MAGNETIC CLASSIFICATION OF METEORITES (V): IRON METEORITES

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***Abstract*:** Sixteen iron meteorites are magnetically classified into three major classes; hexahedrite plus Ni-poor ataxite, octahedrite and Ni-rich ataxite on the basis of their thermomagnetic characteristics. Magnetic parameters for the classification scheme are ratio of saturation magnetization of kamacite, $I_s(\alpha)$, to total saturation magnetization, I_s, namely $I_s(\alpha)/I_s$, and transition temperature from γ-phase to α-phase of kamacite in the cooling process, $\Theta^*_{\gamma\to\alpha}$.

On an $I_s(\alpha)/I_s$ *vs.* $\Theta^*_{\gamma\to\alpha}$ diagram, the three major classes of iron meteorites are represented by their respective domains well separated from one another.

1. Introduction

A magnetic classification scheme for stony meteorites has been proposed separately for the group of chondrites and that of achondrites (NAGATA and SUGIURA, 1976; NAGATA, 1978a, 1979a, b, 1980a, b). In the case of chondrites, the five chemical classes, *i.e.* E, H, L, LL and C chondrites, can be represented by five mutually separated domains on a two-parameter diagram of the saturation magnetization intensity (I_s) *vs.* the ratio of the saturation magnetization intensity of the α-phase (kamacite phase) component to the total saturation magnetization ($I_s(\alpha)/I_s$). In the case of achondrites also, three groups of achondrites, *i.e.* diogenites, ureilites and eucrites plus howardites, can be represented by three respective domains in an $I_s(\alpha)/I_s$ *vs.* I_s diagram.

The basic principle of the magnetic classification scheme for chondrites comprises two remarkably characteristic features of the ferromagnetic constituents, such as metals or magnetites, in these stony meteorites. The two characteristic features are: (a) that the abundance of ferromagnetic metals decreases in the sequence of order from E chondrites through H, L and LL chondrites to C chondrites which contain zero or very small amount of metal, and (b) that the Ni-content in metals in chondrites generally increases in the same sequence, so that the relative content of kamacite in metal phases is greatest in E chondrites and least in LL and/or C chondrites.

The abundance of ferromagnetic metals in achondrites, (except the ureilite group), is distinctly smaller than that in the ordinary chondrites. In terms of the I_s-value, therefore, a chondrites with the exception of ureilites can be definitely distinguished from chondrites. The I_s-value of ureilites is of the same order of magnitude as that of LL chondrites, but the Ni-content in the metal of ureilites is distinctly smaller than that in LL chondrites.

Since the Ni-content in eucrite metal is much less than that in diogenite metals, and that in howardite metal is in between, a group of eucrites plus howardites can be clearly distinguished from the group of diogenites in terms of the $I_s(\alpha)/I_s$ value. Thus, E, H, L, LL and C chondrites, eucrites plus howardites, ureilites and diogenites are separately grouped within respectively identified domains on the same $I_s(\alpha)/I_s$ *vs.* I_s diagram.

In these cases of chondrites and achondrites, distinct differences of the content of metal in them play a significant role in the proposed magnetic classification scheme. In the case of iron meteorites, however, the I_s-values range only between 220 emu/g and 125 emu/g regardless of sharp differences between their metallographic structures and textures of those classified as hexahedrites, octahedrites, ataxites and so on. A dependable characteristic feature in various groups of iron meteorites for a magnetic classification purpose is a difference in their Ni-content. In the present short note, a preliminary trial to identify the metallographically classified classes in terms of observable magnetic parameters will be discussed.

2. Magnetic Parameters of Iron Meteorites

Thermomagnetic characteristics of 14 iron meteorites were extensively examined by LOVERING and PARRY (1962). The main aim of their thermomagnetic studies of iron meterorites was to quantitatively identify the nickel contents of co-existing kamacite, taenite and plessite in all major structure classes of iron meteorites. In addition to the three major phases of iron meteorites, they magnetically detected iron-nickel phosphides such as schreibersite and rhabdite also in those iron meteorites.

Metallographic and magnetic studies of individual iron meteorites newly retrieved from Antarctica have been carried out by the present writer and his colleagues in recent years (NAGATA *et al.*, 1976; NAGATA, 1978b; FISHER *et al.*, 1978a, b, 1979, 1980). These works also dealt with semi-quantitative analyses of co-existing kamacite, taenite, plessite and iron-nickel phosphide phases.

In Table 1, saturation magnetization (I_s), ratio of saturation magnetization of kamacite phase to the total saturation magnetization ($I_s(\alpha)/I_s$), and transition temperature from γ-phase to α-phase of kamacite component in the cooling process from 850°C ($\Theta^*_{\gamma\to\alpha}$) of meteorites are summarized, together with their bulk Ni-contents estimated by electron-microprobe analysis. Histograms of the Ni-content in the 16 iron meteorites are illustrated in Fig. 1. These data of I_s, $I_s(\alpha)/I_s$ and $\Theta^*_{\gamma\to\alpha}$ are taken from experimental results obtained by LOVERING and PARRY, NAGATA and FISHER and others. In magnetic measurements of NAGATA's group, I_s is evaluated from magnetic hysteresis curves determined in a magnetic field range between -15 and $+15$ kOe at room temperature, while $I_s(\alpha)/I_s$ and $\Theta^*_{\gamma\to\alpha}$ are evaluated from thermomagnetic curves obtained in a magnetic field of 10 kOe and in vacuum of 1×10^{-5} Torr. In the experiments by LOVERING and PARRY (1962), thermomagnetic analysis was carried out for an iron meteorite sample scaled into a silica capsule at 0.1 mmHg pressure and the applied magnetic field was large enough to make the magnetization saturated or at least almost saturated. Sikhote-Alin hexahedrite was magnetically examined by both groups. Since the magnetic parameters of Sikhote-Alin measured by the present writer's group by use of a vibration magnetometer are in reasonably good agreement with those obtained by LOVERING and PARRY by use of a pendulum magnetometer, we may be able to assume that all the magnetic parameters summarized in Table 1 have equal weight.

Table 1. Magnetic parameters of iron meteorites.

Meteorite	Saturation magnetization (I_s) (emu/g)	$I_s(\alpha)/I_s$	$\Theta^*_{\gamma\to\alpha}$ (°C)	Ni-content (wt%)
(Hexahedrite)				
Coya Norte	195	0.80	650	5.63
Sikhote-Alin	215	0.95	650	5.27
Y-75105	190	0.89	660	5.4
DRP-78003	200	0.97	640	5.4
(Ni-poor ataxite)				
Bingera	220	0.96	645	5.75
(Octahedrite)				
Canyon Diablo	210	0.80	600	7.3
Cranbourne	200	0.95	600	7.18
Mount Tabby	180	0.80	610	6.82
Kyancutta	195	0.92	600	7.66
Toluca	180	0.85	585	8.31
Mungindi	200	0.70	590	12.36
(Ni-rich ataxite)				
Mount Magnet	190	0.20	600	14.72
Tawallah Valley	200	0.15	600	18.21
Wedderburn	140	0.15	630	22.2
ALH-77255	185	~0	550	12.2
Y-75031	125	0.06	560	15.3

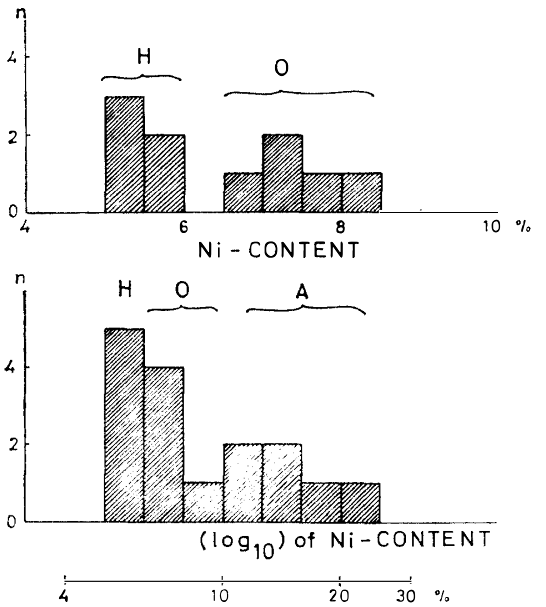

Fig. 1. Histograms of Ni-content determined by electron microprobe in iron meteorites. Top: Octahedrite (O), hexahedrite and Ni-poor ataxite (H). Abscissa. Ni-content in weight, linear scale. Bottom: All iron meteorites (H, O and Ni-rich ataxite, A). Abscissa. Ni-content in weight, logarithmic scale.

In Table 1, magnetic data of an anomalous ataxite Arltunga and an anomalous Ni-rich ataxite Santa Catharina are excluded, but their magnetic properties will be discussed separately.

As shown in Table 1, the bulk Ni-content ranges between 5.3 and 5.8 wt% for hexahedrites and Ni-poor ataxites, and between 6.8 and 12.4 wt% for octahedrites, while the relative proportion of kamacite phase in metal in terms of the saturation magnetization, $I_s(\alpha)/I_s$, ranges between 0.80 to 0.97 for the hexahedrite (plus Ni-poor ataxite) class and between 0.70 and 0.95 for the octahedrite class. As the bulk Ni-content in the hexahedrite class is less than 5.8 wt%, it appears that all $I_s(\alpha)/I_s$ values of this class should be close to 1.00, as far as the Fe-Ni binary system is concerned. However, some hexahedrites contain a considerable amount of phosphorus too. For example, Yamato-75105 hexahedrite contains 1.0 wt%P, which forms a high-P kamacite phase of 0.07 I_s and a Fe-Ni phosphide phase of 0.04 I_s in terms of the saturation magnetization intensity (NAGATA *et al.*, 1976). Thus the $I_s(\alpha)/I_s$ value of this hexahedrite amounts to only 0.89. P-contents in Sikhote-Alin and DRP-78003 are 0.46 and 0.40 wt% respectively and they also contain small amounts of Fe-Ni phosphide phase (FISHER *et al.*, 1980).

The Ni-content in all the examined octahedrites exceeds 7 wt%, so that these octahedrites contain more or less taenite and plessite in addition to kamacite. A small amount of Fe-Ni phosphide is also present in these octahedrites. A typical magnetic parameter to distinguish the octahedrites from the hexahedrites plus Ni-poor ataxites is $\Theta^*_{\gamma\to\alpha}$ which represents the Ni-content in the kamacite phase. (Although the transition temperature from α-phase to γ-phase of kamacite component in a heating process also is dependent on Ni-content, the dependence of the difference of $\Theta^*_{\gamma\to\alpha}$ on the difference in Ni-content is considerably larger than that of $\Theta^*_{\alpha\to\gamma}$, whence $\Theta^*_{\gamma\to\alpha}$ is selected in the present work.) As shown in Table 1, all $\Theta^*_{\gamma\to\alpha}$ values of octahedrites are lower than 610°C, whereas all $\Theta^*_{\gamma\to\alpha}$ values of hexahedrites and Ni-poor ataxites are higher than 640°C. The difference of $\Theta^*_{\gamma\to\alpha}$ values between octahedrites and hexahedrites corresponds to a difference of Ni-content in their kamacite phases which is illustrated in the top histogram in Fig. 1.

The Ni-content in Ni-rich ataxites is larger than 12.2 wt%, and consequently the $I_s(\alpha)/I_s$ value is smaller than 0.20, while the $\Theta^*_{\gamma\to\alpha}$ value is kept within a temperature range larger than 550°C which is approximately the minimum value of $\Theta^*_{\gamma\to\alpha}$ for kamacite phase.

3. Magnetic Classification Scheme for Iron Meteorites

In the $I_s(\alpha)/I_s$ *vs.* I_s diagram which is convenient and useful for classifying chondrites and achondrites, the Ni-rich ataxite class can be confined within a domain well separated from domains of octahedrite, hexahedrite and Ni-poor ataxite. However, octahedrites, hexahedrites and Ni-poor ataxites occupy almost the same domain in the diagram, because I_s and $I_s(\alpha)/I_s$ of the octahedrite class range between 190 and 220 emu/g and between 0.80 and 0.97 respectively, while those of the class of hexahedrite and Ni-poor ataxite range between 180 and 210 emu/g and between 0.70 and 0.95 respectively. Thus it may be concluded that the $I_s(\alpha)/I_s$ value is a reasonably good parameter to distinguish only the Ni-rich ataxite class from other iron meteorites. In order to separate the octahedrite class from iron meteorites which contain a little less nickel than in octahedrites, it seems that the $\Theta^*_{\gamma\to\alpha}$ value which sensitively represents Ni-content in kamacite phase in each iron meteorite will be the best magnetically observable parameter. In Fig. 2, therefore, the observed magnetic data of 16 iron meteorites

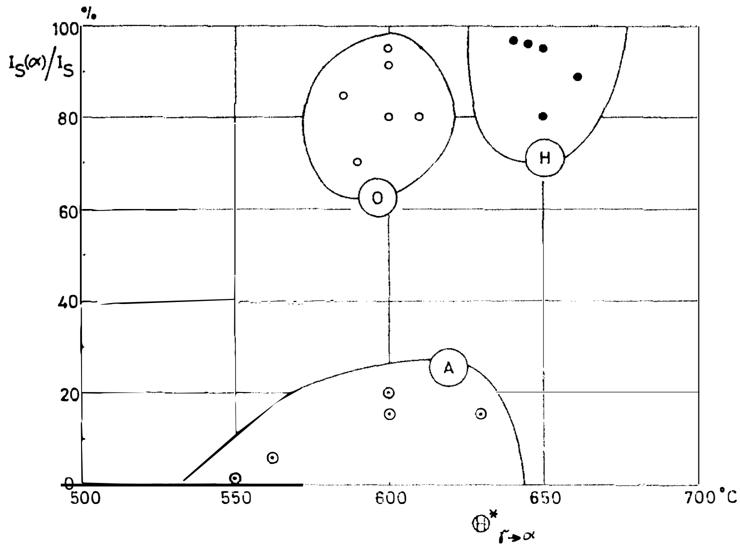

Fig. 2. $I_s(\alpha)/I_s$ vs. $\Theta^*_{\gamma\to\alpha}$ diagram for a magnetic classification of iron meteorites. O: Octahedrite class, H: Hexahedrite and Ni-poor ataxite class, A: Ni-rich ataxite class.

given in Table 1 are plotted on a $I_s(\alpha)/I_s$ *vs* $\Theta^*_{\gamma\to\alpha}$ diagram. In the $I_s(\alpha)/I_s$ *vs* $\Theta^*_{\gamma\to\alpha}$ diagram, the octahedrites and hexahedrites (plus a Ni-poor ataxite) are represented by their respective domains which are well separated from each other.

4. Remarks on Exceptional Cases

An anomalous ataxite, Arltunga, and a Ni-rich ataxite, Santa Catharina, are eliminated from Table 1, though their thermomagnetic properties were measured by LOVERING and PARRY (1962). The bulk Ni-content in Arltunga is 10.08 wt% and its I_s, $I_s(\alpha)/I_s$ and $\Theta^*_{\gamma\to\alpha}$ are 210 emu/g, 0.75 and 590°C respectively, which can be plotted within the octahedrite domain in Fig. 2. The bulk Ni-content of Arltunga is between Ni-poor ataxite and Ni-rich ataxite, and therefore it is reasonable that its magnetic properties are similar to these of octahedrites which are metallographically and chemically between Ni-poor ataxite and Ni-rich ataxite. Since the anomalous ataxite itself is an exceptional case, however, the magnetic data of Arltunga are eliminated from the present general discussion of the major classes of iron meteorites.

Santa Catharina Ni-rich ataxite, whose bulk Ni-content is 32.6 wt%, is a particularly exceptional iron meteorite with respect to its metallographic structure. Metallographically, Fe-Ni metal of this iron meteorite consists of an ordered taenite (tetrataenite) phase of about 50 wt% Ni and an ordinary disordered taenite phase of 27 wt% Ni which is paramagnetic at room temperature (DANON *et al.*, 1979). Magnetically, $I_s=90$ emu/g and $I_s(\alpha)/I_s\simeq 0$, and therefore no kamacite phase exists in the Santa Catharina iron meteorite, but instead the Curie point of tetrataenite is $\Theta_c=550$°C.

By heating the tetrataenite above 500°C, its ordered structure is destroyed and transformed to the ordinary disordered taenite of fcc structure. The observed magnetic data well represent the metallographic structure. In the $I_s(\alpha)/I_s$ *vs.* $\Theta^*_{\gamma\to\alpha}$ diagram in Fig. 2, the magnetic data of Santa Catharina can be plotted within the Ni-rich ataxite domain, provided that Θ_c is replaced by $\Theta^*_{\gamma\to\alpha}$. The magnetic properties of tetrataenite in meteorites are of special important interest for meteorite magnetism, and therefore will be discussed elsewhere.

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