-phase tentatively proposed in the present work can be identified to a pure metallic iron or a kamacite of less than 3 wt% in Ni-content or a Ni-poor schreibersite, $(FeNi)_3P$, which can not be magnetically distinguished from one another in the present magnetic method.

As already described, α_2-phase and schreibersite are products of a rapid cooling of the melt having the corresponding chemical compositions. Therefore, a coexistence of an α-phase and an α_2-phase can be interpreted as a result of a rapid cooling from the melting state of Ni-poor and Ni-rich metallic grains, and a coexistence of an α-phase and a schreibersite-phase may be a result of a rapid cooling of a P-rich Fe-Ni melt. A coexistence of an α-phase and a pure metallic iron should be interpreted as an addition of pure metallic iron-phase produced by a subsolidus reduction of Fe-bearing silicates to the existing α-phase metals. A coexistence of a Ni-poor kamacite phase (less than 3 wt% in Ni-content) and a Ni-rich kamacite phase cannot be assumed if the metallic melt is slowly cooled down. On the basis of these metallographic interpretations, the observed coexistence of α- and α_2-phases or of α- and α_0-phases in lunar materials strongly suggest that these lunar materials were reheated and rapidly cooled down, probably owing to the shock metamorphism caused by repeated severe meteorite impacts. On the other hand, a coexistence of $(\alpha+\gamma)$- or γ-phase with α-phase in stony meteorites should be a result of slow cooling of metallic nickel-iron of larger than 8 wt% in Ni-content, where the phase equilibrium has been approximately kept during the cooling process. Such a coexistence of an $(\alpha+\gamma)$-phase or a γ-phase with an α-phase is not detected in lunar materials, as summarized in Table 2.

In concluding, therefore, both statistical results given in Tables 1 and 2 indicate that the most lunar surface materials, particularly lunar fines and breccias, were very severely shock metamorphased, whereas the grade of shock metamorphism of stony meteorites is much smaller than that of lunar materials.

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