

# MAGNETIC CLASSIFICATION OF ANTARCTIC ACHONDRITES

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**Abstract:** The magnetic hysteresis curves and the thermomagnetic curves of 17 Antarctic achondrites are measured. The saturation magnetization ( $I_s$ ) of 3 ureilites ranges 2.2–6.4 emu/gm while  $I_s$  is smaller than 0.53 emu/gm for 7 diogenites, 6 eucrites and 1 howardite.

By the thermomagnetic analysis, the  $I_s$  value of each achondrite is resolved into the saturation magnetization of kamacite,  $I_s(\alpha)$ , that of plessite,  $I_s(\alpha+\gamma)$ , that of taenite  $I_s(\gamma)$ , and that of shreibersite,  $I_s(\text{Ph})$ . Results show that  $I_s(\alpha)/I_s \leq 0.40$  for diogenites, whereas  $1 \geq I_s(\alpha)/I_s \geq 0.79$  for eucrites and howardites, which indicate that Ni-content in metallic nickel-irons in diogenites is definitely larger than that in eucrites and howardites.

On an  $I_s(\alpha)/I_s$  versus  $I_s$  diagram, therefore, the three groups of achondrite are well separately grouped, just as so in the magnetic classification of chondrites.

## 1. Introductory Remarks

A trial to magnetically classify stony meteorites into the five chemical groups of chondrites, *i.e.*, E-, H-, L-, LL- and C-chondrites and a group of achondrites appears to be satisfactorily successful (NAGATA and SUGIURA, 1976; NAGATA, 1979a, c). The basic principle of the magnetic classification comprises three markedly characteristic features of the ferromagnetic constituents in these stony meteorites; namely

(a) an inequality relationship of metallic iron content among E- and the ordinary chondrites, which is expressed in terms of the saturation magnetization ( $I_s$ ) as

$$I_s(\text{E}) > I_s(\text{H}) > I_s(\text{L}) > I_s(\text{LL}), \quad (1)$$

(b) an inequality relationship of Ni-content in the ferromagnetic constituent among E-, C-, and the ordinary chondrites, which is represented in terms of the ratio of saturation magnetization of kamacite phase to that of total magnetization,  $I_s(\alpha)/I_s$ , as

$$[I_s(\alpha)/I_s]_{\text{E}} \geq [I_s(\alpha)/I_s]_{\text{H}} > [I_s(\alpha)/I_s]_{\text{L}} > [I_s(\alpha)/I_s]_{\text{LL}} > [I_s(\alpha)/I_s]_{\text{C}}, \quad (2)$$

and (c) an extremely small content of metallic iron in achondrites which is expressed as

$$I_s(\text{achondrite}) \ll I_s(\text{LL}), I_s(\text{achondrite}) < I_s(\text{C}). \quad (3)$$

The inequality relation given by eq. (1) approximately corresponds to Urey-Craig law (UREY and CRAIG, 1953), which shows that the total amount of Fe in metal, troilite (FeS) and FeO in silicates is approximately constant throughout all kinds of chondrite, and

$$C_E(\text{Fe}^*) > C_H(\text{Fe}^*) > C_L(\text{Fe}^*) > C_{LL}(\text{Fe}^*) > C_C(\text{Fe}^*), \quad (4)$$

$$C_E(\text{FeO}) < C_H(\text{FeO}) < C_L(\text{FeO}) < C_{LL}(\text{FeO}) < C_C(\text{FeO}), \quad (5)$$

where  $C$  denotes the content of a chemical component given within the parenthesis for a chondrite group assigned by the suffix, and  $\text{Fe}^*$  presents the sum of metallic iron ( $\text{Fe}^\circ$ ) and Fe in FeS. Since the content of FeS is roughly constant in all kinds of chondrite, eq. (4) can be practically replaced by

$$C_E(\text{Fe}^\circ) > C_H(\text{Fe}^\circ) > C_L(\text{Fe}^\circ) > C_{LL}(\text{Fe}^\circ) > C_C(\text{Fe}^\circ). \quad (4^*)$$

In the proposed scheme of magnetic classification of stony meteorite,  $I_s$  is approximately proportional to  $C(\text{Fe}^\circ)$  for E-, H-, L- and LL- chondrites because the ferromagnetic constituent in these chondrites is only native iron, thus the inequality relation given by eq. (1) holding for these chondrites.

In carbonaceous chondrites (C-chondrites), however, the main ferromagnetic component is often magnetite ( $\text{Fe}_3\text{O}_4$ ) in a well oxidized C-chondrite group, whereas it is still Ni-rich metal (taenite) and the iron oxide is mostly of the form of FeO and no or very little  $\text{Fe}_2\text{O}_3$  in an insufficiently oxidized group of C-chondrite. It has been proposed by NAGATA (1979c), therefore, that C-chondrites could be magnetically classified into two groups, *i.e.*, (i) magnetite C-chondrite, in which  $I_s$  of magnetite (Mt) is much larger than that of metallic iron, namely  $I_s(\text{Mt}) \gg I_s(\text{FeNi})$ , and (ii) taenite C-chondrite, in which  $I_s$  is mostly due to the presence of taenite, namely  $I_s(\text{FeNi}) \gg I_s(\text{Mt})$ .

For magnetite C-chondrites,  $I_s$ -value caused by the presence of magnetite amounts to 8–12 emu/gm, which is a little larger than  $I_s(\text{LL})$  and almost equal to or a little smaller than  $I_s(\text{L})$ . For taenite C-chondrites,  $I_s$ -value is considerably smaller than  $I_s(\text{LL})$ , thus an inequality relationship,  $I_s(\text{Taenite-C}) \ll I_s(\text{LL})$ , holding in correspondence to eq. (4\*). Since the proposed classification of C-chondrites into Magnetite-C and Taenite-C has not yet been internationally accepted and magnetite C-chondrites appear to be more abundant than taenite C-chondrites,  $I_s(\text{C})$  is not taken into consideration in the inequality sequence given by eq. (1). If the paramagnetic susceptibility ( $\chi_p$ ) of chondrites could be sufficiently precisely measured, eq. (5) would be magnetically represented by

$$\chi_p(\text{E}) < \chi_p(\text{H}) < \chi_p(\text{L}) < \chi_p(\text{LL}) < \chi_p(\text{C}), \quad (5^*)$$

because the paramagnetism of natural rocks is mostly due to FeO in olivines, pyroxenes and other Fe-bearing silicate minerals (NAGATA, 1961). Because of the co-existence of a fair amount of ferromagnetic minerals such as native irons and mag-

netites in chondritic meteorites, however, an experimental technique to precisely measure their paramagnetic susceptibility has not yet been established.

On the other hand, an inequality sequence presented by eq. (2) may approximately represent Prior rule (PRIOR, 1920), which shows that ratio  $C(\text{Ni})/C(\text{Fe})$  in metallic phase in chondrites is characterized by

$$\left[ \frac{C(\text{Ni})}{C(\text{Fe})} \right]_{\text{E}} < \left[ \frac{C(\text{Ni})}{C(\text{Fe})} \right]_{\text{H}} < \left[ \frac{C(\text{Ni})}{C(\text{Fe})} \right]_{\text{L}} < \left[ \frac{C(\text{Ni})}{C(\text{Fe})} \right]_{\text{LL}}, \quad (6)$$

because an increase of Ni-content in the metallic phase, which is composed mostly of Fe and Ni, results in a decrease of  $\alpha$ -phase (kamacite phase) and an increase of  $(\alpha + \gamma)$ -phase (plessite phase) and/or  $\gamma$ -phase (taenite phase). Since, further, there is no or very little presence of kamacite in both magnetite and taenite C-chondrites and their ferro- or ferri-magnetism is almost completely due to either magnetite or taenite, it is experimentally obvious that  $[I_s(\alpha)/I_s]_{\text{C}} \ll [I_s(\alpha)/I_s]_{\text{LL}}$ . Thus, an inequality sequence expressed by eq. (2) generally holds for chondrites.

Inequality relationship eq. (1) can reasonably well group E-, H- and L-chondrites separately from one another with respect to a parameter value  $I_s$ , but the  $I_s$ -value range of LL-chondrites partially overlaps with that of L-chondrites. Inequality relationship eq. (2) can group L-, LL- and C-chondrites well separately from one another, but the range of  $I_s(\alpha)/I_s$  of H-chondrites partially overlap with that of

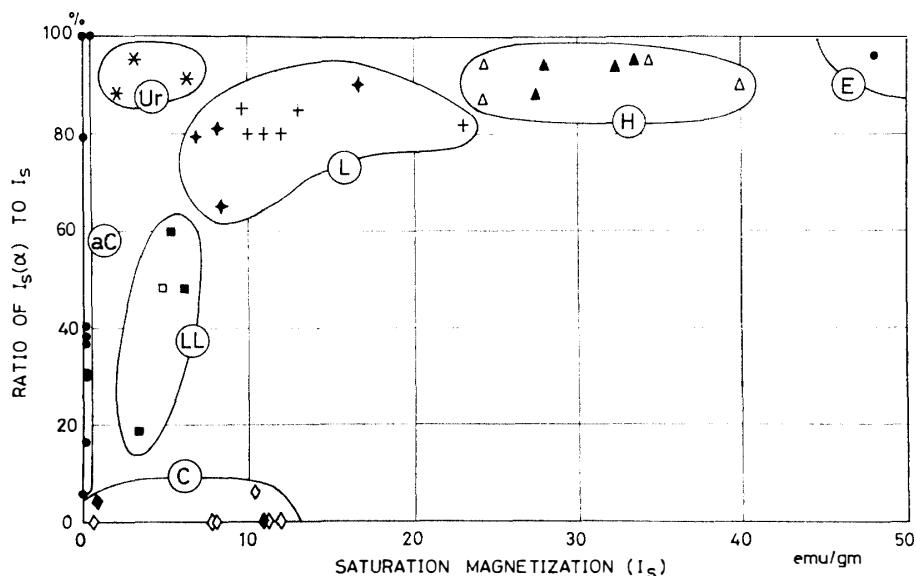


Fig. 1.  $I_s(\alpha)/I_s$  versus  $I_s$  diagram to magnetically classify 5 chemical groups of chondrites, ureilites and a group of other achondrites.

E: E-chondrite domain. Ur: Ureilite domain. H: H-chondrite domain. C: C-chondrite domain. L: L-chondrite domain. aC: Domain for eucrites, howardites and diogenites. LL: LL-chondrite domain.

E-chondrites on one hand and that of L-chondrites on the other hand. On a two-dimensional diagram of  $I_s$  versus  $I_s(\alpha)/I_s$ , however, all five chemical groups of chondrites are grouped well separately from one another, as illustrated in an example in Fig. 1.

All kinds of achondrites except a group of ureilite contain a very small amount of native iron, less than 0.3 wt%, so that an inequality relation eq. (3) generally holds except for ureilites. In an  $I_s$  versus  $I_s(\alpha)/I_s$  diagram for stony meteorites, therefore, the domains of achondrites (except ureilites) occupies a very narrow strip of width from 0 to 0.6 emu/gm on abscissa, which is well separated from the domains of five groups of chondrites. However, achondrites also have been petrographically and chemically classified into several groups, particularly Ca-poor achondrite groups such as aubrites, diogenites and ureilites, and Ca-rich groups such as eucrites and howardites, which are relatively abundant in identified achondrites. Probably because of a small amount of its presence, characteristic features of native iron in various achondrites have not yet been fully clarified. Since the magnetic method to identify  $\alpha$ -,  $(\alpha+\gamma)$ - and  $\gamma$ -phases in metallic irons in chondrites appears to be reasonably successful, a similar magnetic method could be used in characterizing metallic phases in various achondrites to a certain extent. As an extension of the magnetic classification studies of stony meteorites, the present note will deal with the magnetic characteristics of Antarctic achondrites.

## 2. Basic Magnetic Properties of Antarctic Achondrites

Magnetic properties of 17 Antarctic achondrites have been examined to date. These achondrites are petrographically and chemically classified into 7 diogenites, 5 eucrites, 1 howardite, 3 ureilites and 1 eucritic unique achondrite.

The magnetic parameters of these achondrites, such as the saturation magnetization ( $I_s$ ), the saturation remanence or the saturated isothermal remanent magnetization ( $I_R$ ), the coercive force ( $H_c$ ), the remanence coercive force ( $H_{RC}$ ), and the paramagnetic susceptibility ( $\chi_p$ ), all at room temperature (20°C), are summarized in Table 1.

As expected,  $I_s$ -values of three ureilites are much larger than those of other achondrites such as diogenites, eucrites and howardites, being the same order of magnitude as those of LL-chondrites. Although the petrological composition and texture of these three ureilites have been studied in some detail (TAKEDA *et al.*, 1979, 1980), no special mineralogical studies on the metallic component in these ureilites have been made yet. However, it is clearly observed by qualitative electron-microprobe analysis that these three ureilites contain much more nickel-iron metals than the other 14 examined achondrites such as diogenites, eucrites, a howardite and an eucritic unique achondrite. The content of nickel-iron metal in Yamato-74123, -74659 and ALHA77257 are 3.20, 1.12 and 1.57 wt% respectively in the

Table 1. Basic magnetic properties of Antarctic achondrites at room temperature.

Achondrites	$I_s$ (emu/gm)	$I_R$ (emu/gm)	$H_c$ (Oe)	$H_{RC}$ (Oe)	$\chi_p$ (emu/gm/Oe)
Yamato-692 (Diogenite)	0.19	0.0035	42	—	$2.8 \times 10^{-5}$
Yamato-74013 ( " )	0.17	0.0012	10	—	3.0 "
Yamato-74037 ( " )	0.22	0.0045	73	140	2.68 "
Yamato-74097 ( " )	0.32	0.0040	13	210	2.40 "
Yamato-74136 ( " )	0.038	0.0037	56	320	2.47 "
Yamato-74648 ( " )	0.20	0.0075	85	520	2.35 "
Yamato-75032 ( " )	0.042	0.0065	93	320	2.65 "
ALHA77256 ( " )	0.16	0.0048	48	260	2.50 "
Yamato-74159 (Eucrite)	0.061	0.0040	265	420	$3.09 \times 10^{-5}$
Yamato-74450 ( " )	0.215	0.0044	58	72	2.94 "
ALHA76005* ( " )	0.076	0.00085	15	—	3.23 "
ALHA77302 ( " )	0.012	—	—	—	3.0 "
ALHA78040 ( " )	0.083	0.0072	90	560	2.83 "
Yamato-7307 (Howardite)	0.53	0.0027	42	—	$3.3 \times 10^{-5}$
ALHA77005 (Sh)	0.085	0.013	56	320	$2.45 \times 10^{-5}$
Yamato-74123 (Ureilite)	6.43	0.14	41	285	$3.5 \times 10^{-5}$
Yamato-74659 ( " )	2.23	0.071	76	590	1.65 "
ALHA77257 ( " )	3.14	0.105	100	420	2.85 "

Sh: Eucritic unique achondrite similar to shergottite.

\* Allan Hills-765.

results of magnetic measurement.

Compared with the  $I_s$ -values of ureilites, those of all the other achondrites listed in Table 1 are smaller than 0.53 emu/gm, which corresponds to 0.27 wt% in the content of metallic nickel-iron. Except Yamato-7307 howardite, the  $I_s$ -values of examined diogenites and eucrites are either in a range of 0.16–0.32 emu/gm or in a range of 0.012–0.083 emu/gm, which correspond to 0.08–0.16 and 0.006–0.042 wt% in the weight content of metallic nickel-iron. We may provisionally conclude therefore that the content of metallic nickel-iron is very small, being less than 0.16 wt% in Antarctic diogenites and eucrites.

Another point to be worthwhile to be remarked in Table 1 may be that the coercive force ( $H_c$ ) of achondrites is, statistically speaking, considerably larger than that of chondrites as shown by the histograms of occurrence frequency of  $H_c$  for Antarctic achondrites (Table 1) and for chondrites except carbonaceous chondrites (NAGATA and SUGIURA, 1976) in Fig. 2. The comparatively large coercive force of achondrites may be one of the main reasons why the natural remanent magnetization (NRM) of achondrites is generally much stabler against the AF-demagnetization.

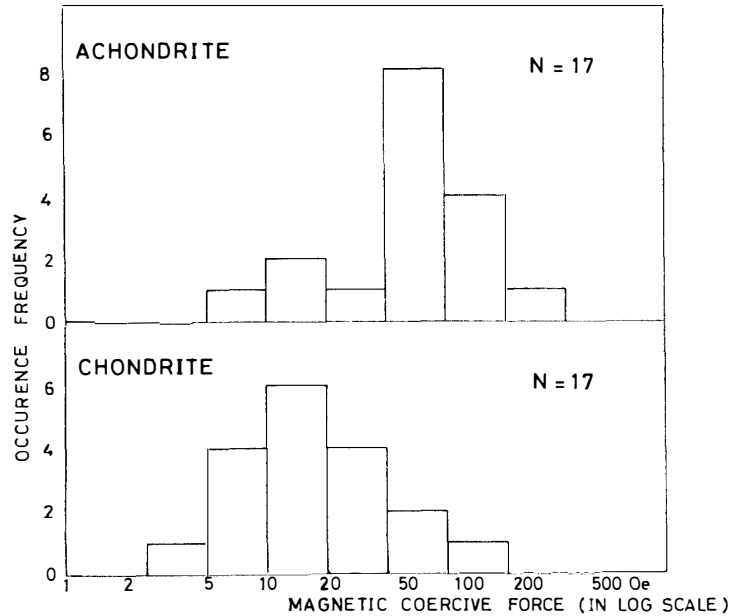


Fig. 2. Occurrence frequency histograms of magnetic coercive force of achondrites and chondrites.

zation than that of ordinary chondrites and E-chondrites (LARSON *et al.*, 1973; NAGATA, 1979b).

The paramagnetic susceptibility ( $\chi_p$ ) of achondrites given in Table I has been determined with the mean error of less than 5% (except for ureilites), because the paramagnetization occupies a considerably large portion of the total magnetization for these achondrites in the observed magnetization curves of magnetization ( $I$ ) versus magnetic field ( $H_{ex}$ ) at room temperature in a magnetic field range from  $-16$  kOe to  $+16$  kOe. In the cases of ureilites, however, the probable error in a determination of  $\chi_p$  amounts to 20–25%, because of the co-existence of a much larger amount of ferromagnetization of metallic nickel-iron which occupies the major portion of magnetization.

The paramagnetization of achondrites is due to the presence of  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$  in their silicate minerals. Since the content of  $\text{Mn}^{2+}$  is very small compared with that of  $\text{Fe}^{2+}$  in stony meteorites and the content of  $\text{Fe}^{2+}$  considerably varies in various stony meteorites, the paramagnetic susceptibility can be a reasonably good indicator of the content of  $\text{Fe}^{2+}$ . When the content of  $\text{Fe}^{2+}$  in weight in non-magnetic matrix is noted by  $m(\text{Fe}^{2+})$ , the paramagnetic susceptibility ( $\chi_p$ ) at temperature  $T$  ( $^{\circ}\text{K}$ ) is given by

$$\chi_p(T) = \frac{6.45 \times 10^{-2}}{T} m(\text{Fe}^{2+}). \quad (\text{emu/gm/Oe}). \quad (7)$$

Then,  $m(\text{FeO})$  denoting the content of FeO,  $\chi_p$  at  $T=300^{\circ}\text{K}$  is numerically expressed

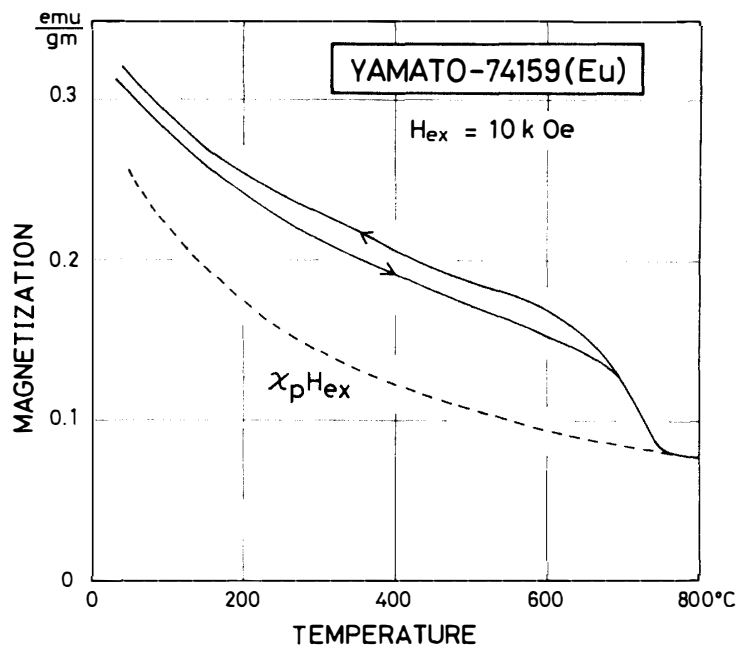


Fig. 3. Thermomagnetic curves of Yamato-74159 eucrite.

as

$$\chi_p(300^\circ\text{K}) = 1.67 \times 10^{-4} m(\text{FeO}). \quad (\text{emu/gm/Oe}). \quad (8)$$

$\chi_p(300^\circ\text{K})$  values of diogenites, eucrites and howardites, given in Table 1, range from  $2.35 \times 10^{-5}$  to  $3.3 \times 10^{-5}$  emu/gm/Oe, which correspond to the FeO content of 14.1–19.8 wt%. These amounts of FeO content are reasonable values for hypersthene achondrites and pyroxene-plagioclase achondrites.  $\chi_p$  of Yamato-74659 ureilite is unusually small, being  $1.65 \times 10^{-5}$  emu/gm/Oe, which corresponds to  $m(\text{FeO})=9.9$  wt%. Chemical analysis data also have shown that the FeO content in Yamato-74659 is 8.83 wt% which is the lowest among known ureilites (TAKEDA *et al.*, 1979). Fig. 3 through Fig. 6 show four typical examples of the thermomagnetic curves of Antarctic achondrites. The thermomagnetic (TM) curves of Yamato-74159 eucrite (Fig. 3) consist of a paramagnetization in  $H_{ex}=10$  kOe ( $\chi_p H_{ex}$ ) and a ferromagnetization of almost pure metallic iron or Ni-poor (<3 wt%) kamacite. The TM-curve of Yamato-74136 diogenite for the initial heating process (Fig. 4) consists of  $\chi_p H_{ex}$ , an  $(\alpha+\gamma)$ -phase (plessite) magnetization having the  $(\alpha+\gamma)\rightarrow\gamma$  transition temperature at  $560^\circ\text{C}$  and a Ni-poor kamacite magnetization, whereas the cooling TM-curve comprises  $\chi_p H_{ex}$ , a Ni-poor kamacite magnetization and an additional  $\gamma$ -phase magnetization in a temperature range below about  $200^\circ\text{C}$ . In the TM-curves of Yamato-74659 ureilite (Fig. 5), the heating curve consists of an  $(\alpha+\gamma)$ -phase magnetization of  $555^\circ\text{C}$  in the  $(\alpha+\gamma)\rightarrow\gamma$  transition temperature and a Ni-poor kamacite magnetization having Curie point at  $770^\circ\text{C}$ , while the cooling curve comprises the Ni-poor kamacite magnetization, a small

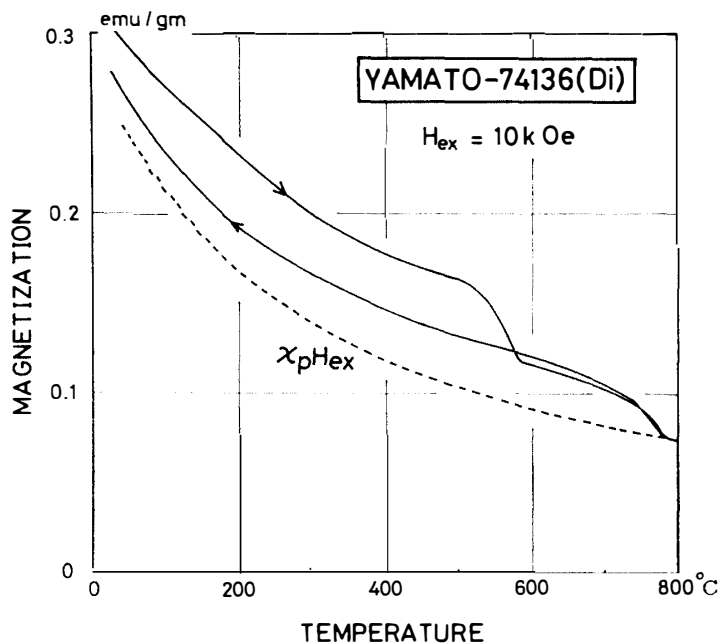


Fig. 4. Thermomagnetic curves of Yamato-74136 diogenite.

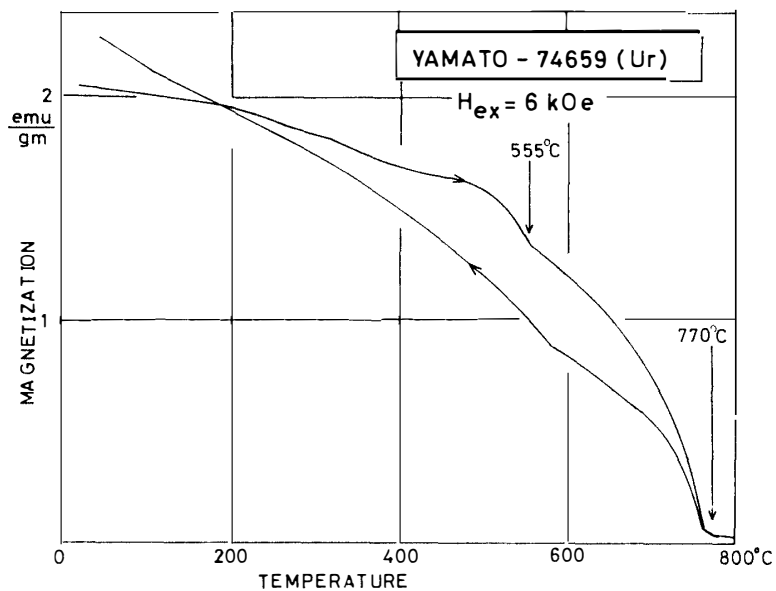


Fig. 5. Thermomagnetic curves of Yamato-74659 ureilite.

remanence of the  $(\alpha + \gamma)$ -phase magnetization and an additional  $\gamma$ -phase magnetization in a temperature range below about 300°C. The paramagnetic magnetization ( $\chi_p H_{ex}$ ) is relatively much smaller than these ferromagnetizations in this ureilite. The TM-curves of ALHA77257 ureilite (Fig. 6) appear to be a little complicated



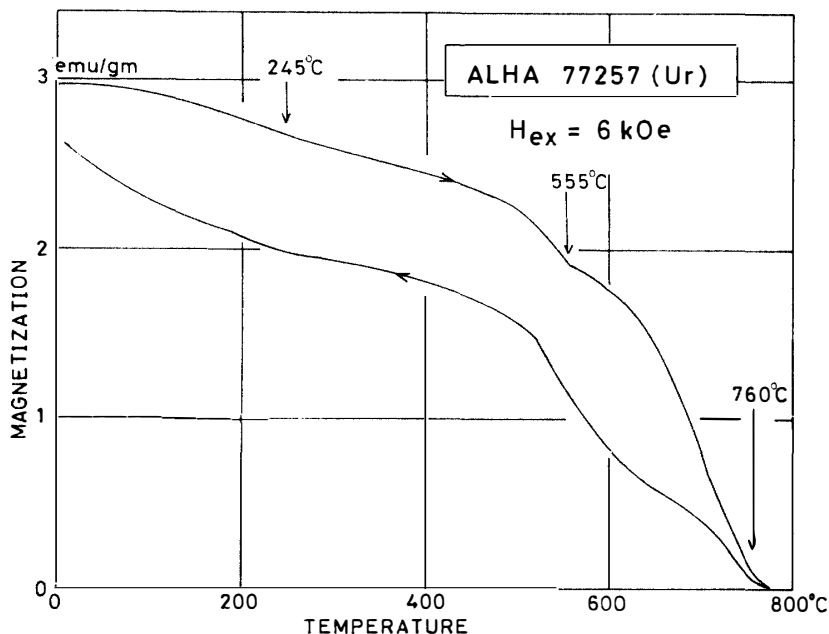


Fig. 6. Thermomagnetic curves of ALHA77257 ureilite.

compared with the above-mentioned three TM-curves. The ferromagnetization in the initial heating process consists of 3 phases, *i.e.*, a kamacite magnetization having the highest  $\alpha \rightarrow \gamma$  transition temperature at 760°C, an  $(\alpha + \gamma)$ -phase magnetization having the  $(\alpha + \gamma) \rightarrow \gamma$  transition temperature at 555°C and a small amount of ferromagnetic phase of about 245°C in Curie point. The last ferromagnetic phase is very likely to be identified to a iron-nickel phosphide,  $(\text{FeNi})_3\text{P}$ . The cooling TM-curve comprises a kamacite phase magnetization whose highest  $\gamma \rightarrow \alpha$  transition temperature is 740°C but the  $\gamma \rightarrow \alpha$  transition is continuously distributed down to about 600°C, and an additional magnetization of  $\gamma$ -phase in a temperature range below about 200°C. The ferromagnetic phase of FeNi phosphide seems to be hid under the  $\gamma$ -phase magnetization in the cooling curve.

By analyzing 17 TM-curves, ratios of saturation magnetization of  $\alpha$ -, (kamacite),  $(\alpha + \gamma)$ -, (plessite) and  $\gamma$ -(taenite) phases of metallic nickel-iron and FeNi-phosphide to the total saturation magnetization at room temperature,  $I_s(\alpha)/I_s$ ,  $I_s(\alpha + \gamma)/I_s$ ,  $I_s(\gamma)/I_s$  and  $I_s(\text{Ph})/I_s$ , are determined, as summarized in Table 2. The general behaviors of TM-curves of Yamato-74159, -74450, Allan Hills-765, ALHA77302, Yamato-7307 and ALHA77005 are similar to those shown in a typical example given by Fig. 3, while those of Yamato-74037, -74136 and ALHA77256 are similar to those given in Fig. 4. Typical examples of the TM-curves of Yamato-692, -74013, -74648 and -75032 have already been described for Yamato-692 and -74013 diogenites in previous papers (NAGATA *et al.*, 1975, 1976). Namely, both heating and cooling TM-curves consist of a Ni-poor kamacite magnetization and a ferromagnetic mag-

Table 2. Magnetic phases of metallic component in Antarctic achondrites.

Achondrite	$I_s$ (emu/gm)	$\frac{I_s(\alpha)}{I_s}$	$\frac{I_s(\alpha+\gamma)}{I_s}$	$\frac{I_s(\gamma)}{I_s}$	$\frac{I_s(\text{Ph})}{I_s}$
Yamato-692 (Diogenite)	0.19	0.40	0	0.60	0
Yamato-74013 ( " )	0.17	0.37	0	0.63	0
Yamato-74037 ( " )	0.22	0.38	0.62	0	0
Yamato-74136 ( " )	0.038	0.40	0.60	0	0
Yamato-74648 ( " )	0.20	0.29	0	0.71	0
Yamato-75032 ( " )	0.042	0.08	0	0.92	0
ALHA77256 ( " )	0.16	0.17	0.83	0	0
Yamato-74159 (Eucrite)	0.061	1.00	0	0	0
Yamato-74450 ( " )	0.215	1.00	0	0	0
ALHA76005* ( " )	0.076	1.00	0	0	0
ALHA77302 ( " )	0.012	1.00	0	0	0
ALHA78040 ( " )	0.083	0.79	0.21	0	0
Yamato-7307 (Howardite)	0.53	1.00	0	0	0
ALHA 77005 (Sh)	0.085	1.00	0	0	0
Yamato-74123 (Ureilite)	6.43	0.91	0.09	0	0
Yamato-74659 ( " )	2.23	0.88	0.12	0	0
ALHA77257 ( " )	3.14	0.87	0.09	0	0.04

$I_s(\text{Ph})$ : Saturation magnetization of FeNi phosphide.

(Sh): Eucritic unique achondrite similar to shergottite.

\* Allan Hills-765.

netization phase of Curie point at 550–570°C. The second thermally stable ferromagnetic phase can be identified to either taenite of 50–60 wt% in Ni-content or magnetite. Since no trace of magnetite has been found in these diogenites, it would be rather reasonable to provisionally identify this ferromagnetic phase to taenite.

A remarkable contrast between the hypersthene achondrite group and the pyroxene-plagioclase achondrite group (eucrite, howardite and a eucritic unique achondrite) in regard to the composition of their metallic components, shown in Table 2, is that the metals in pyroxene-plagioclase achondrites are of a single phase of Ni-poor kamacite except for ALHA78040 eucrite, whereas those in diogenites consist of two phases, a kamacite phase and a plessite or taenite phase.

Petrologically, DUKE (1965) analyzed Ni-content in metallic nickel-iron in 7 eucrites and 1 howardite. The nickel-irons in these 7 eucrites are all kamacites of less than 1% in Ni-content, while the Ni-content in nickel-iron metals in a howardite is about 3.5%. If these eucrites and howardite are thermomagnetically analyzed, therefore, they all should give  $I_s(\alpha)/I_s=1.00$  and  $I_s(\alpha+\gamma)/I_s=I_s(\gamma)/I_s\cong 0$ .

A bulk chemical analysis of Yamato-7307 howardite has given 0.39 wt% of Fe,

115 ppm of Ni and 70 ppm of Co for metallic components, so that the Ni-content in the metal itself amounts to 2.8 wt% (YAGI *et al.*, 1978). The electron-microprobe analyses of some metallic grains in this howardite sample have shown that the majority of metallic phases are kamacite of about 5 wt% in average Ni-content but some small metallic grains are taenites of about 54 wt% in Ni-content (MIYAMOTO *et al.*, 1978).

On the other hand, a little information is available for the chemical composition of metallic component in several Antarctic diogenites. Yamato-692 diogenite contains 0.66 wt% of Fe, less than 0.004 wt% of Ni and 0.003 wt% of Co, so that the Ni-content in the metals amounts only to 0.6 wt% or less (SHIMA *et al.*, 1975). In results of electron-microprobe analyses of some metallic grains in Yamato-74013 and -74136 diogenites also, iron occupies about 98% of the total metal, Ni and Co sharing only 0–0.3% and about 0.7% respectively (TAKEDA *et al.*, 1978). As far as available chemical data of Antarctic diogenites are concerned, no evidence for the presence of taenite phase or plessite phase has been detected. Mineralogically and chemically speaking, therefore, the second ferromagnetic phase having its magnetic transition temperature at 540–560°C in diogenites has not yet been certainly identified. When the second ferromagnetic phase observable in the first heating process disappears and the  $\gamma$ -phase magnetization newly appears in the cooling process, the second phase can almost certainly be identified to the plessite phase magnetization. The thermally stable second ferromagnetic phase, however, could be attributed to magnetite or taenite of 50–60 wt% in Ni-content or a solid solution between chromite and magnetite. This problem will have to be examined in detail in the future.

It will be clear in Table 2, however, that the ferromagnetic component of diogenites is composed of two distinct phases; one is a kamacite phase and the other has its magnetic transition temperature in a range of 540–560°C.

### 3. Magnetic Classification of Antarctic Achondrites

The three magnetically examined ureilites which have large  $I_s$ -values,  $I_s = 2.23$ – $6.43$  emu/gm, can be clearly distinguished from the groups of hypersthene achondrites and pyroxene-plagioclase achondrites whose  $I_s$ -values are smaller than 0.53 emu/gm. The range of  $I_s$ -values of ureilites overlaps the  $I_s$ -value range of LL-chondrites which is  $I_s = 3.2$ – $6.0$  emu/gm (NAGATA, 1979b). However, the Ni-content in metallic nickel-irons in LL-chondrites is the largest among the ordinary chondrites so that their  $I_s(\alpha)/I_s$  values range from 0.19 to 0.60, whereas ratios  $I_s(\alpha)/I_s$  for ureilites are 0.87–0.91, as given in Table 2. In terms of  $I_s(\alpha)/I_s$ , therefore, the ureilite group can be definitely separated from the LL-chondrite group.

There is no systematic difference in the  $I_s$ -value between hypersthene achondrites and pyroxene-plagioclase achondrites. However, the ferromagnetic metal component in pyroxene-plagioclase achondrites is almost entirely the Ni-poor kamacite or its

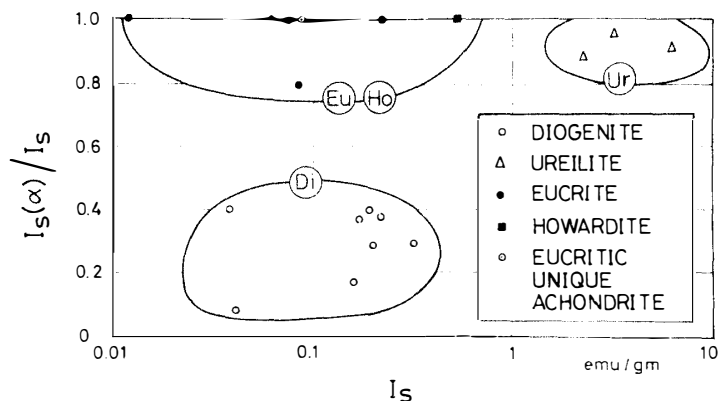


Fig. 7.  $I_s(\alpha)/I_s$  versus  $I_s$  diagram to magnetically classify 3 groups of achondrites. Ur: Ureilite domain. Di: Diogenite domain. Eu+Ho: Pyroxene-plagioclase achondrite (eucrite and howardite) domain.

major parts are the Ni-poor kamacite, thus  $I_s(\alpha)/I_s \geq 0.79$  for this group, whereas the ferromagnetic component in hypersthene achondrites is occupied by the Ni-poor kamacite only less than 40%, the major ferromagnetic component being either plesite or unidentified ferromagnetic phase whose magnetic transition temperature is 540–560°C, thus  $I_s(\alpha)/I_s \leq 40\%$  for this group. In terms of  $I_s(\alpha)/I_s$ , therefore, the hypersthene achondrite group can be fairly clearly distinguished from the pyroxene-plagioclase achondrite group.

In Fig. 7, 17 Antarctic achondrites are plotted on an  $I_s(\alpha)/I_s$  versus  $I_s$  diagram. On this diagram, the three achondrite groups, hypersthene achondrites (diogenites), pyroxene-plagioclase achondrites (eucrites and howardites) and olivine-pigeonite achondrites (ureilites) are confined to respective domains which are well separated from one another.

Combining Fig. 7 with Fig. 1, therefore, 8 chemical groups of stony meteorites, *i.e.*, E-, H-, L-, LL- and C-chondrites, and hypersthene-, olivine-pigeonite-, and pyroxene-plagioclase-achondrites, should be able to be well separately expressed on an  $I_s(\alpha)/I_s$  versus  $I_s$  diagram.

#### 4. Concluding Remarks

It appears from results of the present study that achondrites also can be magnetically classified into their chemical groups on an  $I_s(\alpha)/I_s$  versus  $I_s$  diagram, just as so in the case of chondrites. It seems, however, that mineralogical and chemical justifications for separating the hypersthene achondrite group from the pyroxene-plagioclase achondrite group in terms of  $I_s(\alpha)/I_s$  must be much more endeavored. It has been reasonably suggested by DUKE (1965) that the Ni-content, in both silicates and metals, in hypersthene achondrites are definitely larger than that in pyroxene-

plagioclase achondrites, and a possible genetic reason for the difference has been hypothesized.

As described in Section 2, however, the ferromagnetic phases revealed by the magnetic analysis for diogenites have not yet been fully clarified in terms of mineralogy and chemistry. This situation of achondrites would be a considerably conspicuous contrast to that of chondrites, for which the observed differences in both  $I_s$  and  $I_s(\alpha)/I_s$  in different chemical groups can be reasonably well interpreted on the basis of Urey-Craig-Mason law and Prior rule.

In concluding, there still remains significant problems in regard to the ferromagnetic component(s) and the structure of metallic grains in achondrites, even though a trial of magnetic classification of achondrites appears to achieve a reasonable success.

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