MAGNETIC CHARACTERISTICS OF SOME YAMATO METEORITES —MAGNETIC CLASSIFICATION OF STONE METEORITES—

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Abstract: 13 Yamato stone meteorites have been magnetically examined. They are one enstatite chondrite (E), 6 olivine-bronzite chondrites (H), 2 olivine-hypersthene chondrites (L), one carbonaceous chondrite (C) and 3 achondrites (aC). The intrinsic magnetic parameters of these stone meteorites obtained from their magnetic hysteresis curves and thermomagnetic curves, together with those of other 7 known chondritic meteorites, are specifically examined in terms of the compositional and petrographical classification of stone meteorites.

The saturation magnetization (I_s) and major magnetic transition temperature (Θ_c) in the cooling process can be taken as the representative magnetic parameters in the proposed magnetic classification of stone meteorites. In the I_s versus Θ_c diagram, those examined stone meteorites, 25 in total, are separated into groups; namely, $I_s(E)>I_s(H)>I_s(L)>I_s(aC)$, $\Theta_c(H \text{ and } L)<\Theta_c(E \text{ and } aC)\simeq 770°\text{C}$, $I_s(C)\simeq I_s(L)$ but $\Theta_c(C)<600°\text{C}<\Theta_c(L)$.

Although the boundary between the L-group and the H-group is not sharp enough in the I_s–Θ_c diagram, the L-group chondrites contain a distinctly larger amount of plessite phase which can be magnetically identified.

1. Introduction

It seems that significance of the magnetic characteristics of individual meteorites has recently been recognized in general meteoritics (*e.g.* HERNDON and ROWE, 1974). Since the time when STACEY *et al.* (1961) published results of their systematic studies on the thermomagnetic properties of eight chondritic meteorites, however, rather few works on the basic magnetic characteristics of meteorites have been reported to date. Comprehensive thermomagnetic analyses of thirty-eight carbonaceous chondrites have been carried out by LARSON *et al.* (1974), WATSON *et al.* (1975) and HERNDON *et al.* (1976). A large number of data of the magnetic susceptibility of various types of meteorites in comparison with their natural remanent magnetization have been obtained by GUS'KOVA (1962), GUS'KOVA and POCHTAREV (1969) and other Soviet scientists (see HERNDON *et al.*, 1972). The thermal demagnetization experiment on the Brewstar chondrite (WEAVING, 1962) and the thermomagnetic studies by BUTLER (1972) and by BANERJEE and HARGRAVES (1972) on the Allende carbonaceous chondrite also have contributed much to the knowledge of the magnetic properties of meteorites. The thermomagnetic characteristics and the basic magnetic properties at room temperature of four Yamato meteorites were examined in detail by NAGATA *et al.* (1975).

Summarizing the main results of these reported papers on the thermomagnetic properties of meteorites, it may be generally concluded that the main ferromagnetic constituent in the ordinary chondrites (olivine-bronzite chondrites and olivine-hypersthene chondrites) is *kamacite* of α-phase containing 4–7 wt% of Ni, whereas that in the carbonaceous chondrites is mostly *magnetite*. These works further suggest that the ferromagnetic metal is the richest in the enstatite chondrites and the Ni-content in the metal phase is considerably smaller than that in the ordinary chondrites, being less than 3 wt%, and that the achondrites contain an extremely small amount of the ferromagnetic constituent (which is mostly metallic iron) in comparison with the chondrites. More quantitatively describing, the saturation magnetization (I_s) is about 50 emu/gm or larger for enstatite chondrites, 20–30 emu/gm for olivine-bronzite chondrites, 6–15 emu/gm for olivine-hypersthene chondrites and 0.2–0.5 emu/gm for achondrites. Carbonaceous chondrites have the saturation magnetization of about 10 emu/gm in intensity. In the comprehensive studies on the thermomagnetic curves of carbonaceous chondrites, LARSON *et al.* (1974), WATSON *et al.* (1975) and HERNDON *et al.* (1976) concluded that the weight content of magnetite in C_1, C_2, C_3 and C_4 types of carbonaceous chondrite ranges from 2.0 to 13.5%, which indicates that I_s of carbonaceous chondrites ranges from 2.0 to 12.5 emu/gm. Although the I_s-values of carbonaceous chondrites are close to or a little smaller than those of olivine-hypersthene chondrites, these two groups can be easily distinguished in their thermomagnetic characteristics, because the first group's major ferromagnetic constituent is magnetite whose Curie point is about 570°C, whereas the main ferromagnetic constituent in the second group is kamacite of 4–7 wt% of the Ni content whose $\alpha \rightarrow \gamma$ transition temperature is around 760°C.

On the other hand, the magnetic susceptibility values of various chondrites obtained by the Soviet group also are correlated well with the compositional difference of meteorites. Fig. 1 shows statistical histograms of the specific magnetic susceptibility (χ) separately for enstatite chondrites (E), olivine-bronzite chondrites (H), olivine-hypersthene chondrites (L) and amphoterites (LL). The average values of χ are 198×10^{-3} emu/gm for enstatite chondrites, 60.4×10^{-3} emu/gm for olivine-bronzite chondrites, 24.3×10^{-3} emu/gm for olivine-hypersthene chondrites and 5.4×10^{-3} emu/gm for amphoterites. As far as the median values are concerned, the χ-values are positively correlated with the abundance of metallic iron in these compositionally classified types of chondrites. The average of χ-values of 7 achondrites in the Soviet data amounts to 1.5×10^{-3} emu/gm, which is much smaller than the χ-value of any chondrite.

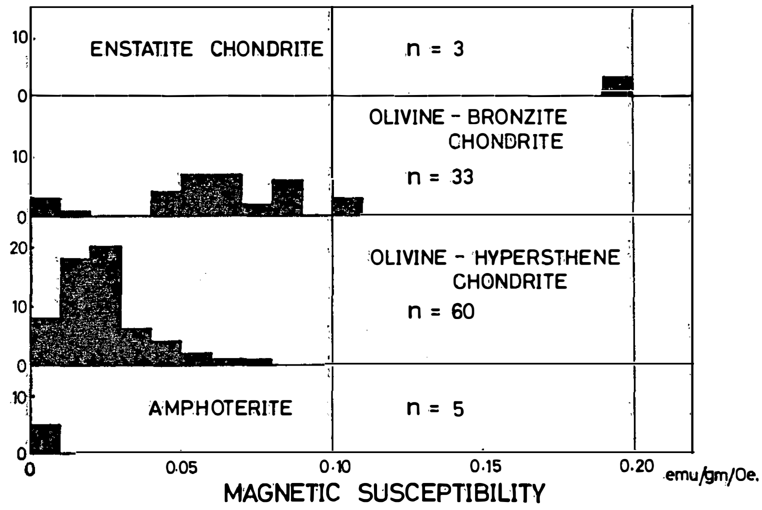


Fig. 1. Occurrence histograms of the specific magnetic susceptibility of various groups of stone meteorites.
Enstatite chondrites (examined sample number $n=3$)
Olivine-bronzite chondrites ($n=33$)
Olivine-hypersthene chondrites ($n=60$)
Amphoterites ($n=5$)
(After GUS'KOVA and POCHTAREV, 1969)

It seems thus that the magnetic properties such as the saturation magnetization, the magnetic transition temperature and the magnetic susceptibility of various stone meteorites can reasonably well represent their compositional difference. As shown by UREY and CRAIG (1953) and later by MASON (1962), the content of metallic iron (together with a smaller amount of Fe in FeS) is the largest in enstatite chondrites, and it decreases with the compositional change from olivine-bronzite chondrites, olivine-hypersthene chondrites, amphoterites and carbonaceous chondrites in the order. It seems therefore that the correspondence of the magnetic classification to the compositional classification for the stone meteorites is sufficiently reasonable.

The thermomagnetic characteristics and the basic magnetic properties at room temperature of 13 Yamato meteorites have recently been examined in detail, and in addition, those magnetic characteristics of 7 well known stone meteorites also have been studied. In this preliminary note, the correlation of the magnetic parameters with the compositional classification of these stone meteorites will be more extensively discussed.

2. Metallic Irons in Stone Meteorites

It has been established by UREY and CRAIG (1953) and MASON (1962) that the weight percent of iron in metal and FeS, $W(Fe^0)$, is correlated with that of oxidized iron, $W(\text{FeO})$, in chondrites, approximately in such a way as represented by

$$W(\text{Fe}^0) \simeq W^0(\text{Fe}^0) - \frac{W^0(\text{Fe}^0)}{W^0(\text{FeO})} W(\text{FeO}), \tag{1}$$

where $W^0(\text{Fe}^0)$ and $W^0(\text{FeO})$ denote respectively $W(\text{Fe}^0)$ value for $W(\text{FeO})=0$ and $W(\text{FeO})$ value for $W(\text{Fe}^0)=0$, and numerically $W^0(\text{Fe}^0) \simeq 30$ wt%, and $W^0(\text{FeO}) \simeq 25$ wt%.

Among the 13 Yamato meteorites, one enstatite chondrite, two olivine-bronzite chondrites, one carbonaceous chondrite and two Ca-poor achondrites were chemically analyzed (SHIMA, 1974; SHIMA and SHIMA, 1975). The bulk chemical composition of Kesen (olivine-bronzite chondrite), Fukutomi (olivine-hypersthene chondrite) and Mino (olivine-hypersthene chondrite), the magnetic properties of which are discussed in the next section, have been reported (MIYASHIRO, 1962a, b; MIYASHIRO *et al.*, 1964). The Fe values in metallic and sulfide phases and the FeO values of these 9 stone meteorites are summarized in Table 1, and the weight percent of iron in metal and FeS is plotted against that of FeO for each sample in Fig. 2. Except for two achondrites, the Fe^0–FeO relation for the UREY-CRAIG-MASON relationship is expressed by eq. (1). Two achondrites are of course much deviated from the chondrite relationship with respect to the Fe^0 and FeO contents, but one of the compositional characteristics of achondrites—the abundance of metallic iron is extremely poor—is satisfied by these two achondrite samples.

The UREY-CRAIG-MASON law for chondrites represented by eq. (1) indicates that the total content of iron, namely the sum of contents of Fe^0, Fe^{2+} and Fe^{3+}, is approximately constant throughout all compositional types of chondrites. Achondrites which contain no chondrule have been interpreted to represent an entirely different part of the parent meteorite planet, because the total content of iron in achondrites is definitely different from that in chondrites. It has been believed

Table 1. Fe in metal and sulfide and FeO in Yamato meteorites and three other chondrites collected in Japan.

Meteorite	Classification	Fe in metal	Ni in metal	Fe in sulfide	FeO
Yamato (a)	Enstatite chondrite	22.18	1.86	7.20	0.48
Yamato (b)	Ca-poor achondrite	0.66	0.004	0.85	12.58
Yamato (c)	Carbonaceous chondrite (C3)	0.15	1.32	2.30	27.84
Yamato (d)	Olivine-bronzite chondrite	12.69	1.52	3.38	12.02
Yamato-73-04	Olivine-bronzite chondrite	12.5	1.6	3.5	12.3
Yamato-73-07	Ca-poor achondrite	0.5	trace	0.9	12.5
Kesen	Olivine-bronzite chondrite	18.23	1.59	3.68	9.47
Fukutomi	Olivine-hypersthene chondrite	9.83	1.33	4.05	11.62
Mino	Olivine-hypersthene chondrite	7.86	1.16	3.73	14.48

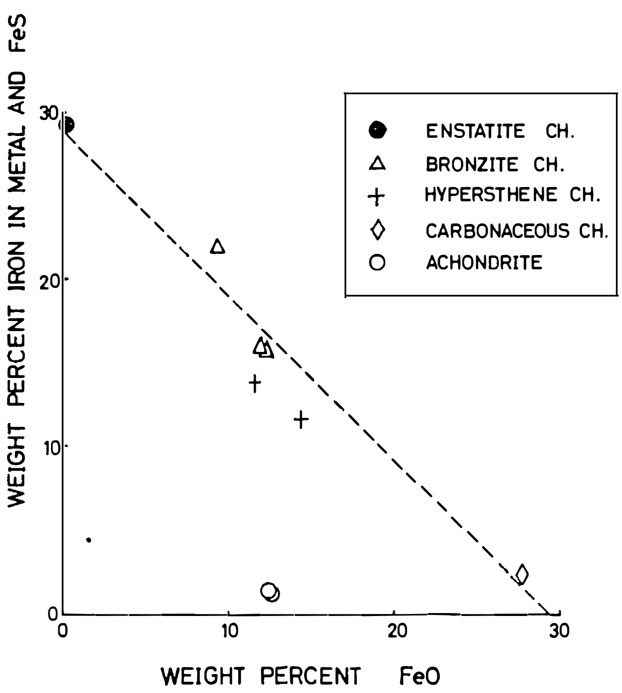


Fig. 2. UREY-CRAIG-MASON diagram to show a relationship of Fe in metal and FeS with FeO in 9 stone meteorites.

that the chondrites and the achondrites represent respectively the mantle and the crust of the parent meteorite planet.

From the viewpoint of rock magnetism, the distinctly different grouping of metallic iron abundance in the different types of stone meteorites may become a fundamental basis for a possible magnetic classification of stone meteorites. The saturation magnetization (I_s^0) of kamacite decreases at a small rate with an increase of the nickel content, but its decreasing rate is small for a range of the Ni content from 0 to 20%, I_s^0 being 218 emu/gm for the pure iron and 210 emu/gm for 20 wt% Ni kamacite (*e.g.* BOZORTH). Hence, the saturation magnetization (I_s) of a stone meteorite having low content of Ni kamacite (less than 20 wt% of nickel) in W in weight content can be approximately represented by

$$I_s = WI_s^0, \tag{2}$$

where I_s^0 can be practically considered constant.

On the other hand, the content of FeO in rocks could be evaluated from the paramagnetic susceptibility (χ_p), because χ_p is dependent on the abundance of Fe^{2+}, Fe^{3+} and Mn^{2+} in rock-forming silicate minerals (*e.g.* NAGATA, 1961) and practically the abundance of Mn^{2+} can be ignored in comparison with that of Fe^{2+} and Fe^{3+} in terrestrial and lunar rocks as well as in meteorites. Actually, an approximately linear relationship between the χ_p-values and the FeO contents (W(FeO)) has been established with a reasonable value of the proportion coefficient in the case of lunar surface materials (NAGATA *et al.*, 1973). A similar trial to magnetically evaluate the FeO content in stone meteorites by measuring χ_p was carried out for the stone meteorites. However, the correlation between the observed values of χ_p and W(FeO) obtained in the chemical analysis in the case of stone meteorites is so bad that this method cannot be used for evaluating W(FeO) in stone meteorites (NAGATA *et al.*, 1975). The reason why the χ_p method for the evaluation of W(FeO) is applicable to the lunar rocks but not to the stone meteorites has not yet been fully clarified. It seems likely, however, that the χ_p-method is safely applicable to rocks containing a small amount of metallic iron (less than 1 wt%) such as lunar rocks and achondrites, but in the case of metallic iron-rich chondrites such as the enstatite chondrites and the ordinary chondrites the apparent value of χ_p is much increased by an addition of a spurious paramagnetism which may probably be due to the presence of extremely fine grains of metallic iron associated with larger grains of metallic iron of a larger amount (see NAGATA *et al.*, 1973). For the above-mentioned reason, the observed values of χ_p will not be discussed in terms of W(FeO) at present, though theoretically an $I_s \sim \chi_p$ diagram should be able to represent the UREY-CRAIG-MASON diagram of W(Fe) $\sim$ W(FeO) relationship.

3. Magnetic Properties of Seven Known Stone Meteorites

The thermomagnetic characteristics and the basic magnetic properties at room temperature of seven reasonably well known stone meteorites were examined for the standard reference. They are three olivine-bronzite chondrites (Kesen, Seminole and Yonozu), three olivine-hypersthene chondrites (Dalgety Downs, Fukutomi and Mino) and one C_4 carbonaceous chondrite (Leoville). Prior to the magnetic experiments, the opaque ferromagnetic minerals in these stone meteorites were examined with the aid of an optical microscope and an electron microprobe. Results of the observations are briefly summarized in the following:

(*H*–1) Kesen (spherical olivine-bronzite chondrite*) contains large grains of kamacites (up to several hundred microns in diameter) and no taenite grain.

(*H*–2) Seminole (olivine-bronzite chondrite*) contains clear taenites which suggest the formation of this chondrite under a quasi-equilibrium state at low temperature. The observed fact that the composition of plessites in this sample represented by 4 wt% Ni in α-phase and 50 wt% Ni in γ-phase may also suggest the formation of this meteorite under a low temperature.

(*H*–3) Yonozu (crystalline olivine-bronzite chondrite*) contains kamacite grains which are partially covered with pale-blue minerals—probably maghemites.

* The classification is after "Catalogue of Meteorites" by M. H. HEY (1966 edition).

(L–1) Dalgety Downs (olivine-hypersthene chondrite*) contains typical zoned taenites: the Ni content is about 45 wt% at the rim and about 26 wt% at the center. The relation between the nickel concentration and the distance from the nearest boundary of the grain (WOOD, 1967) suggests that the cooling rate of the taenites can be estimated as 10°–100°C per one million years.

(L–2) Fukutomi (veined gray olivine-hypersthene chondrite*) contains a certain kind of polycrystalline kamacites and a large number of kamacite grains, the margins of which suggest traces of the thermal metamorphism. The zoned taenites in this chondrite contain 35–38 wt% Ni at the centers. These observed features may suggest that this chondrite was once reheated.

(L–3) Mino (olivine-hypersthene chondrite*) contains a large number of plessites which can be classified into two groups, *i.e.*, a group of about 6 wt% Ni in α-phase and about 45 wt% Ni in γ-phase, and the other group of about 20 wt% in α-phase and 45 wt% Ni in γ-phase. The Ni-content in α-phase in the second group is unusually high.

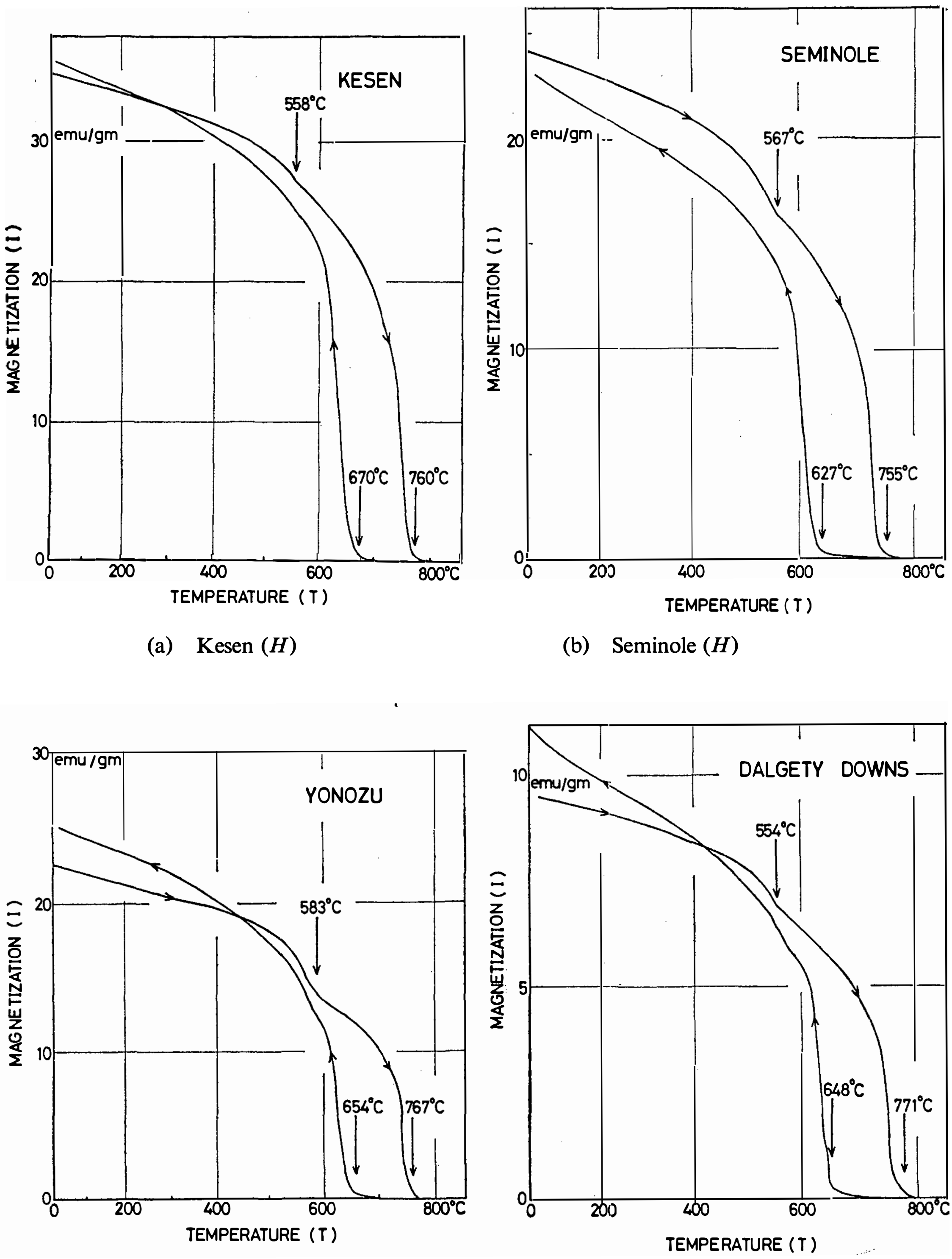
(C–1) Leoville (C_4 carbonaceous chondrite*) contains kamacite, taenites and unidentified fine opaque mineral grains in the matrix. The kamacite grains are inhomogeneous in regard to their Ni content, and contain Co up to 2 wt% and a little sulpher inhomogenuity. The taenites contain 35–40 wt% Ni and do not show the zoning of Ni concentration. The fine opaque mineral grains may probably be magnetite, though they are too small to be identified by an electron microprobe analyzer.

The thermomagnetic curves of these seven stone meteorites obtained under experimental conditions where the external magnetic field (H_{ex})=5.85 kOe and the air pressure=$(0.8\text{–}1.2)\times 10^{-5}$ torr are summarized in Fig. 3 (a)–(g). The observed thermomagnetic curves generally comprise those of several different ferromagnetic phases. The thermomagnetic characteristics of the elemental ferromagnetic phases in the stone meteorites are as follows:

(*a*) *Kamacite*

The thermomagnetic curve of kamacite is irreversible with respect to temperature, because of a difference between the $\alpha\rightarrow\gamma$ phase transition temperature in the heating curve and the $\gamma\rightarrow\alpha$ phase transition temperature in the cooling curve. In the heating process, the initial α-phase whose Curie point is about 770°C is ferromagnetic up to the $\alpha\rightarrow\gamma$ phase transition temperature ($\Theta^*_{\alpha\rightarrow\gamma}$). As the temperature after the $\alpha\rightarrow\gamma$ phase transition in the heating process is well above Curie point of the γ phase, the transformed γ-phase at the temperatures is paramagnetic. In the cooling process, the γ-phase is transformed into the ferromagnetic α-phase at the $\gamma\rightarrow\alpha$ phase transition temperature ($\Theta^*_{\gamma\rightarrow\alpha}$), where $\Theta^*_{\gamma\rightarrow\alpha}<\Theta^*_{\alpha\rightarrow\gamma}$. As the $\alpha\rightarrow\gamma$ and $\gamma\rightarrow\alpha$ phase transition temperatures depend on the Ni-content in kamacite, the Ni-content in the kamacite can be determined from the thermomagnetic data.

* The classification is after "Catalogue of Meteorites" by M. H. HEY (1966 edition).



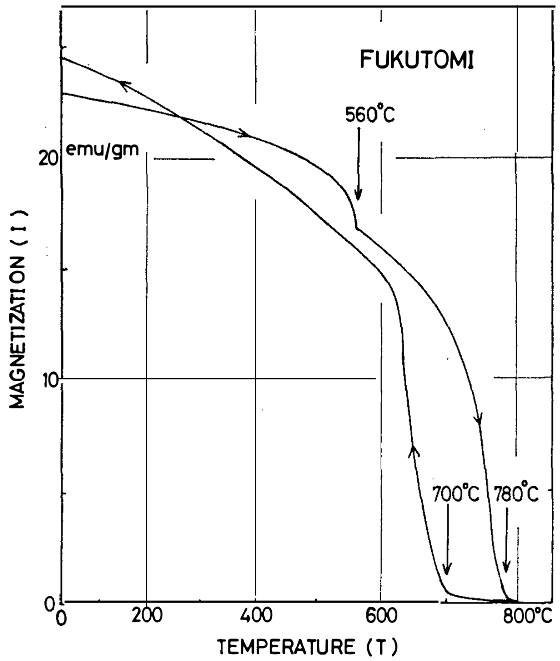
(a) Kesen (*H*)

(b) Seminole (*H*)

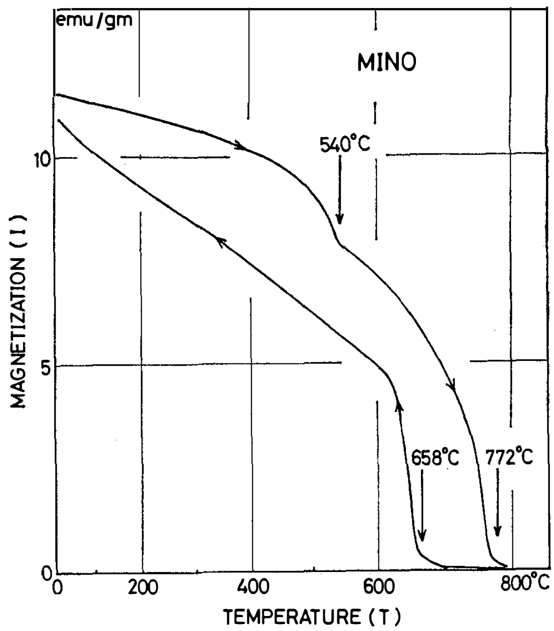
(c) Yonozu (*H*)

(d) Dalgety Downs (*L*)

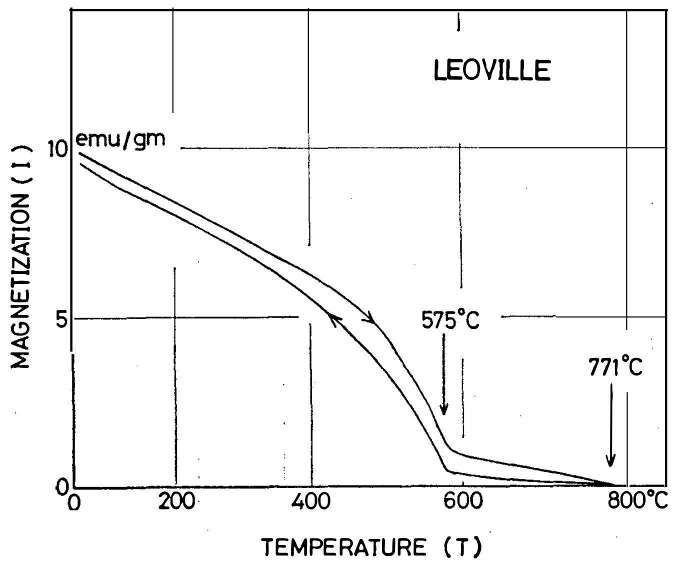
Fig. 3. Thermomagnetic curves of 7 known chondritic meteorites.



(e) Fukutomi (*L*)



(f) Mino (*L*)



(g) Leoville (*C*)

Fig. 3. Thermomagnetic curves of 7 known chondritic meteorities.

(*b*) *Taenite*

The taenite is the γ-phase of FeNi alloy, which has a reversible thermomagnetic curve and whose Curie point depends on the nickel content. The Ni content in the zoned taenite continuously varies from 30 to 50 wt%, which corresponds to a continuous change of Curie point from about 400°K to 800°K.

(*c*) *Plessite*

As this mineral is a mixture of the α and γ phases, the magnetization of the original plessite is a superposition of the α- and γ-magnetizations. However, after the temperature is once increased beyond the boundary of the $\alpha+\gamma$ phase to the γ-phase, the resultant γ-phase cannot be inverted to the original $\alpha+\gamma$ phase even if the temperature is lowered. Hence, the apparent thermomagnetic curve becomes irreversible with temperature and not reproducible. This homogenization of the α and γ phases to the γ phase can be almost completed by a laboratory time heating procedure for fine-grain plessite such as in the dark etching region of taenites. In the case of coarse plessites, however, the α- and γ-phases are gradually homogenized by successive heat treatments. In most cases, the total Ni content in plessites is 25–30 wt% and the magnetic transition to the γ phase takes place around the temperature of 550°C.

(*d*) *Martensite*

As the martensite is a metastable phase, its thermomagnetic characteristics are much complicated depending on the Ni content because the phase transition in the martensite is essentially subjected to the diffusion of nickel.

(*e*) *Magnetite and substituted magnetite*

Curie point of pure magnetite is 570°C. The substitution of Fe^{3+} in magnetite by Al, Mn, Cr, etc. always results in a decrease of Curie point. The substitution of Fe^{2+} in magnetite by Co, Mg and Cu causes a decrease of Curie point, but that by Ni results in a slight increase of Curie point.

Based on the fundamental thermomagnetic characteristics of the meteorite-forming ferromagnetic minerals, the thermomagnetic curves of the seven chondrites (Fig. 3) will be interpreted. In Table 2, the magnetic transition temperatures (Curie point or the $\alpha\rightarrow\gamma$ and $\gamma\rightarrow\alpha$ phase transition temperatures) of these samples are summarized together with their saturation magnetization (I_s), the saturation remanence (I_R), the coercive force (H_c) and the remanence coercive force (H_{Rc}), which are derived from the magnetic hysteresis curves at room temperature. All the seven chondrites contain kamacite of α phase, the $\alpha\rightarrow\gamma$ phase transition temperature ($\Theta^*_{\alpha\rightarrow\gamma}$) and the $\gamma\rightarrow\alpha$ phase transition temperature ($\Theta^*_{\gamma\rightarrow\alpha}$) of which indicate the Ni-content in respective kamacites of α phase. The percentage given in the parenthesis next to the $\Theta^*_{\alpha\rightarrow\gamma}$ temperature represents the relative portion of α-phase kamacite in I_s. As seen in the percentage value in Table 2, the major part of

Table 2. Basic magnetic parameters of seven chondrites.

Magnetic parameters	Kesen (H)	Seminole (H)	Yonozu (H)	Dalgety Downs (L)	Fukutomi (L)	Mino (L)	Leoville (C)	Unit
Saturation magnetization (I_s)	34.4	24.3	24.2	9.7	22.9	11.0	10.3	emu/gm
Staturation remanence (I_R)	0.23	0.29	0.79	0.49	0.75	0.021	0.58	emu/gm
Coercive force (H_c)	8	18	42	117	20	3	34	Oersteds
Remanence coercive force (H_{Rc})	110	490	210	675	500	70	225	Oersteds
(Heating)								
Θ	—	—	—	—	—	—	575 (86%)	°C
$\Theta^*_{\alpha\to\gamma}(\alpha)$	760 (97%)	755 (95%)	767 (86%)	771 (87%)	780 (92%)	772 (86%)	771 (14%)	°C
$\Theta^*(\alpha+\gamma)$	558 (03%)	567 (05%)	583 (14%)	554 (13%)	560 (08%)	540 (14%)	None	°C
(Cooling)								
$\Theta^*_{\gamma\to\alpha}$	670	627	654	648	700	658	679	°C
Ni in α kamacite	4.7	6.3	5.4	5.6	4.0	5.3	4.4	wt%

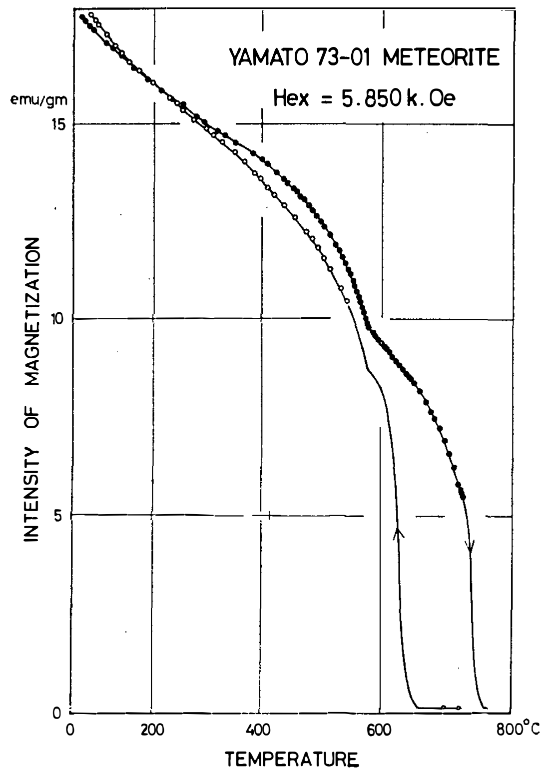
magnetization of the bronzite and hypersthene chondrites is due to the kamacite of α-phase, whereas the major magnetization of a carbonaceous chondrite (Leoville) is due to magnetite.

As seen in Fig. 3 (a)–(f), the initial heating curve of thermomagnetic cycles of the six ordinary chondrites has a magnetic transition around 550°C, which almost disappears in the cooling curve and in the heating and cooling curves of the second and third run thermomagnetic cycles. By taking into consideration the results of the election microprobe study of these samples and the metallographic and magnetic characteristics of fine grain plessites, this ferromagnetic phase can be identified to the plessite of 25–30 wt% in Ni content. Since the saturation magnetization of kamacite of the Ni content of this range is sharply dependent on the Ni content, it is hardly possible to quantitatively estimate the abundance of plessite phase only from the magnetic data. For three chondrites, Kesen, Fukutomi and Mino, however, the contents of Fe and Ni have been determined chemically as given in Table 1. Then, the average weight content of Ni in the metal phase is estimated to be 8.0, 11.9 and 12.9% for Kesen, Fukutomi and Mino respectively. If this average content of Ni is interpreted to represent the weighted average of the Ni contents in the kamacite phase containing Ni as given in Table 1 and the plessite phase of about 30 wt% Ni, then the weight abundance ratio of the plessite to the kamacite in the metal phase can be approximately estimated. Results of such an estimation suggests that the ratio of plessite to kamacite in weight is about 10: 90 for Kesen, 30: 70 for Fukutomi and 30: 70 for Mino. Roughly speaking, the relative content of plessite in the metal phase is approximately proportional to the relative magnitude of saturation magnetization, $I_s^0(\alpha+\gamma)$, of the plessite phase given in Table 1, where the ratio of $I_s^0(\alpha+\gamma)$ to the saturation magnetization of α phase, $I_s^0(\alpha)$, can be approximately estimated to be $I_s^0(\alpha+\gamma)$: $I_s^0(\alpha)\simeq 1:3$.

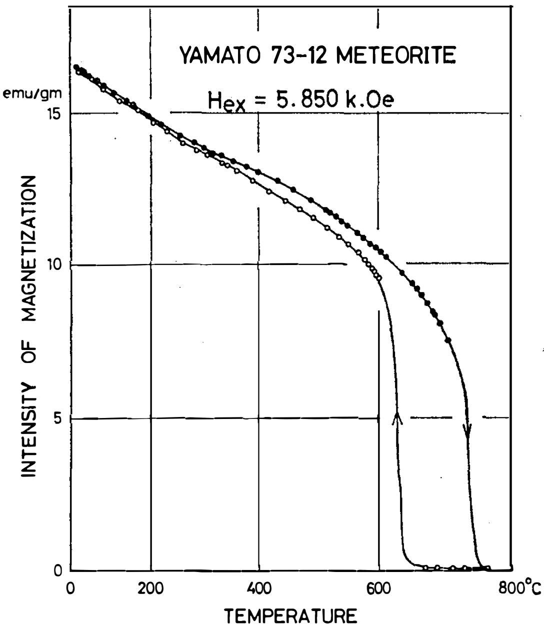
In the case of a carbonaceous chondrite, Leoville, the thermomagnetic curve shown in Fig. 3 (g) indicates a small magnetic transition at 250–300°C, which represents the taenite of about 40 wt% in Ni content.

4. Magnetic Properties of Yamato Meteorites

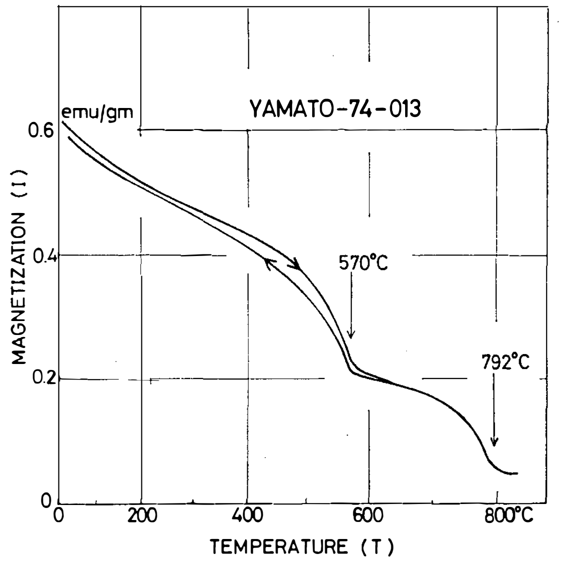
Fourteen Yamato meteorites have been magnetically examined. An example of the magnetic hysteresis curve and the thermomagnetic curves of Yamato (a), (b), (c) and (d) meteorites have already been published (NAGATA *et al.*, 1975), and the magnetic hysteresis curves and the thermomagnetic curves of two other Yamato meteorites, Yamato-73-04 and Yamato-73-07, are shown in a separate paper (NAGATA *et al.*, 1976 b). Another Yamato meteorite, Yamato-75-150 which is iron, is metallographically and magnetically described in detail in a separate paper (NAGATA *et al.*, 1976 a). The thermomagnetic curves of other 7 Yamato



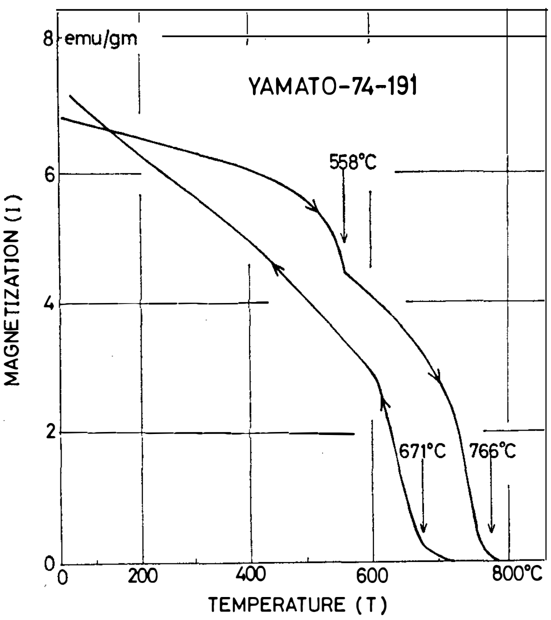
(a) Yamato-73-01 (*H*)



(b) Yamato-73-12 (*H*)

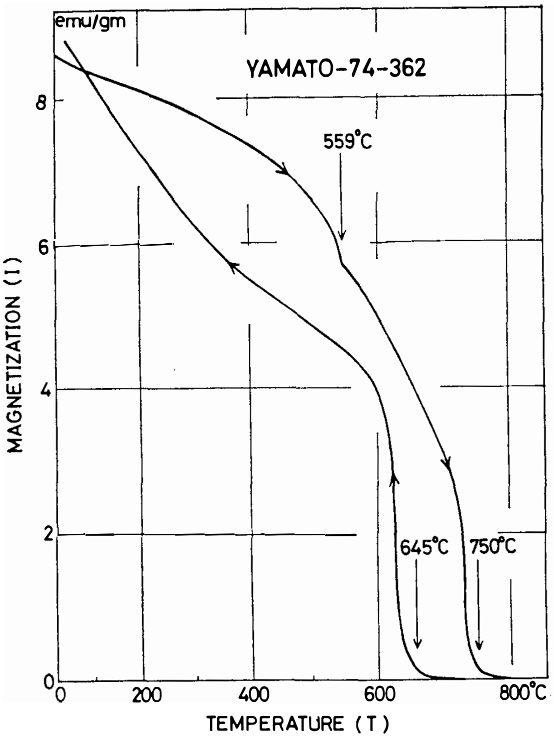


(c) Yamato-74-013 (achondrite)

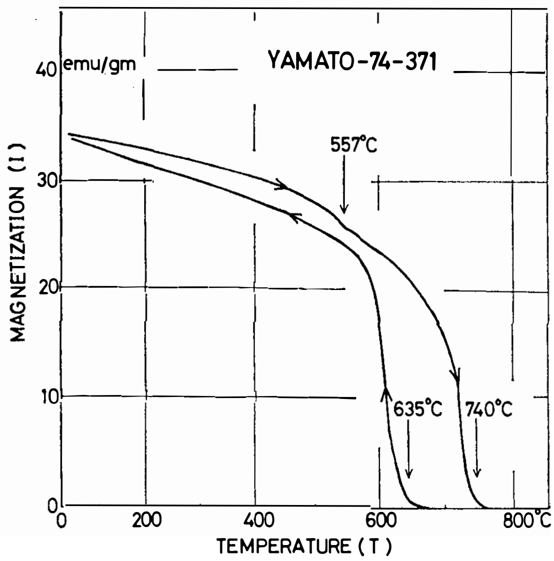


(d) Yamato-74-191 (*L*)

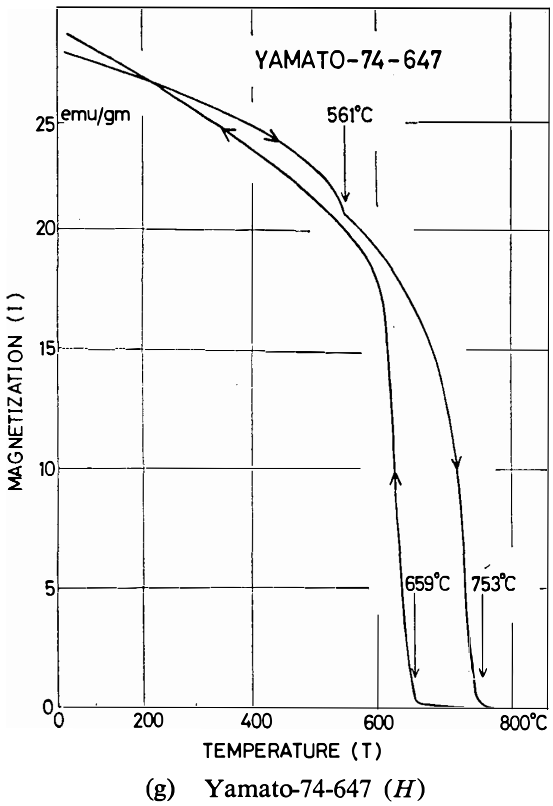
Fig. 4. Thermomagnetic curves of 7 Yamato meteorites.



(e) Yamato-74-362 (*L*)



(f) Yamato-74-371 (*H*)



(g) Yamato-74-647 (*H*)

Fig. 4. Thermomagnetic curves of 7 Yamato meteorites.

Table 3. Basic magnetic properties of eight Yamato meteorites.

Magnetic parameters	Yamato (a) (*E*)	Yamato (b) (*aC*)	Yamato (c) (*C*)	Yamato (d) (*H*)	Yamato 73-01 (*H*)	Yamato 73-04 (*H*)	Yamato 73-07 (*aC*)	Yamato 73-12 (*H*)	Unit
Magnetic susceptibility (χ_0)	21.4×10^{-3}	0.0090×10^{-3}	5.36×10^{-3}	13.6×10^{-3}	7.0×10^{-3}	4.1×10^{-3}	0.088×10^{-3}	4.5×10^{-3}	emu/gm/Oe
Paramagnetic susceptibility (χ_p)	2.5×10^{-4}	0.28×10^{-4}	0.53×10^{-4}	2.0×10^{-4}	0.96×10^{-4}	0.60×10^{-4}	0.33×10^{-4}	0.96×10^{-4}	emu/gm/Oe
Saturation magnetization (I_s)	48.0	0.19	10.8	32.3	15.5	14.3	0.53	17.5	emu/gm
Saturation remanence (I_R)	0.035	0.0035	1.69	0.60	0.14	0.045	0.0027	0.024	emu/gm
Coercive force (H_c)	12	42	157	23	15.5	8	13	3.8	Oersteds
Remanence coercive force (H_{Rc})	—	—	—	—	1,700	375	—	175	Oersteds
(Heating)									
Θ	—	780 (81%) 567 (19%)	540	—	577 (22%)	—	792	—	°C
$\Theta^*_{\alpha\to\gamma}(\alpha)$	769 (87%) 300 (13%)	None	None	759 (96%)	755 (78%)	740 (38%) 659 (62%)	None	754 (96%)	°C
$\Theta^*\ (\alpha+\gamma)$	None	None	None	542 (04%)	None	None	None	540 (04%)	°C
(Cooling) $\Theta^*_{\gamma\to\alpha}$	764 40	None	None	685	660	624 403	None	644	°C
Ni in α kamacite	2.5 25.0	~0	None	4.3	5.3	6.5 13.0	~0	5.7	wt%

Table 4. Basic magnetic properties of Yamato-74 meteorites.

Magnetic parameters	Yamato-74 013 (*aC*)	191 (*L*)	362 (*L*)	371 (*H*)	647 (*H*)	Unit
χ_p	0.3×10^{-4}	1.0×10^{-4}	1.1×10^{-4}	3.1×10^{-4}	2.3×10^{-4}	emu/gm/Oe
I_s	0.17	6.8	8.1	33.5	27.9	emu/gm
I_R	0.00122	0.22	0.27	0.29	0.34	emu/gm
H_c	<10	30	38	10	14	Oersteds
H_{Rc}	—	1,330	1,300	125	1,080	Oersteds
(Heating)						
Θ	{792 (56%) 570 (44%)	—	—	—	—	°C
$\Theta^*_{\alpha\to\gamma}$	None	766 (89%)	750 (84%)	740 (97%)	753 (96%)	°C
$\Theta^*(\alpha+\gamma)$	None	558 (11%)	559 (16%)	557 (03%)	561 (04%)	°C
(Cooling)						
$\Theta^*_{\gamma\to\alpha}$	None	671	645	635	659	°C
Ni in α kamacite	~0	4.7	5.6	6.0	5.4	wt%

meteorites, Yamato-73-01 (olivine-bronzite chondrite), Yamato-73-12 (olivine-bronzite chondrite), Yamato-74-013 (achondrite), Yamato-74-191 (olivine-hypersthene chondrite), Yamato-74-362 (olivine-hypersthene chondrite), Yamato-74-371 (olivine-bronzite chondrite) and Yamto-74-647 (olivine-bronzite chondrite) are illustrated in Fig. 4 (a)–(g). The magnetic hysteresis curves of these 13 Yamato meteorites are measured at room temperature. The basic magnetic parameters such as the saturation magnetization (I_s), the saturation remanent magnetization (I_R), the coercive force (H_c) and the remanence coercive force (H_{Rc}) at room temperature derived from the magnetic hysteresis curves are summarized in Tables 3 and 4, where the initial magnetic susceptibility (χ_0) and the paramagnetic susceptibility (χ_p) also are given as far as they were measured. It will be clearly observed in Tables 3 and 4 that I_s and I_R of the achondrites are much smaller than those of the chondrites.

The characteristic parameters of thermomagnetic curves also are listed in Tables 3 and 4. The characteristic parameters are Curie point (Θ), the $\alpha\to\gamma$ phase transition temperature of kamacite, ($\Theta^*_{\alpha\to\gamma}(\alpha)$), and the irreversible transition temperature of plessite ($\Theta^*(\alpha+\gamma)$) in the heating curve, and $\gamma\to\alpha$ phase transition temperature of kamacite ($\Theta^*_{\gamma\to\alpha}$). From the observed values of $\Theta^*_{\alpha\to\gamma}(\alpha)$ and $\Theta^*_{\gamma\to\alpha}$, the Ni content of the kamacite phase can be estimated. The Ni content in the α kamacite phase thus estimated also is given at the bottom of Tables 3 and 4. The transition temperature of plessites in the Yamato meteorites ranges between 540°C and 560°C, which suggest that the Ni content in the plessite phase is about 30 wt%. As already mentioned in the preceding section, Curie point (Θ) can be determined only for magnetites (including substituted magnetites) and almost pure iron, in which the Ni content is sufficiently small so that the $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \alpha$ phase transitions do not disturb the determination of Curie point.

The magnetic characteristics of individual Yamato stone meteorites, summarized in Tables 3 and 4, will be briefly discussed in the following, where a brief petrographic description also is given for the stone metorites newly reported in this paper.

(*i*) *Yamato* (*a*) (enstatite chondrite): Yamato (a), (b), (c) and (d) meteorites were already described in detail (NAGATA *et al.*, 1975). Yamato (a) meteorite contains 18.9 wt% of 2.5 wt% Ni kamacite and 5.2 wt% of 25 wt% Ni kamacite. The magnetic characteristics well represent the metallic phase composition.

(*ii*) *Yamato* (*b*) (Ca-poor achondrite): The main ferromagnetic phase having Curie point at 780°C represents almost pure metallic iron which contains very small amounts of Ni and Co. The second ferromagnetic phase having Curie point at 567°C may represent magnetites or substituted magnetites, because this magnetic transition does not disappear in repeated heat treatments.

(*iii*) *Yamato* (*c*) (Type III carbonaceous chondrite): The ferromagnetic phase is represented only by substituted magnetites having Curie point at 540°C.

(*iv*) *Yamato* (*d*) (olivine-bronzite chondrite): The ferromagnetic phase is represented by a single α-kamacite phase, in which the Ni content is about 4.3 wt%.

(*v*) *Yamato-73-01* (olivine-bronzite chondrite): This chondrite is covered with a fusion crust of brownish gray colour. In addition to olivines, bronzites, clinophyroxenes and plagioclases, a number of FeNi grains are observable in the matrix. A large number of chondrule comprise olivines and bronzites with smaller amounts of clinopyroxene and plagioclase. The main ferromagnetic phase is represented by kamacites of 5.3 wt% Ni, but in addition the second ferromagnetic phase having Curie point at 577°C is not negligible. The second ferromagnetic phase is most likely to be due to the presence of magnetite. It was observed under an optical microscope that some of metallic grains have been weathered and have brownish red colour, suggesting the presence of hydroxides of FeNi.

(*vi*) *Yamato-73-04* (olivine-bronzite chondrite): The petrographic and magnetic characteristics of Yamato-73-04 and Yamato-73-07 are described in some detail in a separate paper (NAGATA *et al.*, 1976 b). Yamato-73-04 chondrite contains two well defined groups of kamacites, namely Ni-rich (13 wt% Ni) and Ni-poor (7 wt% Ni) kamacites.

(*vii*) *Yamato-73-07* (Ca-poor achondrite): The ferromagnetic phase in this achondrite is represented by almost pure metallic irons containing small amounts of Ni and Co.

(*viii*) *Yamato-73-12* (olivine-bronzite chondrite): This chondrite is covered with a fusion crust of light yellowish colour with finger-prints. The petrographic characteristics of this chondrite are very similar to those of Yamato-73-01. However, the magnetic characteristics of this chondrite are represented not only by kamacites of 5.7 wt% Ni but also by an additional small amount of plessites.

(*ix*) *Yamato-74-013* (hypersthene achondrite): This achondrite also is covered with a dark brownish fusion crust. The petrographic characteristics of this achondrite are similar to those of Yamato (b) achondrite. In addition to orthopyroxenes and clinopyroxenes, small amounts of chromite and FeNi metal are contained. The ferromagnetic component comprises two distinctly separated phases, namely almost pure metallic irons containing small amounts of Ni and Co and the other ferromagnetic phase having Curie point at 570°C. The second ferromagnetic phase is due very likely to magnetites.

(*x*) *Yamato-74-191* (olivine-hypersthene chondrite): This chondrite also is covered with a dark brownish fusion crust. The petrographic characteristics are represented by olivines, hypersthenes (En 74), and clinopyroxenes with small amounts of kamacite, taenites and troilites. The magnetic characteristics of this chondrite are represented by the main ferromagnetic phase of kamacites of 4.7 wt% Ni and the second phase of plessites. The intrinsic magnetic parameters (such as I_s, $\Theta^*_{\alpha\to\gamma}(\alpha)$, $\Theta^*(\alpha+\gamma)$, and $\Theta^*_{\gamma\to\alpha}$) of this chondrite also are similar to those of Yamato-74-362 chondrite.

(*xi*) *Yamato-74-362* (olivine-hypersthene chondrite): This chondrite also is covered with a fusion crust and contains olivines, hypersthenes (En 75), clinopyroxenes and a smaller amount of plagioclases together with FeNi grains. The boundary of chondrules is not sharp as in the usual case with the olivine-hypersthene chondrites. The ferromagnetic component in this chondrite is represented by a kamacite phase of 5.6 wt% Ni and a plessite phase of a smaller amount.

(*xii*) *Yamato-74-371* (olivine-bronzite chondrite): This chondrite also is covered with a fusion crust and its petrographic characteristics are very similar to those of Yamato (d). The magnetic characteristics also are similar to those of Yamato (d); namely they are represented by kamacites of 6.0 wt% Ni and plessites of a much smaller amount.

(*xiii*) *Yamato-74-647* (olivine-bronzite chondrite): The petrographic characteristics of this chondrite, covered with a fusion crust, are very similar to those of Yamato (d) and Yamato-74-371. The magnetic characteristics of this chondrite also are similar to those of the two olivine-bronzite chondrites, being represented by kamacites of 5.4 wt% Ni as the major ferromagnetic phase and a much smaller amount of plessites at the transition temperature of 561C°.

Summarizing the magnetic characteristics of these 13 Yamato stone meteorites, they may be approximately classified into six groups. (1) An enstatite chondrite, Yamato (a), is a typical enstatite chondrite, having the largest value of I_s and containing a Ni-poor kamacite (2.5 wt% Ni) phase as the major ferromagnetic constituent. (2) A carbonaceous chondrite, Yamato (c), well represents its carbonaceous chondritic characteristic by its single ferromagnetic constituent—magnetite. (3) The magnetic properties of olivine-hypersthene chondrites, Yamato-74-191 and 74-362, are well represented by the smaller value of I_s in comparison with that of enstatite chondrites and olivine-bronzite chondrites, and the structure of ferromagnetic metals consisting of kamacites of 5.6 wt% Ni and plessites of about 30 wt% Ni of non-negligible amount. These magnetic characteristics of these chondrites are very similar to those of Mino olivine-hypersthene chondrite. (4) The magnetic characteristics of the examined 6 Yamato olivine-bronzite chondrites could be classified into two groups. One group may consist of Yamato (d), Yamato-73-12, Yamato-74-371 and Yamato-74-647. In this group chondrites, the ferromagnetic metals comprise the α-kamacite of (4.3–6.0) wt% Ni and the plessites of about 30 wt% Ni. (5) The second group of Yamato olivine-bronzite chondrite, Yamato-73-01 and Yamato-73-04, do not contain the plessites. (6) The three examined Yamato achondrites, Yamato (b), Yamato-73-07 and Yamato-74-013, have several common magnetic characteristics: *i.e.* (i) their I_s values are extremely small, being smaller than 0.53 emu/gm; (ii) their main ferromagnetic phase is almost pure metallic iron containing very little amount of Ni and Co (Ni in α-kamacite$\simeq$0); (iii) two of the three Yamato achondrites have the second ferromagnetic phase which can be identified to the magnetite or the substituted magnetite.

5. Magnetic Classification of Stone Meteorites

In comparing the magnetic parameters of Yamato stone meteorites, given in Tables 3 and 4, with those of the other stone meteorites given in Table 2, reasonably good common magnetic characteristics are observable in each groups of olivine-bronzite chondrites (*H*), olivine-hypersthene chondrites (*L*) and carbonaceous chondrites (*C*). For the purpose of a preliminary statistical analysis of the general magnetic characteristics of the stone meteorites, as much more observed data as possible of similar experimental examinations of the other stone meteorites may be desirable. Up to the present time, a report by STACEY *et al.* (1961) is only an available collection of extensive experimental data of "meteoritic magnetism" at the level of the present study. STACEY *et al.* examined the thermomagnetic characteristics of 8 stone meteorites. However, their results on 5 meteorites which are registered in HEY's "Catalogue of Meteorites" only will be referred to be discussed together with the present data. These five stone meteorites are Mt. Brown (olivine-bronzite chondrite), Bjurböle (olivine-hypersthene chondrite), Barratta (olivine-hypersthene chondrite), Homestead (olivine-hypersthene chondrite) and Mokoia (carbonaceous olivine-pigeonite chondrite). The approximate value of

Table 5. Basic magnetic properties of 5 chondrites (after STACEY *et al.).*

Magnetic parameters	Mt. Brown (H)	Bjurböle (L)	Barratta (L)	Homestead (L)	Mokoia (C)	Unit
I_s	40	13	12	10	8	emu/gm
(Heating)						
Θ	—	—	—	—	570	°C
$\Theta^*_{\alpha\to\gamma}(\alpha)$	750 (90%)	760 (85%)	760 (80%)	750 (80%)	None	°C
$\Theta^*(\alpha+\gamma)$	570 (05%)	580 (10%)	400∼700 (15%)	570 (15%)	None	°C
(Cooling)						
$\Theta^*_{\gamma\to\alpha}$	640	660	655	650	None	°C
Ni in α kamacite	5.9	5.2	5.3	5.5	None	wt%

I_s (actually $I[H_{ex}=5{,}000$ Oe] which is close to I_s), Θ of the carbonaceous chondrite, $\Theta^*_{\alpha\to\gamma}(\alpha)$ and $\Theta^*_{\gamma\to\alpha}$ of kamacites and $\Theta^*(\alpha+\gamma)$ of plessites of these chondritic samples are summarized in Table 5. Although the authors of this work pointed out several other minor ferromagnetic phases in addition to the main magnetic phases given in Table 5, these minor magnetic constituents will be ignored in the present discussion. As shown in Table 5, however, the listed major magnetic phases whose contribution to the magnetization is shown in unit of percent may reasonably well represent the magnetic characteristics as a whole of these selected stone meteorites. The Ni-content of α-kamacite phase given at the bottom of Table 5 are re-estimated in the present study from the observed values of $\Theta^*_{\alpha\to\gamma}$ and $\Theta^*_{\gamma\to\alpha}$, whence the listed values of the Ni-content are slightly different from the estimations by the original authors. The original authors' conclusion that eighty to ninety percent of the saturation magnetic moment are due to α-phase iron-nickel (kamacite) containing 5 to 6 percent of nickel (in the ordinary chondrites) is in general agreement with the results of the present study.

On the other hand, the thermomagnetic characteristics of a large number of carbonaceous chondrites were systematically measured by LARSON *et al.* (1974), WATSON *et al.* (1975) and HERNDON *et al.* (1976). Although these workers have so far been concerned only with the carbonaceous chondrites, results of their studies have indicated a certain systematic regularity of the magnetic properties of carbonaceous chondrites. According to their results, the magnetic characteristics of carbonaceous chondrites become more complicated in accordance with an increase of metamorphism from C_1 to C_4. However, it is a general conclusion for all 38 examined carbonaceous chondrites that these chondrites contain magnetites as one of the major ferromagnetic constituents. In the most of unmetamorphosed carbonaceous chondrites, C_1, in particular, the ferromagnetic minerals are only pure magnetities (Fe_3O_4) or substituted magnetites expressed by $x NiFe_2O_4 \cdot (1-x) Fe_3O_4$. The three carbonaceous chondrites, Leoville, Yamato (c) and Mokoia, whose magnetic properties are given in Table 2 through Table 5, may therefore well represent comparatively little metamorphosed carbonaceous chondrites.

The 25 stone meteorites described in Table 2 through Table 5, can be classified into one enstatite chondrite, (E), 10 olivine-bronzite chondrites, (H), 8 olivine-hypersthene chondrites, (L), 3 carbonaceous chondrites, (C) and 3 achondrites (aC). The saturation magnetization (I_s) of these stone meteorites at room temperature were measured and are shown in Table 2 through Table 5. Then, the average I_s values of these classified groups are

$I_s(E)=48.0$ emu/gm (for enstatite chondrites),

$\bar{I}_s(H)=(26.4\pm7.3)$ emu/gm (for olivine-bronzite chondrites),

$\bar{I}_s(L)=(11.4\pm3.1)$ emu/gm (for olivine-hypersthene chondrites),

$\bar{I}_s(C)=(9.7\pm1.1)$ emu/gm (for carbonaceous chondrites),

$\bar{I}_s(aC)=(0.30\pm0.16)$ emu/gm (for achondrites),

where the numeral after ($\pm$) gives the mean deviation of individual observations from the average value.

Although we have only one sample of enstatite chondrite in the present study, we may conclude that

$$\bar{I}_s(E)>\bar{I}_s(H)>\bar{I}_s(L)>\bar{I}_s(aC).$$

Although the I_s-values of carbonaceous chondrites are close to those of olivine-hypersthene chondrites, the major ferromagnetic constituent in the former is magnetite or substituted magnetite, Curie point of which is definitely lower than the $\Theta^*_{\alpha\to\gamma}(\alpha)$ temperature of kamacite in the latter. If the magnetization of metal phase only is taken into consideration for carbonaceous chondrites, we get

$$\bar{I}_s(\text{C. metal})=(0.5\pm0.8)\ \text{emu/gm}\ .$$

Thus,

$$\bar{I}_s(\text{C. metal})\ll\bar{I}_s(L)\ .$$

Since the identification of ferromagnetic phase is possible by analyzing the thermomagnetic characteristics, a two-dimensional expression, one by I_s and the other by a certain representative parameter of the thermomagnetic characteristics, may give rise to a more definitive representation of the magnetic properties of stone meteorites. As a preliminary trial, the major magnetic transition temperature (Θ_c) in the cooling branch of thermomagnetic curves could be taken as the representative parameter. The Θ_c value takes different physical meanings in different cases. Θ_c is identical to Curie point of the thermally reversible magnetization of pure iron or Fe-Ni-Co alloys and magnetite or substituted magnetites, when these ferromagnetic materials play the principal role in the magnetic properties. When kamacites are the main ferromagnetic constituent, Θ_c must represent the $\Theta^*_{\gamma\to\alpha}$ temperature of kamacite

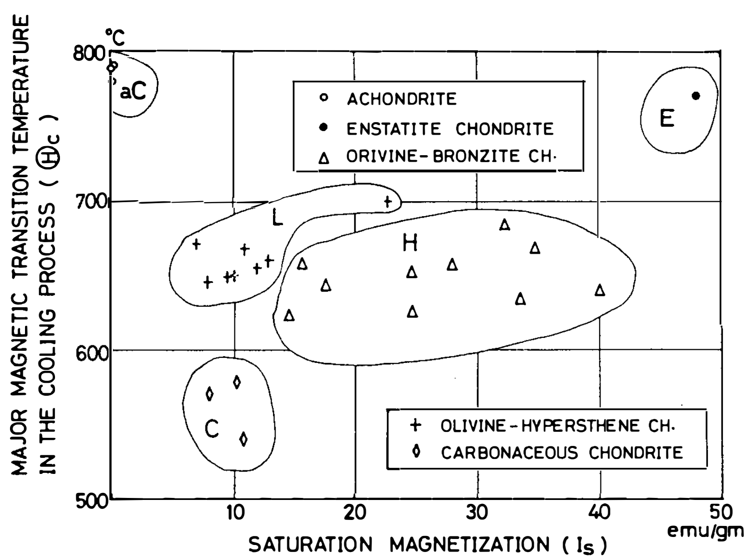


Fig. 5. Saturation magnetization (I_s) versus magnetic transition temperature (Θ_c) diagram for a magnetic classification of stone meteorites.

phase. As already mentioned, the $\Theta^*_{\gamma\to\alpha}$ transition in the cooling process can be easily distinguished from Curie point of magnetites or taenites by referring to the magnetic transitions in the heating process.

In Fig. 5, the observed Θ_c values are plotted against the I_s values for the 25 stone metorites described in Table 2 through Table 5. In this diagram, five different groups of stone meteorites, *i.e.* enstatite chondrite (*E*), olivine-bronzite chondrites (*H*), olivine-hypersthene chondrites (*L*), carbonaceous chondrites (*C*) and achondrites (*aC*), are well separated from one another. The *E*-group has high values of I_s and Θ_c, which indicate that the metallic iron content is the richest and the metallic phase comprises mostly Ni-poor kamacites. The *H*-group chondrites have comparatively large values of I_s, ranging from 20 to 40 emu/gm, but their Θ_c values which represent the $\Theta^*_{\gamma\to\alpha}$ temperature of kamacite phase range between 620°C and 680°C, suggesting that Ni-content in the kamacite ranges from 4.5 to 6.5 wt%. The *L*-group chondrites have their I_s values around 10 emu/gm and their $\Theta^*_{\gamma\to\alpha}$ values range from 640°C to 700°C. Namely, the metallic iron content in the *L*-group is considerably smaller than that in the *H*-group, but the Ni-content in the kamacite phase in the *L*-group chondrites is not much different from that in the *H*-group chondrites.

As already noted, the I_s values of the *C*-group chondrites are approximately the same as those of the *L*-group chondrites, but the Θ_c values representing Curie point of magnetites in the former are clearly lower than the $\Theta^*_{\gamma\to\alpha}$ transition temperature in the latter. The magnetic properties of the achondrite group are well characterized by the smallest value of I_s and high values of Θ_c; namely, a very small amount of metallic phase in achondrites consists of almost pure metallic iron.

The essential key points in the above-mentioned magnetic classification of stone chondrites can be symbolically summarized as

$$I_s(E)>I_s(H)>I_s(L)>I_s(aC)\,, \tag{I}$$

$$\Theta_c(E \text{ and } aC)>\Theta_c(H \text{ and } L)\,, \tag{II}$$

and

$$\Theta_c(C)<\Theta_c(L)\,. \tag{III}$$

In regard to point (I), one exceptional case of olivine-hypersthene chondrite (Fukutomi) is noted in Fig. 5: The I_s-value of this olivine-hypersthene chondrite is unusually high, being about 23 emu/gm. As reported by MIYASHIRO *et al.* (1964), however, the composition of orthopyroxene in this chondrite is represented by En_{79} Fs_{21} in mol percentage, which indicates that the orthopyroxene is compositionally between bronzite and hypersthene and is rather closer to bronzite. As shown in Fig. 2, the relationship between FeO and Fe in metal and FeS for this sample is closer to that for the olivine-bronzite chondrite group. If the Fukutomi chondrite can be classified into the *H*-group, the I_s value of the *L*-group chondrites is sharply limited within the range of $7 \leq I_s \leq 13$ in unit of emu/gm and the magnetic classification key point (I) does hold without exception.

It seems thus that the apparent classification of stone-meteoritic magnetic

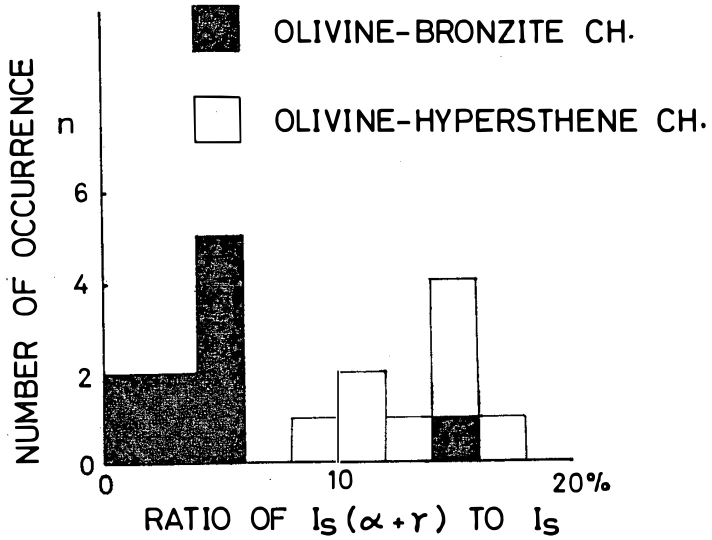


Fig. 6. Occurrence histogram of ratio of the saturation magnetization of plessite phase, I_s $(\alpha+\gamma)$, to the total saturation magnetization, I_s, for olivine-bronzite chondrites (n=9) and olivine-hypersthene chondrites (n=8).

characteristics in terms of I_s and Θ_c is reasonably successful. However, there still remain several points, the physical meanings of which should be examined in more datail. The I_s value in Fig. 5 gives the total sum of the saturation magnetizations of all ferromagnetic phases, whereas the Θ_c value represents either Curie point or the $\gamma\rightarrow\alpha$ transition temperature of the most dominant ferromagnetic component (with respect to its intensity) only. As shown in Table 2 through Table 5, however, all L-group chondrites contain a considerable amount of plessites in addition to kamacites which are their main ferromagnetic constituent, and most of the H-group chondrites also contain a smaller amount of plessite. In Fig. 6, the occurrence frequency of the ratio of saturation magnetization of plessite phase, $I_s(\alpha+\gamma)$, to the total saturation magnetization, I_s, is illustrated separately for the H-group and for the L-group. With one exception (Yonozu), all the other H-group chondrites are charcterized by $I_s(\alpha+\gamma)/I_s$=0–5%, the average value being $(\overline{I_s(\alpha+\gamma)/I_s})=(4.2\pm 2.3)\%$, whereas all the L-group chondrites by $I_s(\alpha+\gamma)/I_s$=8–16%, the average value being $(\overline{I_s(\alpha+\gamma)/I_s})=(12.8\pm2.3)\%$. As the $\Theta^*(\alpha+\gamma)$ transition temperatures of these plessite phases are within a limited range between 540°C to 570°C, the Ni content in the plessites is 25–30 wt%, being approximately constant. It may be concluded from Fig. 6, therefore, that one of characteristic differences of the olivine-hypersthene chondrite group from the olivine-bronzite chondrite group is a considerably larger relative content of the plessite phase in the former than in the latter.

Since the average value of $\Theta^*_{\gamma\rightarrow\alpha}$ is $\bar{\Theta}^*_{\gamma\rightarrow\alpha}(H)=650\pm16$°C and $\bar{\Theta}^*_{\gamma\rightarrow\alpha}(L)=661\pm13$°C, indicating that the mean Ni-content in the kamacite phase is 5.6 wt% and 5.2 wt% respectively in the H- and L-groups, it may be approximately considered that the Ni-content in kamacite is the H-group chondrites is nearly the same as that in the L-group chondrites or the former is a little larger than the latter, as graphically illustrated in Fig. 5. As shown in Fig. 6, however, the relative content of plessites of 25–30 wt% Ni in the L-group chondrites is about three times as much as that in the H-group chondrites. Hence the total percentage of Ni in the metal phases becomes considerably larger in the L-group chondrites than in the H-group chondrites.

In Section 2, we have obtained that the ratio of the saturation magnetization of plessite phase, $I_s^0(\alpha+\gamma)$, is approximately one-third of that of kamacite phase of (0–10) wt% Ni, $I_s^0(\alpha)$. Then, the average Ni content in the sum of kamacite and plessite phases of metal is estimated to be 8.4 and 12.9 wt% for the H-group and L-group chondrites respectively, where the Ni-content in the plessite phase is assumed to be 30 wt%. Assuming further that the average value of $I_s^0(\alpha)$ for 0–10 wt% in the Ni-content is approximately 2×10^2 emu/gm, the average contents of Fe and Ni in both groups are evaluated as 13.1 wt% Fe and 1.2 wt% Ni for the olivine-bronzite chondrite group and 7.2 wt% Fe and 0.9 wt% Ni for the olivine-hypersthene chondrite group. It may be concluded from these results that, on average, the Fe and Ni contents in the L-group chondrites are about one half and three-fourths respectively of those in the H-group chondrites. As for individual ordinary chondritic samples listed in Table 2 through Table 5, these conclusions on the average values of Fe and Ni contents can be considered to hold generally except one case (Yonozu). We may conclude thus

$$(I_s(\alpha+\gamma)/I_s)_L > (I_s(\alpha+\gamma)/I_s)_H \,, \tag{IV}$$

or

$$\left(\frac{W(\alpha+\gamma)}{W(\alpha+\gamma)+W(\alpha)}\right)_L > \left(\frac{W(\alpha+\gamma)}{W(\alpha+\gamma)+W(\alpha)}\right)_H \,. \tag{IV$'$}$$

Point (IV) represented by the above inequality relation could be an additional criterion to separate the L-group chondrites from the H-group chondrites.

6. Concluding Remarks

In the preceding sections, the intrinsic magnetic parameters, such as I_s, Θ, $\Theta^*_{\alpha\to\gamma}(\alpha)$, $\Theta^*(\alpha+\gamma)$ and $\Theta^*_{\gamma\to\alpha}$, of stone meteorites are discussed on the basis of the mineralogical and compositional classification of these meteoritic samples. The proposed method to plot the total I_s value against the major magnetic transition temperature in the cooling process in the I_s versus Θ_c diagram, illustrated in Fig. 5, seems to work reasonably well for the purpose of a magnetic classification of stone meteorites. It seems, however, that the boundary between the olivine-bronzite chondrite group and the olivine-hypersthene chondrite group in the I_s–Θ_c diagram is not clear enough, whereas the other space gaps among the various groups in the diagram may be considered sufficiently wide. On the other hand, a definite difference of the abundance ratio of the plessite phase to the kamacite phase between the H- and L-groups (represented by Fig. 6) can be taken as an additional criterion to separate the L-group chondrites from the H-group chondrites. The magnetic criteria represented by (I) through (IV) should have their physical meanings in terms of the compositional differences among the various groups of stone meteorites.

Since the UREY-CRAIG-MASON diagram has already been established, it may be obvious that the iron oxide is the richest and iron in metal and FeS is the poorest in the carbonaceous chondrites, and in a successively ordered sequence from carbonanceos chondrites to olivine-pigeonite chondrites, olivine-hypersthene chondrites, olivine-bronzite chondrites and enstatite chondrites, the abundance of iron oxide decreases, and on the contrary that of the metallic iron and troilite increases. As already mentioned in the introduction, the compositional characteristics of Fe should be reflected on the magnetic properties of various groups of chondrites. Noting the weight contents in a chondritic sample of pure metallic iron, kamacite of η in Ni content, taenite of p in Ni content, plessite of q in average Ni content and magnetite by $W(\mathrm{Fe}^0)$, $W(\alpha, \eta)$, $W(\gamma, p)$, $W(\alpha+\gamma, q)$ and $W(Mt)$ respectively, the total saturation magnetization (I_s) of the chondrite must be given by

$$I_s = W(\mathrm{Fe}^0)I_s(\mathrm{Fe}^0) + W(\alpha, \eta)I_s^{\alpha}(\eta) + W(\gamma, p)I_s^{\gamma}(p)$$
$$+ W(\alpha+\gamma, q)I_s^{\alpha+\gamma}(q) + W(Mt)I_s(Mt), \tag{3}$$

where $I_s(\mathrm{Fe}^0)$, $I_s^{\alpha}(\eta)$, $I_s^{\gamma}(p)$, $I_s^{\alpha+\gamma}(q)$ and $I_s(Mt)$ denote respectively the spontaneous magnetizations of pure metallic iron, the kamacite, the taenite, the plessite and magnetite. Naturally, η in kamacites, p in taenites and q in plessites do not necessarily take single values, and the magnetite under consideration can be some substituted magnetites.

It has been generally known that the enstatite chondrites have a higher total iron content than other groups of chondrites, and all the iron is present in the metal and the sulfide phases (MASON, 1962). This condition must result in the highest value of I_s for the enstatite chondrites. In the present study, only one sample of enstatite chondrite (Yamato (a)) could be magnetically examined in addition to its chemical and mineralogical analyses, but its I_s value is much higher than that of any other examined chondrites. The enstatite chondrite examined in the present study shows that

$$I_s(E) = W(\alpha, \eta_1)I_s^{\alpha}(\eta_1) + W(\alpha, \eta_2)I_s^{\alpha}(\eta_2), \tag{4}$$

where $\eta_1 = (2.5\text{–}3.0)$ wt%, $\eta_2 \simeq 25$ wt%, and $W(\alpha, \eta_1) + W(\alpha, \eta_2) \simeq 24$ wt%.

The chemical composition of olivine-bronzite chondrites has been characterized by having most of their iron in the free state, the FeO content ranging from 7 to 12 wt% (MASON, 1962). In the present study, 10 samples of olivine-bronzite chondrites are magnetically studied. The ferromagnetic composition of 8 samples among the examined ten is represented by

$$I_s(H) = W(\alpha, \eta)I_s^{\alpha}(\eta) + W(\alpha+\gamma, q)I_s^{\alpha+\gamma}(q), \tag{5}$$

where $\eta = (4.3\text{–}6.3)$ wt%, $q = (25\text{–}30)$ wt%, and $W(\alpha+\gamma, q)I_s^{\alpha+\gamma}(q)/I_s(H) = (3\text{–}5)$%. The I_s composition of other two olivine-bronzite chondrites is represented by

$$I_s'(H) = W(\alpha, \eta)I_s^{\alpha}(\eta) + W(Mt)I_s(Mt) \qquad \text{(Yamato-73-01)},$$

with $\eta = 5.3$ wt% and $W(Mt)I_s(Mt)/I_s'(H) = 22$%, and

$$I_s''(H) = W(\alpha, \eta_1)I_s^{\alpha}(\eta_1) + W(\alpha, \eta_2)I_s^{\alpha}(\eta_2) \qquad \text{(Yamato-73-04)},$$

with $\eta_1 = 6.5$ wt%, $\eta_2 = 13.0$ wt% and

$$I_s^{\alpha}(\alpha, \eta_1)I_s^{\alpha}(\eta_1)/I_s''(H) = 38\,\%.$$

These two samples could be regarded a little unusual at least statistically. Actually, the optical mineralogical study of Yamato-73-01 shows that considerable parts of FeNi metal grains in this sample are weathered, becoming red-brownish colour—probably hydroxides of iron (?). The I_s values of this olivine-bronzite chondrite group range from 15 to 40 emu/gm, which means that the content of nickel-iron, which is $W(\alpha, \eta) + W(\alpha+\gamma, p)$ in most cases, ranges from 8 to 20 wt%.

The chemical composition of olivine-hypersthene chondrites has been characterized by having a large part of their iron in the ferromagnesian silicates, the FeO content ranging from 12 to 22 wt% (MASON, 1962), which means that the content of nickel-iron is considerably smaller in the olivine-hypersthene chondrite group than in the olivine-bronzite chondrite group. In the present study, 8 samples of olivine-hypersthene chondrites are magnetically studied. The ferromagnetic composition of all these chondrites is represented by

$$I_s(L)=W(\alpha,\eta)I_s^{\alpha}(\eta)+W(\alpha+\gamma,q)I_s^{\alpha+\gamma}(q), \qquad (6)$$

where $\eta=(4.0\text{–}5.6)$ wt%, $q=(25\text{–}30)$ wt% and $W(\alpha+\gamma,q)I_s^{\alpha+\gamma}(q)/I_s(L)=(8\text{–}16)$%. A remarkable contrast of the ferromagnetic metal phase characteristics of the olivine-hypersthene chondrite group to those of the olivine-bronzite chondrite group is a high value of ratio $W(\alpha+\gamma,q)I_s^{\alpha+\gamma}(q)/I_s(L)$, which indicates that the abundance ratio of the plessite phase to the kamacite phase in the olivine-hypersthene chondrites is about three times as much as that in the olivine-bronzite chondrites. The exact physical meaning of this difference has not yet been clarified.

Except one example (Fukutomi) which could be alternatively identified to an olivine-bronzite chondrite (MIYASHIRO *et al.*, 1964), the I_s values of other olivine-hypersthene chondrites range from 7 to 13 emu/gm, which indicates that $W(\alpha,\eta)+W(\alpha+\gamma,p)$ ranges from 4 to 7 wt% in the olivine-hypersthene chondrites.

The carbonaceous chondrites are chemically characterized by having higher content of FeO than other chondrites, a considerable abundance of carbon and lack or absence of free nickel-iron (MASON, 1962). The magnetic characteristics of three samples of carbonaceous chondrite examined in the present study may well represent these characteristics. Namely, the ferromagnetic composition of two carbonaceous chondrites (Yamato (c) and Mokoia) is expressed by

$$I_s(C)=W(Mt)I_s(Mt), \qquad (7)$$

and that of a markedly metamorphozed C_4 chondrite (Leoville) is given by

$$I_s'(C)=W(Mt)I_s(Mt)+W(\alpha,\eta)I_s^{\alpha}(\eta),$$

where $\eta=4.4$ wt% and $W(\alpha,\eta)I_s^{\alpha}(\eta)/I_s'(C)$ is 14%. The I_s values of these carbonaceous chondrites are between 8 and 11 emu/gm, which indicates that the weight content of magnetite ranges from 9 to 12%.

It is believed that most achondrites are similar to common terrestrial igneous rocks, suggesting the same magmatic fractionation process in both cases; achondrites are essentially devoid of nickel-iron metal. Actually, the bulk chemical composition of two (Yamato (b) and Yamato-73-07) of three achondrites magnetically examined in the present study have been analyzed (NAGATA *et al.*, 1975; NAGATA *et al.*, 1976 b). Both of them chemically belong to the Ca-poor achondrite group, and their metallic NiFe content is only 0.66 and 0.5 wt% respectively. Thus, the magnetic properties of these three achondrites are characterized by their extremely small value of I_s, which ranges from 0.17 to 0.53 emu/gm.

The ferromagnetic composition of the two chemically analyzed achondrites is represented by

$$I_s(\text{achondrite}) = W(\text{Fe}^0) I_s(\text{Fe}^0)\,, \tag{8}$$

whereas I_s of Yamato-74-013 achondrite can be represented by

$$I_s'(\text{achondrite}) = W(\text{Fe}^0) I_s(\text{Fe}^0) + W(Mt) I_s(Mt)\,,$$

where $W(Mt)I_s(Mt)/I_s'(\text{achondrite}) = 19\%$. The magnetite phase has been often found in augite achondrites and diopside-olivine achondrites (MASON, 1962), but it may be a provisional conclusion at present that the ferromagnetism of achondrites is represented by a very small amount (<1 wt%) of almost pure metallic iron.

As already mentioned in the introduction, this work is only a preliminary trial of a possible magnetic classification of stone meteorites on the basis of experimentally determined magnetic parameters of 25 stone meteorites. Among the magnetically examined stone meteorites, only one was enstatite achondrite (E), three were carbonaceous chondrites (C), three were achondrites (aC) and no olivine-pigeonite chondrite (LL) was examined. It must be noted, therefore, that the present conclusions on a magnetic classification of stone meteorites, summarized in Figs. 5 and 6 and eqs. (4) through (8) in this section, should be regarded as a provisional scheme of a possible magnetic classification of stone meteorites.

On concluding this report, the authors wish to express their sincere thanks to Dr. M. SHIMA, Dr. K. YAGI and Dr. K. YANAI for their very useful suggestions and advice from the cosmochemical and mineralogical viewpoints.

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(*Received October 2, 1976*)