PALEOMAGNETISM OF ANTARCTIC ACHONDRITES

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***Abstract*:** The paleointensity of two eucrites (ALHA77302 and ALHA-78040), a ureilite (ALHA77257) and an eucritic unique achondrite (ALHA-77005) has been newly estimated by means of a comparison of the AF-demagnetization characteristics of their NRM with those of their ARM.

The upper limit of paleointensity (F_p) is 0.049, 0.060, 0.089 and 0.010 Oe for ALHA77302, 78040, 77257 and 77005 respectively. F_p of ALHA77005 may represent the ambient magnetic field when this achondrite was remelted by severe shocks about 1.8 million years ago, whereas F_p-values of the other three achondrites may indicate the paleomagnetic field when these achondrites differentiated about 4.5 billion years ago.

1. Introduction

In previous papers (NAGATA, 1979a, b), it has been suggested that the paleointensity for achondrites is about 0.1 Oe in the order of magnitude, whereas the paleointensity for carbonaceous chondrites is around 1 Oe. In these previous works, the paleointensity (F_p) for Yamato-74013 diogenite was determined with the standard NRM/ARM method (STEPHENSON and COLLINSON, 1974), the result being given by F_p=0.093 Oe. In this experiment, the ratio of TRM/ARM for a same magnetic field is calibrated as 1.3. By the Königisberger-Thellier experiment on Yamato-7307 howardite, the paleointensity is estimated as F_p=0.07 Oe, where a linear relationship between the NRM-lost and the TRM-gained holds up to a temperature, T_o=240°C. Similar results have been obtained by Königisberger-Thellier experiments on the Allende carbonacious chondrite: a linear relationship between NRM-lost and TRM-gained holds for a temperature range only below 130°C (BANERJEE and HARGRAVES, 1972) and for a temperature range below 150°C in the other experiment (BUTLER, 1972).

As far as available data are concerned, no result of a complete covering the whole temperature range from the atmospheric temperature to Curie point in a Königisberger-Thellier experiment on meteorites for the purpose of paleointensity determination has ever been obtained. On the other hand, the magnetic properties of ferromagnetic constituents in meteorites have not yet been reasonably well understood, because possible chemical reactions concerning those ferromagnetic minerals in an extremely reducing atmosphere or in an extremely high vacuum in the extra-terrestrial space have not yet been experimentally confirmed in laboratory experiments on the earth's surface.

Under these circumstances, one of the most plausible ways to estimate the paleointensity of meteorites may be a method to compare the AF-demagnetization characteristics of the natural remanent magnetization (NRM) with those of the anhysteretic remanent magnetization (ARM), which can be acquired without any heating effect (STEPHENSON *et al.*, 1974). Various modifications of this basic NRM/ARM comparison method to estimate the paleointensity have been proposed in order to confirm that NRM under an examination is due to the thermoremanent magnetization (TRM) mechanism. However, once heating of a meteorite in a high vacuum space or even in an equilibriated oxygen atmosphere with the metallic component concerned often results in a catastrophic alteration of ferromagnetic phases in the metal only by the thermal effect. An irreversible change of a martensitic plessite phase ($(\alpha+\gamma)$-phase of FeNi) to a taenite phase (γ-phase of FeNi) only by heating above a critical temperature is an obvious example of the catastrophic alteration of the ferromagnetic constituents in stony meteorites.

It seems therefore that a simple comparison of the AF-demagnetization characteristics of NRM with those of ARM acquired in a stationary magnetic field (h) will be the safest way at the present stage to estimate the paleointensity of stony meteorites, provided that the coefficient (f_0) of an acquisition rate of TRM to that of ARM in a same magnetic field can be appropriately determined. Noting the intensities of ARM and TRM by I (ARM) and I (TRM) respectively and the applied magnetic field intensities for acquisitions of ARM and TRM by h (ARM) and h (TRM) respectively, the coefficient (f_0) can be defined as

$$I\,(\mathrm{TRM})/I\,(\mathrm{ARM})=f_0\cdot h\,(\mathrm{TRM})/h\,(\mathrm{ARM}). \tag{1}$$

In the cases of fine metallic grains for the ferromagnetic constituents, STEPHENSON and COLLISON (1974) have obtained $f_0=1.34$ for a lunar sample, and SUGIURA (1976) had obtained $f_0=1.3$ for three different grain sizes of metallic iron dispersed in a non-magnetic matrix. Although different values of f_0 have been suggested for some terrestrial rocks (*e.g.* DUNLOP and WEST, 1969), the experimentally determined value of $f_0\simeq 1.3$ for an assemblage of fine grains of native iron in the lunar materials and man-made pure iron will be the most reliably applicable value of f_0 in the cases of lunar materials and most stony meteorites, in which metallic nickel-irons are the exclusively dominant ferromagnetic constituent.

2. NRM and Their Stability of Achondrites

NRM's of 2 diogenites (ALHA77219 and 77256), 3 eucrites (ALHA77005, 77302 and 78040) and a ureilite (ALHA77257) have been newly examined for the

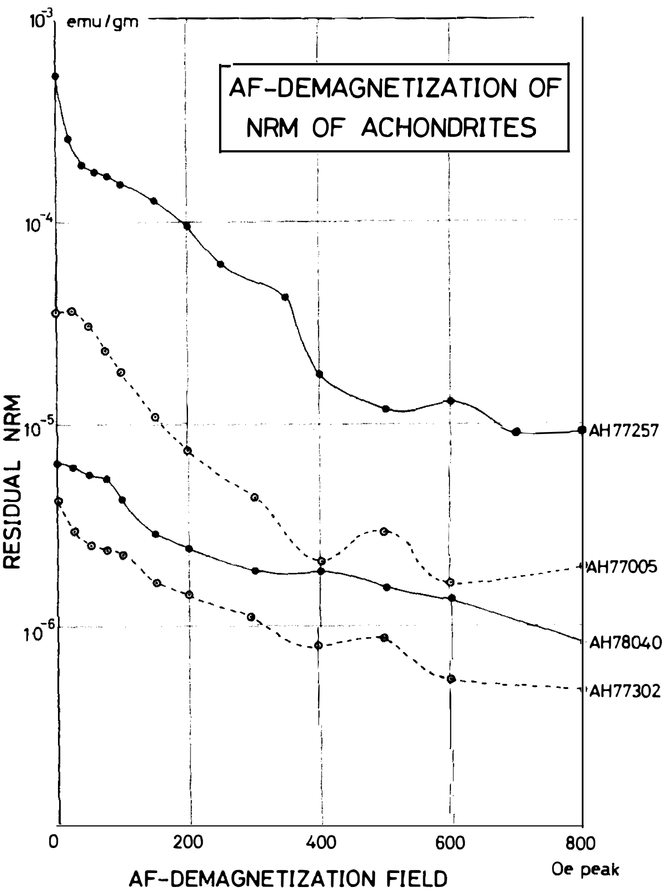

Fig. 1. AF-demagnetization curves of 4 Antarctic achondrites.

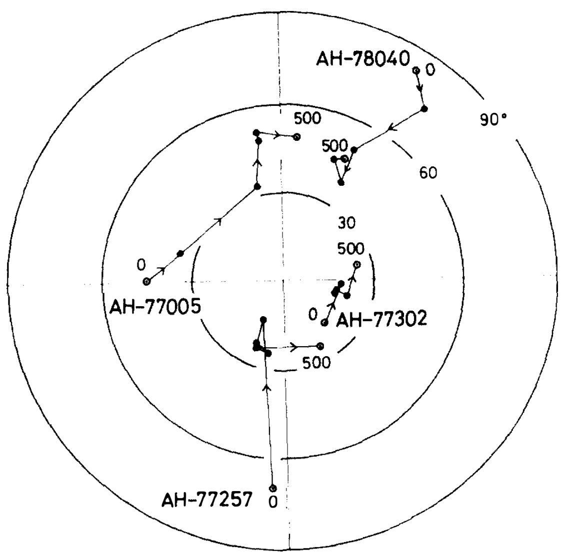

Fig. 2. Change in the direction of residual NRM caused by AF-demagnetization for 4 Antarctic achondrites.

Table 1. NRM and paleointensity of Antarctic achondrites.

Achondrites	NRM (emu/gm) In (0)	In (100)	In (200)	F_p (Oe)
ALHA77005 (Sh)	3.61×10^{-5}	1.95×10^{-5}	0.72×10^{-5}	0.010
〃 77257 (Ureilite)	5.38×10^{-4}	1.57×10^{-4}	0.94×10^{-4}	0.089
〃 77302 (Eucrite)	4.14×10^{-6}	2.26×10^{-6}	1.40×10^{-6}	0.049
〃 78040 (〃)	6.36×10^{-6}	4.17×10^{-6}	2.41×10^{-6}	0.060
Yamato-7307 (Howardite)	6.3×10^{-6}	5.9×10^{-6}	3.5×10^{-6}	0.07
〃 -74013 (Diogenite)	3.4×10^{-6}	3.2×10^{-6}	0.73×10^{-6}	0.093
〃 -74037 (〃)	2.6×10^{-6}	1.8×10^{-6}	1.92×10^{-6}	0.032
〃 -74648 (〃)	3.65×10^{-5}	3.25×10^{-5}	1.80×10^{-5}	0.24

(Sh): Eucritic unique achondrite similar to Shergottite.

purpose of estimating their paleointensity. NRM's of the two diogenites are not sufficiently stable against the AF-demagnetization, in particular, with respect to the direction of their NRM's.

The AF-demagnetization curves of NRM intensity for the other four achondrites up to 800 Oe peak in the AF-field are shown in Fig. 1, while changes in the direction of their residual NRM's after AF-demagnetizing up to 500 Oe peak are illustrated with every 100 Oe interval in Fig. 2. As shown in Figs. 1 and 2, NRM's of ALHA-77302 and 77257 are stable against the AF-demagnetization after AF-demagnetizing up to 100 Oe peak, while NRM's of the other two achondrites are particularly stable only after AF-demagnetizing to 200 Oe peak. It may be considered therefore that the residual NRM's of ALHA77302 and 77257 remaining after AF-demagnetizing to 100 Oe peak and the residual NRM's of the other two achondrites after an AF-demagnetization to about 200 Oe peak are sufficiently stable and reliable for the paleointensity examination purpose. In Table 1, the original NRM intensity, In(0), and the residual NMR intensities after AF-demagnetizing up to 100 and 200 Oe peak respectively, In (100) and In (200), are summarized. It has been often demonstrated (*e.g.* NAGATA, 1961) that NRM's of terrestrial rocks are accompanied by the so-called soft remanence which might be acquired by the viscous magnetization mechanism in the presence of the present geomagnetic field, and which can be AF-demagnetized by alternating magnetic fields up to a certain value, say 100 Oe peak. The viscous magnetic characteristics of achondrites are examined in the present study by a more direct way in relation to the stability of remanent magnetization against the AF-demagnetization.

A newly proposed method of examining the magnetic viscosity is based on the principle to measure a viscous component of a partial ARM which is acquired during an alternating magnetic field range between $\tilde{H}$ and $\tilde{H}+\Delta\tilde{H}$ in the presence of a stationary magnetic field, h, whose direction is in coincidence with the axis of $\tilde{H}$.

Then, the partial ARM obtained will represent a remanent magnetization acquired by the ferromagnetic grains (or domains), the microscopic coercive force (h_c) of which is ranged approximately from $\tilde{H}$ to $\tilde{H}+\Delta\tilde{H}$, provided that h is sufficiently small (*e.g.* Ozima *et al.*, 1963).

In actual measurements, partial ARM's ($I_A(\tilde{H}_i)$) obtained by applying an alternating magnetic field range from various magnitudes of $\tilde{H}_i$ to 0 during a constant time (*i.e.* 120 s in the actual experiment) in addition to the geomagnetic field (0.55 Oe) are continuously measured by a cryogenic super-conductive magnetometer in non-magnetic space. By taking into consideration the addition-law for ARM, $I_A(\tilde{H}_{i+1})-I_A(\tilde{H}_i)$, where $\tilde{H}_{i+1}>\tilde{H}$, is defined as the partial ARM acquired during a field range between $\tilde{H}_i$ and $\tilde{H}_{i+1}$.

Fig. 3 shows an example of the time dependence of partial ARM's, $I_A(\tilde{H}_{i+1})-I_A(\tilde{H}_i)$, for ALHA77005. Generally speaking, partial ARM's are associated with only a small amount of the viscous remanent magnetization (VRM) whose relaxation time is less than 3×10^2 s except for I_A (100 Oe). Although partial ARM's acquired in an AF-field range larger than 100 Oe peak become almost constant about 4×10^2 s after the magnetization, partial ARM acquired in a field range smaller than 100 Oe

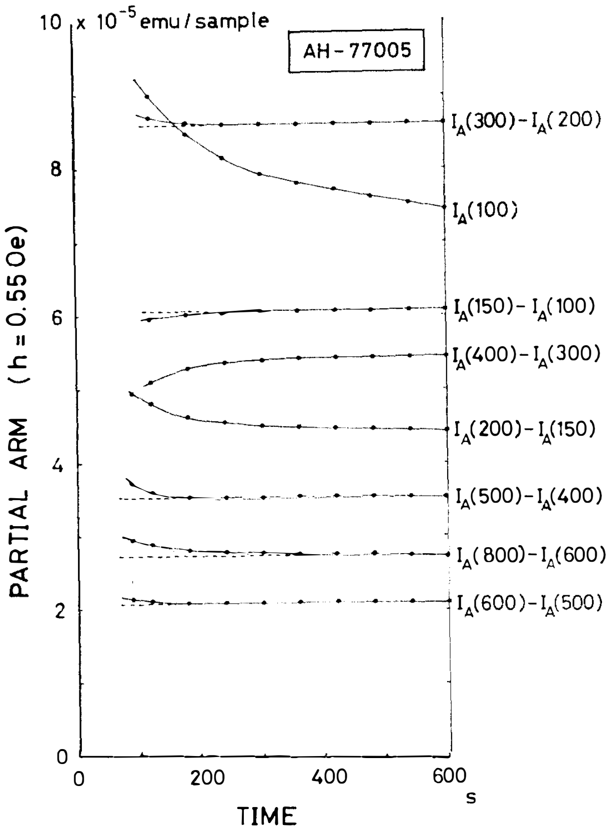

Fig. 3. Time-decay of partial ARM of ALHA77005 achondrite.

peak decreases with time (t) approximately following the law of $I_A(t=t)=I_A(t=o)-S\log t$. In the case of ALHA77005, therefore, we may have to assume that a partial NRM which can be AF-demagnetized by an alternating magnetic field of 100 Oe peak or less is very likely to be due to the geomagnetic field.

Similar experimental tests were made on the viscous decay of partial ARM's of the other three achondrites. The viscous magnetization effect is small for ALHA-77302, while that for ALHA77257 and 78040 is in between that for ALHA77302 and 77005.

3. Paleointensity of Antarctic Achondrites

From results of the AF-demagnetizations of NRM and ARM, the NRM-lost values are plotted against the ARM-lost values for ALHA77005, 77257, 77302 and 78040 achondrites in Figs. 4 through 7 respectively, where the original ARM's were obtained in the maximum alternating magnetic field of 800 Oe peak. The NRM direction of some achondrites becomes markedly unstable after the AF-demagnetization above 600 Oe peak. In such a case, the comparison of the NRM-lost with the ARM-lost is limited within a magnetic field range where the NRM direction remains reasonably stable.

In a diagram of the NRM-lost versus ARM-lost for ALHA77005, shown in Fig. 4, the expected linear relationship between the NRM-lost and the ARM-lost is divided into two AF-demagnetization field ranges, *i.e.* $\tilde{H}\lesssim 100$ Oe peak and $\tilde{H}\gtrsim 150$ Oe peak. In the original ARM before its AF-demagnetization experiment, the VRM component was reduced to its 10% level by keeping the anhysteretically

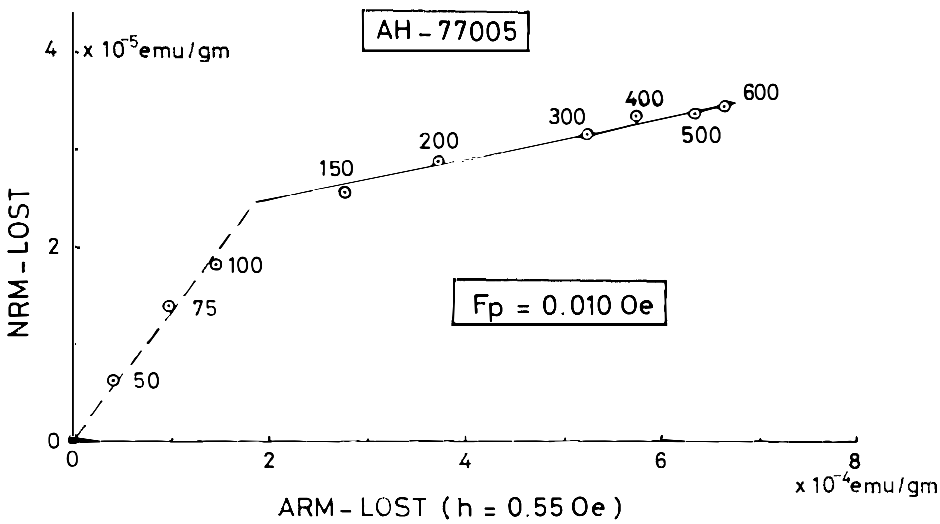

Fig. 4. NRM-lost versus ARM-lost diagram for determining the paleointensity (F_p) of ALHA-77005.

magnetized sample in a non-magnetic space over 3 days. Therefore, the observed large rate of AF-demagnetization of NRM from $\tilde{H}=0$ to about $\tilde{H}=100$ Oe peak may be attributable to the AF-demagnetization rate of the soft component of NRM which is largely due to the VRM-component of this sample acquired in the geomagnetic field, because the viscous magnetization effect on the ferromagnetic metallic grains having the microscopic coercivity less than about 100 Oe has been experimentally demonstrated, as described in Section 2 of this report.

The hard component of NRM, which can be AF-demagnetized by alternating magnetic fields larger than 100 Oe, may be regarded as the stable remanent magnetization which was acquired in the extraterrestrial space. From an approximately linear relationship between the NRM-lost and the ARM-lost for the AF-demagnetization field range from 150 to 600 Oe peak in Fig. 4, the paleointensity (F_p) of ALHA-77005 is estimated to be $F_p=0.010$ Oe on the assumption that the NRM concerned is of the TRM origin.

General tendencies of the NRM-lost versus ARM-lost relationship for ALHA-77257 in Fig. 5 are similar to those for ALHA77005, but the alternating magnetic field range corresponding to the soft component of NRM in ALHA77257 is considerably smaller than that in ALHA77005. From a linear relationship of the NRM-lost versus ARM-lost for the hard component range of NRM of $\tilde{H}\geqq 60$ Oe peak, the paleointensity of ALHA77257 is estimated to be $F_p=0.089$ Oe.

The soft component range of NRM of ALHA77302 is the smallest, as shown in Fig. 6. This result is consistent with the observed facts that the direction of NRM of this achondrite is relatively stable against the AF-demagnetization even in a range of $\tilde{H}<100$ Oe peak and that the viscous magnetization effect on a partial

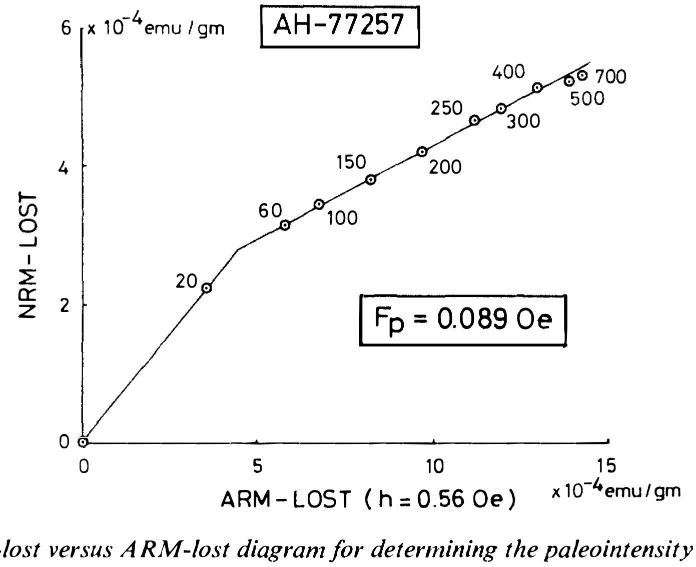

Fig. 5. NRM-lost versus ARM-lost diagram for determining the paleointensity (F_p) of ALHA-77257.

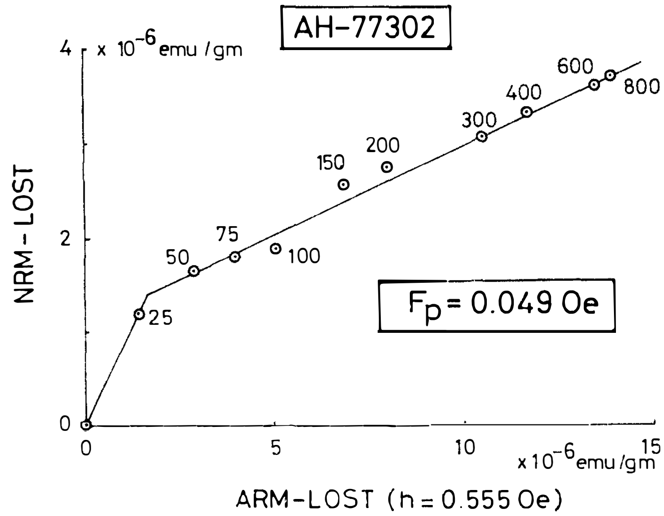

Fig. 6. NRM-lost versus ARM-lost diagram for determining the paleointensity (F_p) of ALHA-77302.

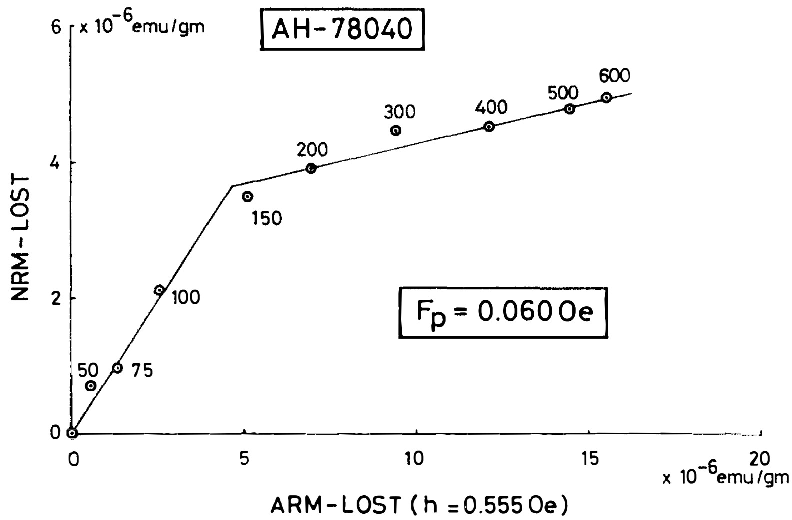

Fig. 7. NRM-lost versus ARM-lost diagram for determining the paleointensity (F_p) of ALHA-78040.

ARM acquired by $\tilde{H}$=100 Oe peak is very small. From a linear relationship between the NRM-lost and the ARM-lost for the hard component range of $\tilde{H}\geqq 50$ Oe peak, the paleointensity of ALHA77302 is given as F_p=0.049 Oe.

As shown in Fig. 2, the soft component of NRM of ALHA78040 seems to occupy a fairly large range from 0 to about 200 Oe in terms of the microscopic coercivity. However, the hard component of NRM of this achondrite corresponding to $\tilde{H}\geqq 200$ Oe is sufficiently stable, as shown in Fig. 7. From the hard component NRM, F_p of this achondrite is determined as F_p=0.060 Oe.

As discussed in Section 2, F_p is determined in the present study by

$$F_p = h \cdot \Delta\mathrm{NRM}/f_0 \cdot \Delta\mathrm{ARM}, \quad (2)$$

where ΔNRM and ΔARM denote the partial NRM and the corresponding partial ARM respectively for the hard component range, and $f_0=1.3$ is assumed throughout the present studies. In the experimental results of determining f_0 for magnetite and maghemite grains (DUNLOP and WEST, 1969), $1/f_0$ ranges from 0.182 to 0.619, and the experimentally observed values of $1/f_0$ are approximately equal to ratios of their respective spontaneous magnetization at average blocking temperature ($\bar{T}_B$) to that at 0°K, $I_s(T=\bar{T}_B)/I_s(T=0°\mathrm{K})$, as theoretically expected. It is almost certain therefore that $f_0>1$, but there may be a possibility of $f_0>1.3$ dependent on $\bar{T}_B$ of individual samples. Taking into consideration such a condition as discussed above, the F_p values of achondrites obtained in the present study may be considered as the upper limit of their probable paleointensity.

In Table 1, the newly determined values of F_p of four Antarctic achondrites are summarized together with four F_p values of other achondrites previously evaluated. In this table, the F_p-value of Yamato-7307 was determined with the aid of Königisberger-Thellier method for a temperature range of 20–240°C, while F_p-values of all the other 7 achondrites were determined with the aid of NRM/ARM method on the assumption of $f_0=1.3$. It may be concluded that all F_p-values of Antarctic achondrites are smaller than 0.24 Oe, and 5 of the 8 F_p-values are within a range of 0.05–0.10 Oe. It was provisionally concluded in previous papers (NAGATA, 1979a, b) that the paleointensity of achondrites is smaller than 0.2 Oe, the average value being $F_p=(0.11\pm0.02)$ Oe. In the present study, the viscous magnetization effect on NRM is specifically examined in the course of paleointensity studies by means of a comparison of the NRM-lost with the ARM-lost (to eliminate a possible error in determining F_p-values). The results of present study have shown that F_p-values of the three achondrites, ALHA77257, 77302, and 78040, except an unusual eucritic unique achondrite, ALHA77005, range from 0.049 to 0.089 Oe. It may thus be confirmed that the upper limit of paleointensity of most achondrites is 0.1 Oe or less.

4. Concluding Remarks

As given in Table 1, the F_p-value of ALHA77005 unique achondrite is 0.010 Oe, which is smaller than the F_p-values of the other achondrites by one order of magnitude. Mineralogical and petrological characteristics of this unique achondrite have been studied in detail (MCSWEEN *et al.*, 1979a, b). According to the result of these studies, this unique achondrite was seriously shock-metamorphosed by a peak shock pressure of about 300 k bars about 1.8 million years ago. Since silicate minerals in this achondrite show evidence of impact melt and recrystallization, the paleointensity of ALHA77005 may represent the ambient magnetic field when it was shock metamorphosed. If the serious shock effect took place about 1.8 million years ago, the nature of the ambient magnetic field would be a significant problem. Since it is difficult to assume the presence of a magnetic field of about 0.01 Oe in the interplanetary space 1.8 million years ago, a plausible interpretation of the magnetic field would be the magnetic field of a parent planet of this basaltic achondrite when the planetary surface was severely bombarded by other asteroidal bodies.

As for the ambient magnetic field for NRM's of the three other achondrites, either a magnetic field of their parent planet(s) or a magnetic field produced by a hypothetical solar nebula dynamo at the time when they differenciated about 4.5 billion years ago could be reasonably considered.

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