MAGNETIC CLASSIFICATION OF STONY METEORITES (IV)

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Abstract: The intensity of saturation magnetization (I_s) and a ratio of the saturation magnetization of α-phase FeNi component to I_s, $I_s(\alpha)/I_s$, of 1 E-chondrite, 8 H-chondrites, 10 L-chondrites, 3 LL-chondrites, 8 C-chondrites, 6 diogenites, 1 howardite and 3 eucrites are plotted on an I_s versus $I_s(\alpha)/\mathrm{I_s}$ diagram. On this diagram, E-, H-, L-, LL- and C-chondrites and achondrites are well separately grouped to be magnetically identified.

1. Introduction

In the previous report (NAGATA, 1979a), E-, H-, L-, LL- and C-chondrites and achondrites are expressed as mutually well separated groups in a diagram of the saturation magnetization (I_s) versus a ratio of the saturation magnetization of kamacite phase ($I_s(\alpha)$) to I_s, namely $I_s(\alpha)/I_s$. Experimentally, the I_s-value is determined from a complete magnetic hysteresis curve measured by a vibration magnetometer at room temperature for a magnetic field range of −15 to +15 kOe; the $I_s(\alpha)$-value is determined from thermomagnetic curves for a temperature range from 0°C to 850°C measured by a vibration magnetometer with 10 kOe in magnetic field.

The I_s-value of stony meteorites can well represent the content of metallic phase component in E-chondrites, ordinary chondrites and achondrites, where generally

$$I_s(\mathrm{E}) > I_s(\mathrm{H}) > I_s(\mathrm{L}) > I_s(\mathrm{LL}) > I_s(\mathrm{achondrite}). \qquad (1)$$

Although the content of native iron is small in C-chondrites, their ferromagnetism is mainly due to the presence of magnetite in most cases so that their I_s-values range from less than 1 emu/gm to 10 emu/gm or a little more, which are comparable with the I_s-values of LL- and L-chondrites. Hence, the chemical classification of stony meteorites cannot be completed by the I_s-value alone.

On the other hand, the composition of metallic grains in stony meteorites can be reasonably well identified by analyzing their thermomagnetic curves. Namely, approximate contents of α-, $(\alpha+\gamma)$ and γ-phases of FeNi-alloy can be evaluated by measuring their respective saturation magnetization intensities, $I_s(\alpha)$, $I_s(\alpha+\gamma)$ and $I_s(\gamma)$. If the Ni-content in metals is less than about 6 wt.%, the whole metal system is in α-phase. When the Ni-content exceeds 6 wt.%, the metal system comprises α-phase and $(\alpha+\gamma)$-phase. When the Ni-content becomes further larger, the metal system consists of α-, $(\alpha+\gamma)$- and γ-phases. With a further increase in the Ni-content, the metal becomes to comprise $(\alpha+\gamma)$- and γ-phases, and finally it becomes γ-phase only for a large Ni-content. Results of thermomagnetic measurements of E-, H-, L-, and LL-chondrites have shown that

$$\left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{E}} > \left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{H}} > \left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{L}} > \left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{LL}} . \qquad (2)$$

This inequality relation of $I_s(\alpha)/I_s$ corresponds to the Prior rule in regard to the Ni-content in metals in E- and ordinary chondrites. Since C-chondrites contain no or only a little amount of metals and their I_s-value is mainly due to magnetite in most cases, their $I_s(\alpha)/I_s$ value is zero or very small. Thus, we get from magnetic measurements,

$$\left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{LL}} > \left\{\frac{I_s(\alpha)}{I_s}\right\}_{\mathrm{C}} . \qquad (2^*)$$

On the basis of eqs. (2) and (2*), C-chondrites can be magnetically identified separately from the two groups of L- and LL-chondrites.

The two inequality relationships in regard to I_s and $I_s(\alpha)/I_s$ of stony meteorites have been generally established as the metallic iron content in chondrites and achondrites and the Ni-content in metallic component in chondrites respectively. In the previous report, experimental results of the magnetic measurements of 33 stony meteorites (1 E-chondrite, 9 H-chondrites, 11 L-chondrites, 3 LL-chondrites, 6 C-chondrites and 3 achondrites) have been summarized, and these stony meteorites have been magnetically classified on the basis of the principles mentioned above.

In the present report, results of magnetic measurements of 2 C-chondrites and 7 achondrites are newly added, and all magnetically examined samples of stony meteorites are re-examined from the viewpoint of their chemical and petrographical compositions. As a consequence, two chondrites which have been too much weathered and oxidized are eliminated from the final summary table of magnetic classification.

As the numbers of magnetically examined C-chondrites and achondrites are increased to 8 and 10 respectively in the present study, their characteristic magnetic properties may have become more statistically representative for respective groups for the purpose of magnetic classification of the stony meteorites. In this regard, the general magnetic properties of C-chondrites will be discussed in some detail.

2. General Magnetic Classification of Stony Meteorites

The observed values of I_s and ratios $I_s(\alpha)/I_s$, $I_s(\alpha+\gamma)/I_s$ and $I_s(\gamma)/I_s$ and

Table 1. Magnetic parameters of stony meteorites for a magnetic classification.

Meteorite	Classification	I_s (emu/gm)	$\frac{I_s(\alpha)}{I_s}$	$\frac{I_s(\alpha+\gamma)}{I_s}$ (%)	$\frac{I_s(\gamma)}{I_s}$	$\frac{I_s(Mt)}{I_s}$	H_c (Oe)	Investigator
(E-chondrite)								
Yamato-691(a)	E	48.0	97	0	3	0	12	(1)
(H-chondrite)								
Seminole	H_4	24.3	94	6	0	0	18	(1)
Kesen	H_4	34.4	95	5	0	0	8	(1)
Yonozu	$H_{4,5}$	24.2	87	13	0	0	42	(1)
Yamato-74371	H_5	33.5	95	5	0	0	10	(1)
Yamato-74647	H_5	27.9	94	6	0	0	14	(1)
Mt. Baldr-b	H_6	27.4	88	10	2	0	10	(1)
Mt. Brown	H_6	40.0	90	5	5	0	—	(2)
Yamato-694 (d)	H	32.3	94	6	0	0	23	(1)
(L-chondrite)								
Yamato-74191	L_3	6.8	79	21	0	0	30	(1)
Dalgety Down	L_4	9.7	85	14	0	0	117	(1)
Bjarböle	L_4	13.0	85	10	0	0	—	(2)
Barratta	L_4	12.0	80	15	3	0	—	(2)
Yamato-7304 (m)	L_5	16.6	90	0	10	0	4	(1)
Fukutomi	L_5	22.9	82	18	0	0	20	(1)
Homestead	L_5	10.0	80	15	5	0	—	(2)
Yamato-74362	L_6	8.1	81	19	0	0	38	(1)
Allan Hills-7609	L_6	8.4	65	35	0	0	160	(0)
Mino	L	11.0	80	20	0	0	3	(1)
(LL-chondrite)								
Yamato-74442	LL_4	6.0	45	35	20	0	85	(0)
Yamato-74646	$LL_{5,6}$	3.2	19	7	74	0	20	(0)
St. Severin	LL_6	4.7	45	55	0	0	500	(1)
(C-chondrite)								
Orgueil	C_1	11.9	0	0	0	100	107	(3.4)
Ivuna	C_1	11.2	0	0	0	100	—	(3.4)
Mokoia	C_2	8.0	0	0	0	100	—	(2)
Yamato-74662	C_2	0.81	5	0	85	10	149	(0)
Yamato-693 (c)	C_3	10.8	0	0	0	100	157	(1)
Allende	C_3	0.61	0	0	95	5	143	(1)
Leoville	C_3	10.3	6	0	0	94	34	(1)
Karoonda	C_4	7.8	0	0	0	100	155	(1)
(Achondrite)								
Yamato-692 (b)	Diogenite	0.19	81	0	19	0	42	(1)
Yamato-74013	Diogenite	0.17	56	0	44	0	10	(1)
Yamato-74037	Diogenite	0.32	100	0	0	0	—	(0)

Table 1 (*continued-2*).

Meteorite	Classification	I_s (emu/gm)	$\frac{I_s(\alpha)}{I_s}$	$\frac{I_s(\alpha+\gamma)}{I_s}$	$\frac{I_s(\gamma)}{I_s}$	$\frac{I_s(Mt)}{I_s}$	H_c (Oe)	Investigator
			(%)					
Yamato-74097	Diogenite	0.32	100	0	0	0	13	(0)
Yamato-74648	Diogenite	0.20	100	0	0	0	85	(0)
Yamato-75032	Diogenite	0.042	100	0	0	0	93	(0)
Yamato-7308 (*l*)	Howardite	0.53	100	0	0	0	13	(1)
Yamato-74159	Eucrite	0.061	100	0	0	0	265	(0)
Yamato-74450	Eucrite	0.22	100	0	0	0	58	(0)
Allan Hills-76005	Eucrite	0.076	100	0	0	0	15	(0)

(0) NAGATA, T. (This paper). (1) NAGATA T. and SUGIURA, N. (1976). (2) STACEY, F. D. *et al.* (1961). (3) LARSON, E. E. *et al.* (1974). (4) BRECHER, A. and ARRHENIUS, G. (1974).

the ratio of saturation magnetization of magnetite to the total saturation magnetization, $I_s(Mt)/I_s$ are summarized in Table 1 for 40 stony meteorites, *i.e.* 1 E-chondrite, 8 H-chondrites, 10 L-chondrites, 3 LL-chondrites, 8 C-chondrites and 10 achondrites. The metamorphism degrees of 5 chemical groups of chondrites and the petrographical classifications of the achondrite group are given in Table 1, as far as petrological data are available. In addition to the intrinsic magnetic parameters such as I_s and $I_s(\alpha)/I_s$, etc., the magnetic coercive force (H_c) of each sample is given in the same table as a representative of the structure-dependent magnetic parameter.

It will be noted in Table 1 that the inequality relationships given by eqs. (1), (2) and (2*) generally hold among the six groups of stony meteorites, E-, H-, L-, LL- and C-chondrites and achondrites. Fig. 1 illustrates the I_s versus $I_s(\alpha)/I_s$ diagram for these 40 stony meteorites. In this diagram, E-, H-, and L-chondrite groups and achondrite group are separated from one another mostly due to the mutual differences of their I_s-values, while LL- and C-chondrites are separately grouped mostly due to their $I_s(\alpha)/I_s$ values. Summarizing these measured values of I_s and $I_s(\alpha)/I_s$ of stony meteorites, their magnetic classification criteria may be given by Table 2.

In the first and second reports of magnetic classification of stony meteorites (NAGATA and SUGIURA, 1976; NAGATA, 1978), the main magnetic transition temperature (Θ_c) in the cooling branch of thermomagnetic curve was proposed in place of the $I_s(\alpha)/I_s$ value. The Θ_c value represents Curie point for Ni-poor α-phase FeNi, γ-phase FeNi and magnetite, while it represents the $\gamma \rightarrow \alpha$ transformation temperature for Ni-rich α-phase FeNi. In the case of stony meteorites, Θ_c represents Curie point of magnetite or γ-phase FeNi in C-chondrites, Curie-point of Ni-poor α-phase FeNi in E-chondrites and some achondrites, and the

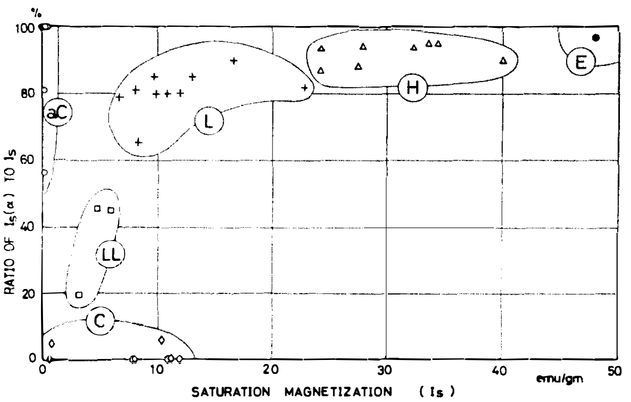

Fig. 1. Diagram of I_S versus $I_S(\alpha)/I_S$ to classify stony meteorites in their chemical groups.

Table 2. Classification of stony meteorites in terms of I_S and $I_S(\alpha)/I_S$.

Meteorite	Range of I_s (emu/gm)	Range of $I_s(\alpha)/I_s$ (%)
E-chondrite	40<	95<
H-chondrite	23–40	80–95
L-chondrite	8–22	60–90
LL-chondrite	3– 6	20–45
C-chondrite	0.5–12	0– 5
Achondrite	<1	50–100

$\gamma \rightarrow \alpha$ transition temperature in H- and L-chondrites and some other achondrites. In an I_s versus Θ_c diagram, E-, H-, L- and C-chondrites and achondrites can be well separately grouped, but the definition of Θ_c becomes ambiguous for LL-chondrites whose metallic components comprise α-, $(\alpha+\gamma)$- and γ-phases. In the third report (NAGATA, 1979a), therefore, a new diagram of I_s verses $I_s(\alpha)/I_s$ has been newly introduced. The physical meaning of $I_s(\alpha)/I_s$ is defined without any ambiguity, as described in the preceding section, and the six chemically classified groups of stony meteorites can be well separately represented on an I_s versus $I_s(\alpha)/I_s$ diagram.

In Fig. 1, $(1-I_s(\alpha)/I_s)$ represents the Ni-content in the ferromagnetic constituent in each meteoritic sample, where $1-I_s(\alpha)/I_s$ is equal to $\{I_s(\alpha+\gamma)+I_s(\gamma)\}/I_s$ for E-, H-, L- and LL-chondrites and achondrites. The plessite phase, $(\alpha+\gamma)$-phase, is usually transformed to γ-phase by the initial heating above a critical $(\alpha+\gamma)\rightarrow\gamma$ transformation temperature in laboratory time-scale. It will be obvious therefore that $\{I_s(\alpha+\gamma)+I_s(\gamma)\}/I_s$ directly represents a relative content of Ni-rich γ-phase at temperatures above the critical transformation temperature. An approximate value of the Ni-content in the metallic component can be estimated from the measured values of $I_s(\alpha)/I_s$, $I_s(\alpha+\gamma)/I_s$ and $I_s(\gamma)/I_s$ for these stony meteorites as Ni°/(Fe°+Ni°) (NAGATA, 1979b). As given in Table 1, the Ni-content, Ni°/(Fe°+Ni°), increases with an increase of $\{I_s(\alpha+\gamma)+I_s(\gamma)\}I_s$ in the order of sequence as E→H→L→LL.

The chemical composition of ferromagnetic constituents in C-chondrites is somewhat complicated as discussed in the following section. It is certain, however, that $I_s(\alpha)/I_s$ of C-chondrites is practically zero or extremely small in comparison with other stony meteorites so that the plots of C-chondrite data are concentrated very close to the $I_s(\alpha)/I_s=0$ axis in an I_s versus $I_s(\alpha)/I_s$ diagram, as shown in Fig. 1.

It seems that the chemical composition of ferromagnetic metals is fairly complicated for individual achondrites. 10 achondrites summarized in Table 1 are chemically and petrographically classified into 6 diogenites, 3 eucrites and 1 howardite, but no special magnetic characteristic can correspond to the classified groups. It is clear in the table, however, that the I_s-value is very small for all achondrites, being smaller than 0.53 emu/gm.

3. Magnetic Characteristics of Carbonaceous Chondrites

The magnetic properties of 8 C-chondrites are summarized in Table 1. Results of chemical analyses have shown that Orgueil, Ivuna and Mokoia contain no metal at all (WIIK, 1956), whence their ferromagnetism is entirely due to the presence of magnetite. Yamato-693(c) C_3-chondrite contains magnetite as the major opaque mineral and a very small amount of metal in addition (OKADA, 1975). The I_s-values of these C-chondrites range from 8 to 12 emu/gm.

On the other hand, the major ferromagnetic constituent in Allende C_3-chondrite was identified to taenite of (31.4% Fe, 67% Ni, 1.6% Co) in composition (CLARK *et al.*, 1970). Since γ-phase FeNi metals of about 65% Ni have their Curie point at about 600°C, it is rather difficult to magnetically distinguish such a γ-phase FeNi alloy from magnetite. Only a possible magnetic method is to check a characteristic phase transition of magnetite between an orthorhombic structure (below the transition temperature) and a cubic structure at a critical temperature which is -153°C for pure magnetite (*e.g.* NAGATA, 1965). This kind of low temperature test of Allende was carried out by WASILEWSKI (private communication, 1978), his result confirming that Allende contains no detectable amount of magnetite. Then, I_s of Allende should be due to the γ-phase FeNi metal of 67% Ni, which has Curie point at 610°C. Yamato-74662 C-chondrite also contains a small amount of metallic grains in addition to a very small amount of magnetite. Since the main Curie point of this C-chondrite is about 600°C, it seems likely that the metallic grains are γ-phase FeNi of about 65% Ni. If so, the observed

I_s-value suggests that the content of metallic grains is about 0.8 wt.%. Actually a chemical analysis of this C-chondrite (YANAI and HARAMURA, 1978) has shown that contents of Ni and Co are 0.66 and 0.06% respectively, though the content of metallic Fe has not yet been determined.

It seems then that the distribution of C-chondrite data on the I_s versus $I_s(\alpha)/I_s$ diagram shown in Fig. 1 could be separated into two groups, *i.e.* a group of 6 C-chondrites having I_s=8–12 emu/gm and the other group of 2 C-chondrites having I_s=0.6–0.8 emu/gm. A possible provisional interpretation of the second group will be such that this group is an extension of a sequence of E→H→L→LL toward smaller values of both I_s and $I_s(\alpha)/I_s$ on the I_s versus $I_s(\alpha)/I_s$ diagram. It may be argued then that the ferromagnetism of some C-chondrites is mainly due to a small amount of Ni-rich taenite but not due to magnetite. The origin of ferromagnetism of the first group of C-chondrite is, as well known, due to magnetite.

References

BRECHER, A. and ARRHENIUS, G. (1974): The paleomagnetic record in carbonaceous chondrites' natural remanence and magnetic properties. J. Geophys. Res., **79**, 2081–2106.

CLARK, R. S., Jr., JAROSEARICH, E., MASON, B., NELSON, J., GOMEX, M. and HUDE, J. R. (1970): The Allende, Mexico, meteorite shower. Smithonian Contrib. Earth Sci., **5**, 1–53.

LARSON, E. E., WATSON, D. E., HERNDEN, J. M. and ROWE, N. W. (1974): Thermomagnetic analysis of meteorites 1. C_1 chondrites. Earth Planet. Sci. Lett., **21**, 345–350.

NAGATA, T. (1965): Low temperature characteristics of rock magnetism. J. Geomagn. Geoelectr., **17**, 315–324.

NAGATA, T. (1978): Supplementary notes on the magnetic classification of stony meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 233–239.

NAGATA, T. (1979a): Magnetic classification of Antarctic stony meteorite (III). Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 223–237.

NAGATA, T. (1979b): Magnetic properties of Yamato-7301(j), -7305(k) and -7304(m) chondrites in comparison with their mineralogical and chemical compositions. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 250–269.

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

OKADA, A. (1975): Petrological studies of the Yamato meteorite, Part I. Mineralogy of the Yamato meteorite. Mem. Natl Inst. Polar Res., Spec. Issue, **5**, 14–16.

STACEY, F. D., LOVERING, J. F. and PARRY, L. G. (1961). Thermomagnetic properties, natural magnetic moments and magnetic anisotropies of some chondritic meteorites. J. Geophys. Res., **66**, 1523–1534.

WIIK, H. B. (1956): The chemical composition of some stony meteorites. Geochim. Cosmochim. Acta, **9**, 279–289.

YANAI, K. and HARAMURA, H. (1978): Yamato-74662 meteorite: a carbonaceous chondrite type II. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 264–267.

(*Received April 24, 1979*)