NATURAL REMANENT MAGNETIZATIONS OF CHONDRULES, METALLIC GRAINS AND MATRIX OF AN ANTARCTIC CHONDRITE, ALH-769

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***Abstract*:** For examining characteristics of NRM, 3 bulk specimens, 9 individual matrix materials, 12 large metallic grains and 12 individual chondrules were picked from the ALH-769 (L6) chondrite and their orientations were determined with respect to the bulk chondrite. NRM of the bulk chondrite is unstable against AF demagnetization. NRM of the matrix materials is stable up to 140 Oe peak, but its stability becomes worse for alternating fields larger than 140 Oe peak. NRM directions of the matrix materials are clustered within a hemisphere, suggesting that the presence of a magnetic field partially influenced the NRM acquisition. NRM of the metallic grains is unstable and its direction is widely scattered. NRM of the chondrules is fairly stable against AF demagnetization and thermal demagnetization. However, the direction of NRM is widely scattered within the bulk chondrite. The result of thermal demagnetization of the chondrules suggests that NRM of individual chondrules was acquired as TRM while they were making precessional motions during their cooling in the presence of a magnetic field before their assembling into the mother chondrite.

1. Introduction

Paleomagnetic studies of the natural remanent magnetization (NRM) of stony meteorites have been carried out with achondrites and carbonaceous chondrites which have fairly stable NRM. On the other hand, ordinary chondrites, which amount to 80% of the whole fall meteorites, have unstable NRM in most cases. The present study aims specifically to clarify the cause of the poor stability of NRM in ordinary chondrites.

The NRM of individual chondrules of the Allende (C3) carbonaceous chondrite was experimentally studied by LANOIX *et al.* (1978a, b) and SUGIURA *et al.* (1979). Their results have shown that the NRM directions of the chondrules are not initially at random, but they become scattered after either AF demagnetization or thermal demagnetization, suggesting that there are two stages in their thermal history with regard to NRM characteristics; one is a high-temperature component acquired before the chondrules were assembled into the meteorite, and the other is a low-temperature component acquired after the meteorite had experienced thermal metamorphism or during the assembly of the meteorite. The paleointensity of these chondrules was estimated to be 1–7 Oe. According to BRECHER and RANGANAYAKI (1975), the NRM intensity of ordinary chondrites decreases in a sequence of E→H→L→LL; shocked meteorites display a distinctive demagnetization curve, and very few ordinay chondrites preserve a useful paleomagnetic record.

The magnetic properties of ALH-769 were experimentally studied by NAGATA (1979a, b). The results have shown that NRM (especially intensity) is very unstable against AF demagnetization up to 200 Oe; this chondrite is classified magnetically as a typical L chondrite and the magnetic minerals contained in bulk samples are 15.7 wt% of FeNi alloy which is composed of 65 wt% of kamacite and 35 wt% of plessite. The intrinsic and bulk densities and porosities of ALH-769 are measured as 2.89 g/cm^3, 3.59 g/cm^3 and 19.4% respectively by MATSUI *et al.* (1980). According to the results of mineralogical investigation based on, olivine, pyroxene and plagioclase by OLSEN *et al.* (1978), this chondrite is placed in L6.

The ALH-769 chondrite is the largest in size of Antarctic stony meteorites, the total weight being 407.041 kg, and it consists of 33 blocks (YANAI, 1978). These meteorite blocks have black fusion crusts on their surface in some parts and the other parts of the surface have been oxidized to become brown in color. Individual blocks of this chondrite have been numbered ALH-769,1 to -769,33. In the present study, 12 individual giant chondrule pieces of 0.14–0.015 g in weight and about 2–5 mm in diameter were systematically picked out; 6 chondrules named D-1 to D-6, 4 chondrules E-1 ~ E-4 and 2 chondrules F-1 and F-2 were picked out respectively from the surface of ALH-769,15 (1942 g), -769,14 (2373 g) and -769,7 (7422 g), and their orientations in each block were determined. The relative orientations of chondrules among the different blocks are undeterminable. Three bulk samples, A-1 ~ A-3 (0.127 ~ 2.431 g in weight), twelve metallic grains, B-1 ~ B-12 (0.023 ~ 0.0018 g in weight) and nine matrix materials C-1 ~ C-9 (0.013 ~ 0.059 g in weight) were picked out from the ALH-769 chondrite blocks, and their relative orientations, were determined. The relative errors of orientation in sampling were within 15° for chondrules and within a few degrees for bulk samples, metallic grains and matrix materials.

Since NRM of meteorites may consist of magnetic hard components such as thermoremanent magnetization (TRM), depositional remanent magnetization (DRM) and chemical remanent magnetization (CRM), and magnetic soft components such as isothermal remanent magnetization (IRM) and viscous remanent magnetization (VRM), a magnetic cleaning by AF demagnetization will be necessary for identifying the hard components of NRM. The stability of NRM against AF demagnetization was tested for several representative samples of each group of bulk, chondrule, matrix and metal specimens by means of a two-axis tumbler demagnetizer placed in a non-magnetic space of a three-layer mumetal shield case. The direction and the intensity of remanent magnetization were measured by a SQUID magnetometer or a Spinner magnetometer. When the characteristics of NRM against the thermal demagnetization were examined in a non-magnetic thermal demagnetizer, individual chondrules were heated after they were enclosed in a quartz tube of 10^{-5} torr under atmospheric pressure. In the case of bluk samples, heating and cooling experiments were performed in argon gas. The saturation magnetization (I_s) and the saturation remanent magnetization (I_R) were determined with the aid of a vibrating sample magnetometer at room temperature. By the use of a special technique to enlarge the abscissa scale for the magnetic field intensity near the zero field intensity, the coercive force (H_c) and the remanent coercive force (H_{RC}) also were determined with the same measurement system.

2. Basic Magnetic Properties

The basic magnetic properties such as I_s, I_R, H_c and H_{RC} of 12 metallic grains, 9 matrix materials and 6 chondrules were measured individually at room temperature. These parameters are summarized in Table 1 together with the intensity of NRM.

The magnetic properties of the nine matrix specimens are given by $I_s=1.65\sim 16.20$ emu/g, $I_R=0.13\sim0.80$ emu/g, $H_c=32\sim166$ Oe and $H_{RC}=1140\sim3350$ Oe; those of the 12 metallic grains by $I_s=30.3\sim157$ emu/g, $I_R=0.018\sim0.053$ emu/g, $H_c=0.6\sim20.5$ Oe and $H_{RC}=63\sim217$ Oe, and those of the 6 chondrules by $I_s=0.99\sim 3.67$ emu/g, $I_R=0.012\sim0.091$ emu/g, $H_c=44.5\sim175.5$ Oe and $H_{RC}=935\sim2650$ Oe. Since the saturation magnetization of metallic iron is 210 emu/g, the metallic content of matrix and chondrules is estimated to more than $0.8\sim7.7$ wt% and $0.5\sim1.8$ wt% respectively from the observed I_s values, because this chondrite contains kamacite and plessite (NAGATA, 1979a). In general, the average values of I_s, I_R, H_c and H_{RC} of the bulk chondrite are approximately identical to those of the matrix materials. As the I_s values of metallic grains are considerably smaller than those of pure kamacite, it is considered that metallic grains could not be perfectly separated from the surrounding silicate matrix. The comparatively large values of H_c and H_{RC} of the matrix materials and the chondrules suggest that their metallic components are largely of very fine metallic grains which are able to have stable TRM. Large-size metallic grains of the multidomain structure associated with smaller values of H_c and H_{RC} are not able to have stable remanence. Roughly speaking, the intensity of NRM (I_n) of these chondrules, matrix materials and metallic grains is approximately proportional to the saturated isothermal remanent magnetization (I_R), as indicated in Table 1.

3. Characteristics of Natural Remanent Magnetization

3.1. *Uniformity of NRM of ALH-769*

The uniformity of natural remanent magnetization (NRM) of ALH-769 is ex-

Table 1. Basic magnetic properties of bulk chondrite, matrix materials, metallic grains and chondrules of ALH-769 (L6) chondrite.

	No.	Weight	I_n	I_s	I_R	H_c	H_{RC}	I_n/I_R
		g	$\times 10^{-4}$ emu/g	emu/g	emu/g	Oe	Oe	$\times 10^{-2}$
Bulk	A-1	2.43129	22.21	9.73	0.34	91.5	2700	0.65
Metallic grain	B-1	0.00415	24.82	157.0	0.38	7.0	63	0.65
	B-2	0.00216	26.85	171.0	0.28	5.0	63	0.96
	B-3	0.00831	71.60	127.0	0.53	13.5	147	1.35
	B-4	0.01372	15.16	81.0	0.18	0.6	135	0.84
	B-5	0.02234	14.15	150.0	0.28	6.0	97	0.51
	B-6	0.0055	108.86	32.2	0.19	6.5	217	5.73
	B-7	0.0089	75.71	30.3	0.25	12.3	132	3.03
	B-8	0.0046	84.27	77.5	0.25	8.5	121	3.37
	B-9	0.0018	135.59	67.0	0.31	6.5	119	4.38
	B-10	0.003	81.21	67.5	0.28	8.5	137	2.90
	B-11	0.0144	15.48	155.5	0.53	4.5	38	0.29
	B-12	0.025	96.97	34.3	0.45	20.5	155	2.16
Matrix	C-1	0.018	6.72	5.68	0.27	132.0	1810	0.24
	C-2	0.02	35.00	9.73	0.80	114.0	2610	0.44
	C-3	0.015	75.47	12.75	0.35	45.0	1140	2.16
	C-4	0.005	3.80	9.53	0.13	153.5	3350	0.29
	C-5	0.005	7.2	1.65	0.18	32.0	2790	0.40
	C-6	0.06	64.17	9.15	0.48	166.0	2210	1.31
	C-7	0.007	16.41	7.40	0.36	136.0	1541	0.46
	C-8	0.013	3.15	16.20	0.43	39.0	1493	0.07
	C-9	0.018	9.50	9.70	0.45	114.0	1815	0.21
Chondrule	D-1	0.0313	0.926	3.67	0.059	115.0	2210	0.16
	D-2	0.022	7.759	—	—	—	—	—
	D-3	0.0192	0.836	3.50	0.091	95.0	1772	0.09
	D-4	0.0284	21.585	—	—	—	—	—
	D-5	0.0148	13.676	—	—	—	—	—
	D-6	0.0138	0.749	1.30	0.016	100.5	1265	0.47
	E-1	0.1417	5.180	—	—	—	—	—
	E-2	0.0254	2.675	1.51	0.068	175.5	2650	0.39
	E-3	0.0146	0.410	—	—	—	—	—
	E-4	0.321	0.321	2.44	0.028	48.0	983	0.11
	F-1	0.0731	23.694	—	—	—	—	—
	F-2	0.0317	0.568	0.99	0.012	4.5	935	0.47

amined by measuring the intensity and the direction of NRM of a sufficiently large specimen and its divided specimens. The intensity (I_n) and the direction cosines (l, m, n) with respect to a fix coordinate system of an ALH-769 sample of 9.883 g in weight are given in Table 2. This rock specimen is divided into two large pieces (a) and (b), one small piece (c) and a number of dust particles by chipping it by a non-magnetic vice in a non-magnetic space, where the orientation in the coordinate system of chipped specimens. (a) and (b), are determined with a possible uncertainty of 5° in angle. The observed values of I_n and (l, m, n) of specimens (a) and (b), I_n of specimen (c), and their respective weights are summarized in Table 2. As for the I_n-value, the deviations of specimens (a), (b) and (c) from the original whole specimen are +9%, −19% and −5% respectively, while the deviations of NRM direction of specimens (a) and (b) from the original whole specimens NRM are 7° and 18° respectively. It may be concluded thus that NRM is fairly uniformly distributed within a test specimen of several grams in weight of the ALH-769 chondrite.

Table 2. Intensity and direction of NRM. Original and chipped specimens of ALH-769.

Sample	Weight (g)	$I_n(\times 10^{-4}$ emu/g)	l	m	n
Original specimen	9.883	18.2	0.733	0.503	0.459
Specimen a	5.234	19.9	0.679	0.463	0.570
b	3.913	14.8	0.525	0.497	0.691
c	0.509	17.3	—	—	—

3.2. *NRM of bulk sample*

NRM of three bulk samples A-1, A-2 and A-3, was tested against AF demagnetization up to 880 Oe peak. Then, TRM of the three samples acquired in 0.5 Oe from 750°C was AF demagnetized. The results of these experiments are shown in Fig. 1 and Fig. 2. The NRM intensity of the bulk samples steeply decreases down to less than 1/5 of the initial value by AF demagnetization up to 60 Oe peak, and the NRM direction becomes widely spread by AF demagnetization beyond 40 Oe peak. Thus, NRM of the bulk sample of ALH-769 is unstable in general against AF demagnetization. On the contrary, the AF demagnetization characteristics of TRM of the bulk sample are reasonably stable with respect to both intensity and direction.

In Table 3, the magnetic parameters given by the magnetic hysteresis curves before and after the heating procedure are compared, because considerable changes of the magnetic properties may have taken place by the heating up to 750°C in argon gas. No drastic change caused by the heating procedure can be detected in I_s, I_R and H_c, but H_{RC} after the heating is much smaller than that before heating. The change of H_{RC} suggests that the shape anisotropy of magnetic phases of very fine size may have been changed by the heating. It could be concluded, however, that

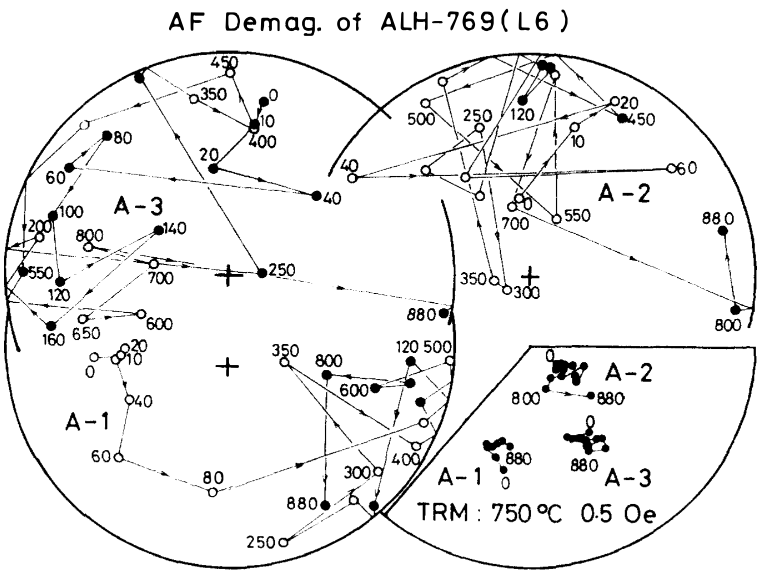

Fig. 1. AF demagnetization of NRM direction and total TRM (bottom-right) of 3 bulk chondrites of ALH-769 chondrite.

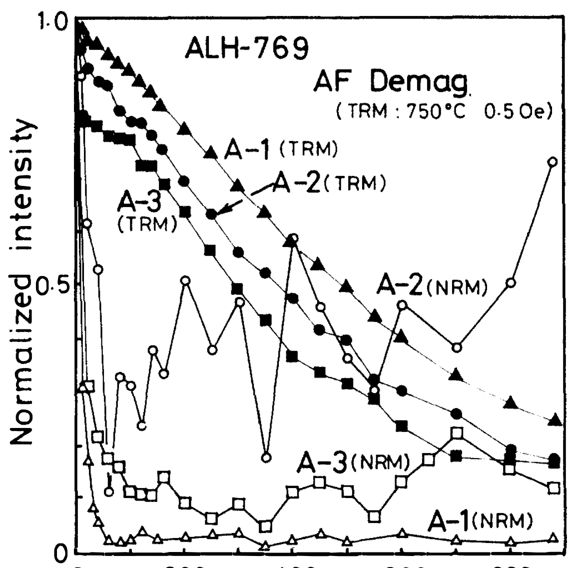

Fig. 2. AF demagnetization of NRM intensity (hollow symbols) and total TRM intensity (full symbols) of 3 bulk chondrites of ALH-769 chondrite.

the bulk NRM of ALH-769 is very unstable in comparison with the bulk TRM against the AF demagnetization test.

Table 3. Basic magnetic properties before and after heating at 750°C (0.5 Oe) of bulk chondrite A-1 of ALH-769 (L6) chondrite.

	I_s emu/g	I_R emu/g	H_c Oe	H_{RC} Oe
Unheated	9.73	0.335	91.5	2700
Heated	8.65	0.349	81.0	402

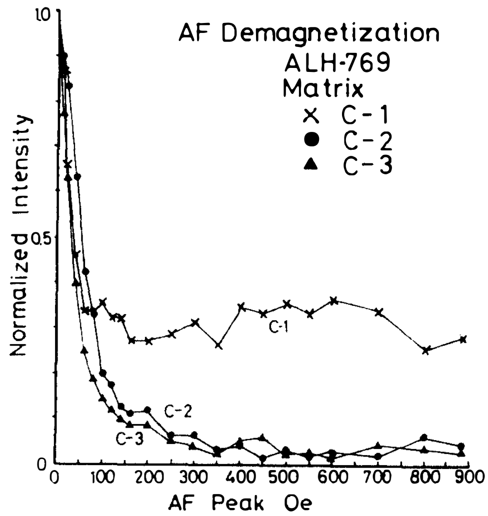

Fig. 3. AF demagnetization of NRM intensity of 3 matrix materials of ALH-769.

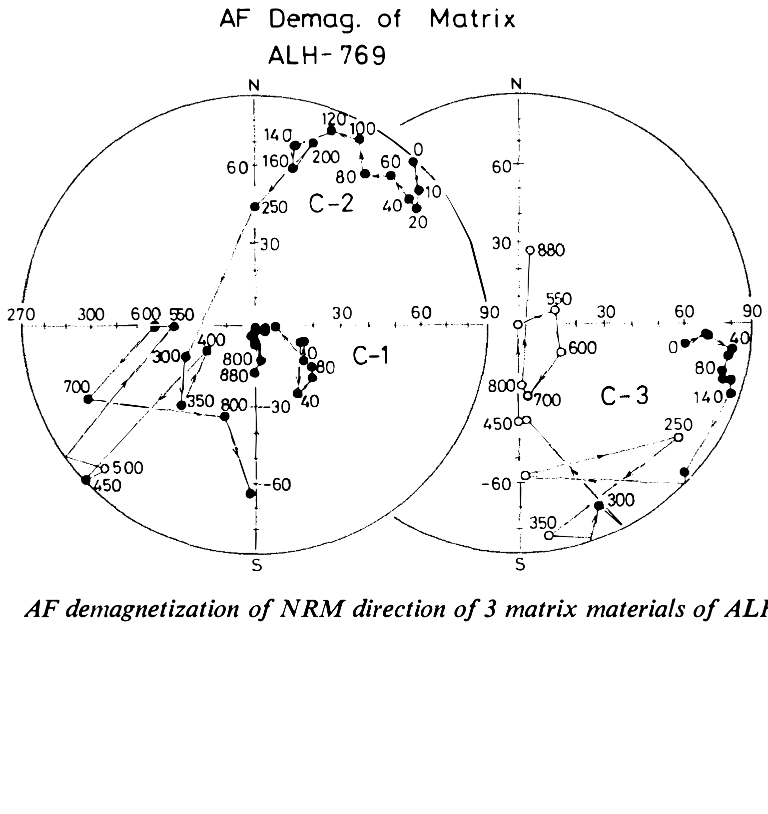

Fig. 4. AF demagnetization of NRM direction of 3 matrix materials of ALH-769.

3.3. NRM of matrix materials

The NRM stability against AF demagnetization of three matrix specimens, C-1, C-2 and C-3, was examined, the results being shown in Figs. 3 and 4. NRM of C-1 is very stable after AF demagnetization up to 60 Oe peak, but NRM's of the other two matrix specimens can be considered stable against AF demagnetization to 140 ~ 160 Oe peak, the direction of remaining NRM changes widely for the demagnetization above the critical magnetic field. Therefore, it could be concluded that NRM of the matrix materials is reasonably stable for AF demagnetization up to about 140 Oe peak, but it becomes unstable for demagnetization by higher fields.

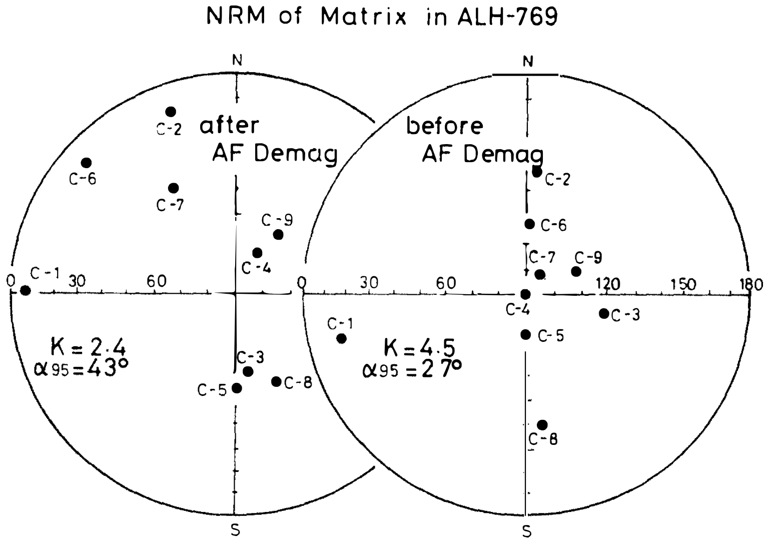

Fig. 5. Distribution of NRM of matrix materials.
Left: After AF demagnetization up to 140 Oe peak.
Right: Before AF demagnetization.

The NRM direction before and after AF demagnetization to 140 Oe peak of 9 individual matrix specimens of 0.005 ~ 0.059 g in weight shown in Fig. 5, are clustered within a hemisphere. However, they are fairly dispersed as indicated by K (precision parameter) $=4.5$ and α_{95} (the radius of circle of 95% confidence) $=27°$ before AF demagnetization, and $K=2.4$ and $\alpha_{95}=43°$ after AF demagnetization. These observed results may suggest that NRM of the matrix is caused by a magnetic orientation mechanism in the presence of a magnetic field which is relatively weak compared with turbulent disturbances of orientations at random such as in the case of a formation of depositional remanent magnetization (DRM).

3.4. NRM of metallic grains

Twelve metallic grains, B-1 ~ B-12, were AF demagnetized stepwise to 880 Oe peak. Three typical AF demagnetization curves are shown in Figs. 6 and 7. In

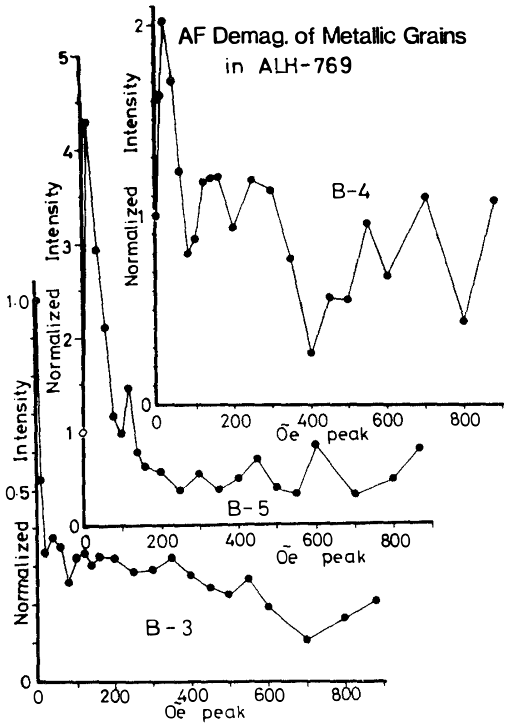

Fig. 6. AF demagnetization of NRM intensity of 3 metallic grains of ALH-769.

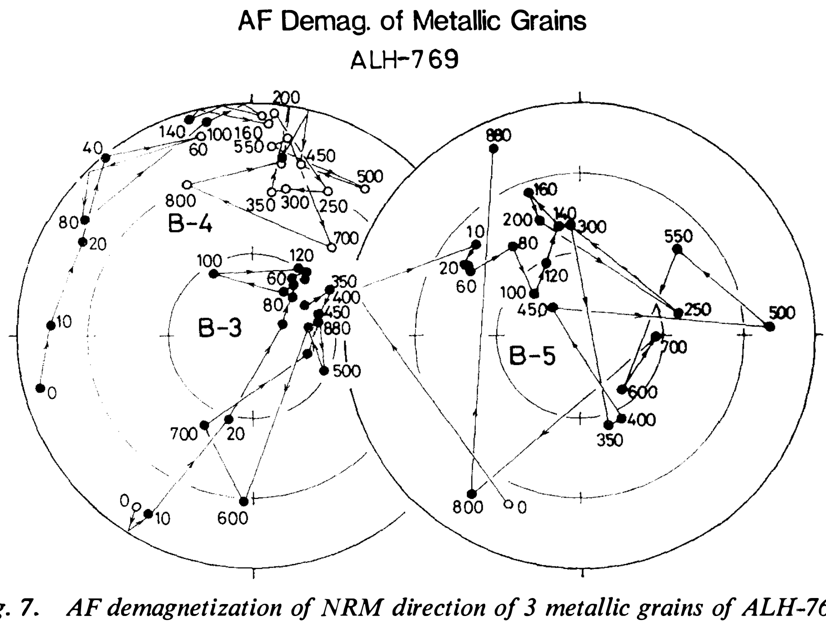

Fig. 7. AF demagnetization of NRM direction of 3 metallic grains of ALH-769.

Fig. 7, the NRM direction of B-3 is stable between 40 and 500 Oe peak, beyond which the NRM direction changes widely. However, the NRM intensity of this specimen steeply decreases with weakening magnetic fields to 60 Oe peak, and then becomes relatively stable against AF demagnetization. NRM's of specimens among 12 are

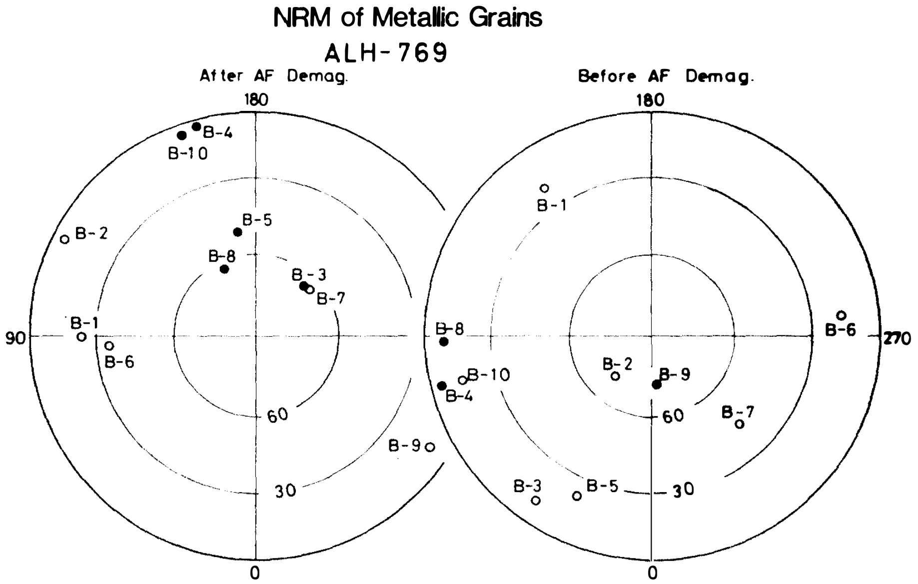

Fig. 8. Distribution of NRM of metallic grains.
Left: After AF demagnetization up to 140 Oe peak.
Right: Before AF demagnetization.

relatively stable, but others are not stable at all.

The directions of NRM's of 10 samples before AF demagnetization up to 140 Oe peak are widely scattered over almost the whole spherical coordinate surface as indicated by $K=1.6$, $\alpha_{95}=60.7°$, while those after AF demagnetization are represented by $K=1.5$, $\alpha_{95}=56.5°$, as shown in Fig. 8. It can be concluded therefore that NRM of metallic grains is unstable and its direction is at random in this chondrite.

3.5. NRM of chondrules

The AF demagnetization characteristics of the intensity and the direction of NRM of 6 chondrules are shown in Figs. 9 and 10. The NRM of 5 among 6 chondrules except E-4 is fairly stable at least for demagnetizing fields up to 800 Oe peak.

The NRM directions of 10 chondrules before AF demagnetization and those of 5 chondrules after AF demagnetization up to 140 Oe peak are shown in Figs. 11 and 12 respectively. In Fig. 11, the NRM directions of 6 chondrules, D-1 ~ D-6, before AF demagnetization are widely scattered over almost the whole spherical surface ($K=1.2$, $\alpha_{95}=141°$), and those of 3 chondrules, D-1, D-3 and D-6, after AF demagnetization to 140 Oe peak are also widely scattered ($K=1.0$, $\alpha_{95}\simeq\infty$). The distribution of NRM directions of 4 chondrules, E-1 ~ E-4 in Fig. 12, also has the same tendency ($K=1.4$, $\alpha_{95}=158°$ before the demagnetization; $K=1.0$, $\alpha_{95}\simeq\infty$ after the demagnetization) that the NRM direction of individual chondrules in ALH-769 is widely scattered though the NRM itself is fairly stable against AF demagnetization.

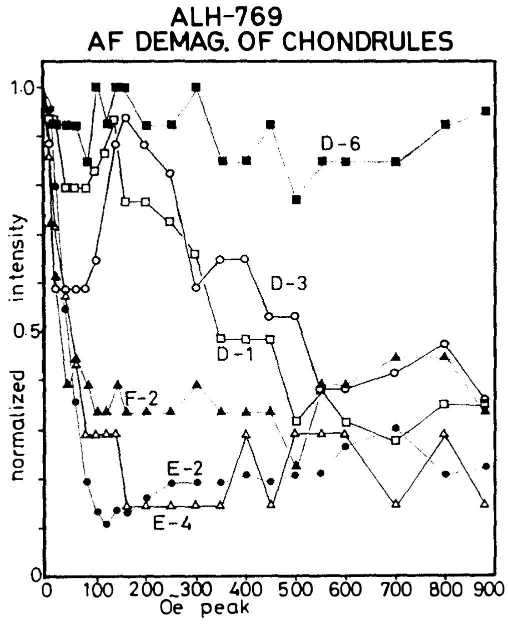

Fig. 9. AF demagnetization of NRM intensity of 6 chondrules of ALH-769.

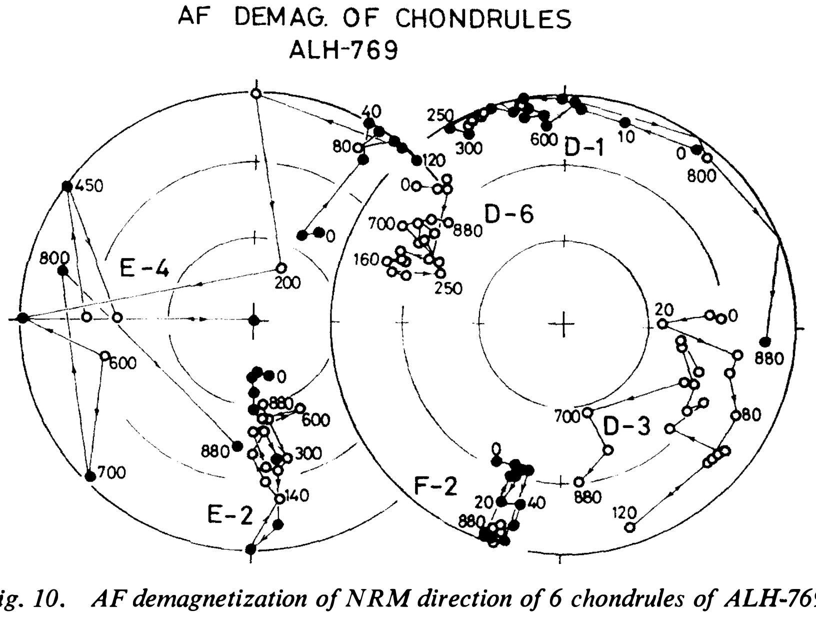

Fig. 10. AF demagnetization of NRM direction of 6 chondrules of ALH-769.

3.6. Thermal demagnetization

The remaining NRM directions in the course of stepwise thermal demagnetization at temperature interval of 50 or 60°C are shown in Fig. 13 for 4 chondrules. It appears that the direction of residual remanent magnetization after the stepwise thermal demagnetization has a tendency of rotation clockwise (D-2, D-4 and E-1) or counter-clockwise (D-5). The direction and the intensity of successive vector differences

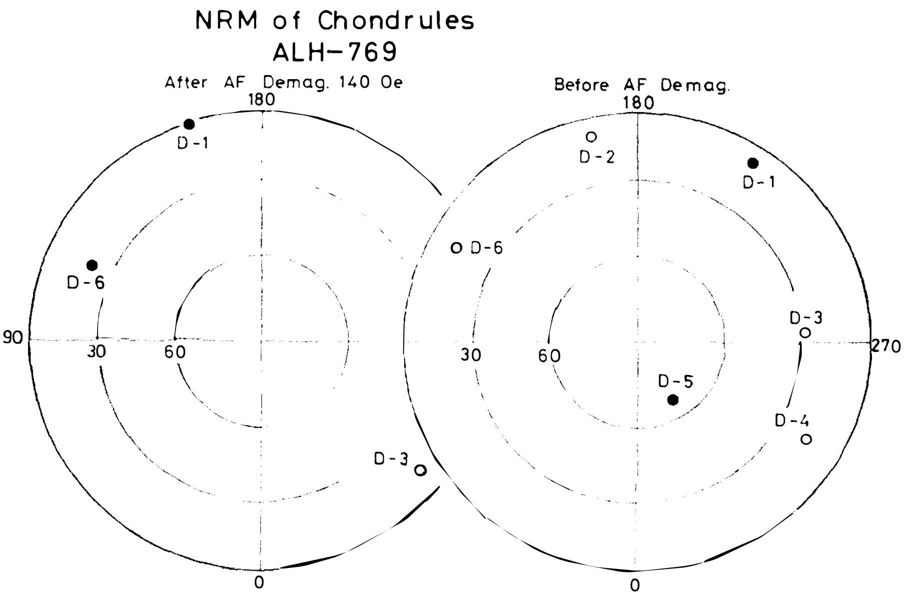

Fig. 11. Distribution of NRM of D-1 ~ D-6 chondrules.
Left: After AF demagnetization up to 140 Oe peak.
Right: Before AF demagnetization.

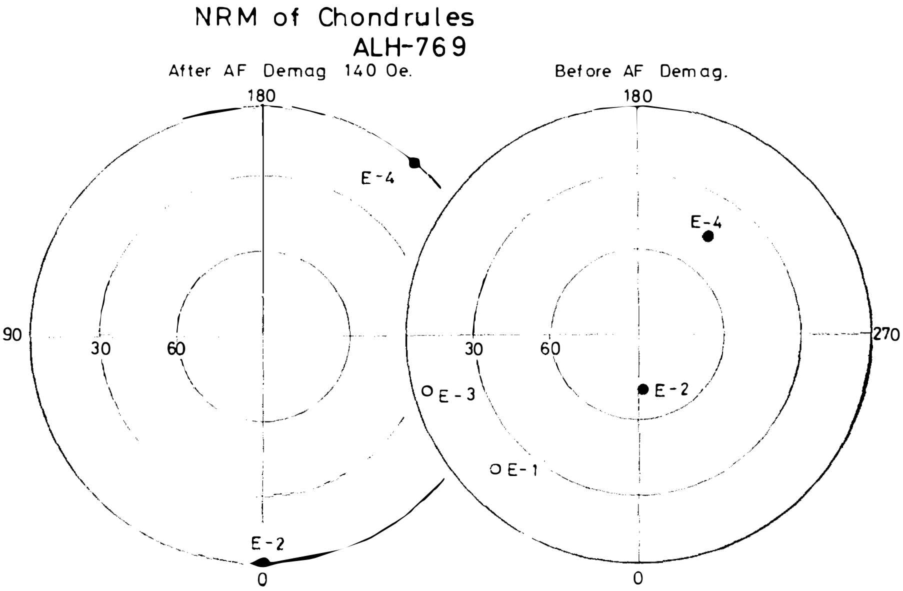

Fig. 12. Distribution of NRM of E-1 ~ E-4 chondrule.
Left: After AF demagnetization up to 140 Oe peak.
Right: Before AF demagnetization.

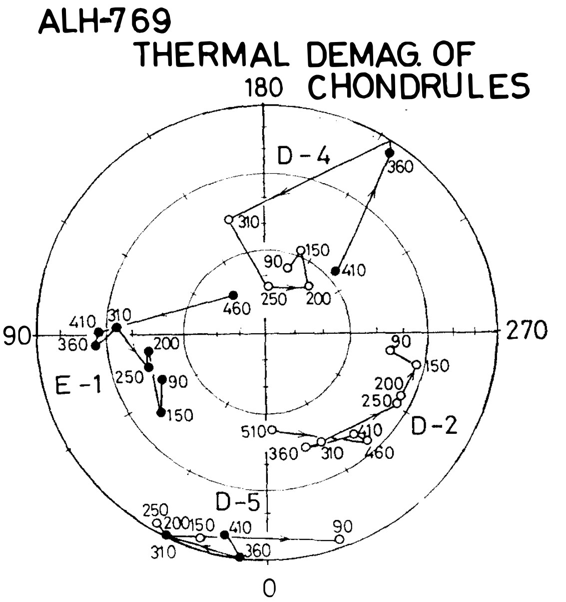

Fig. 13. Thermal demagnetization of NRM direction of 4 chondrules of ALH-769.

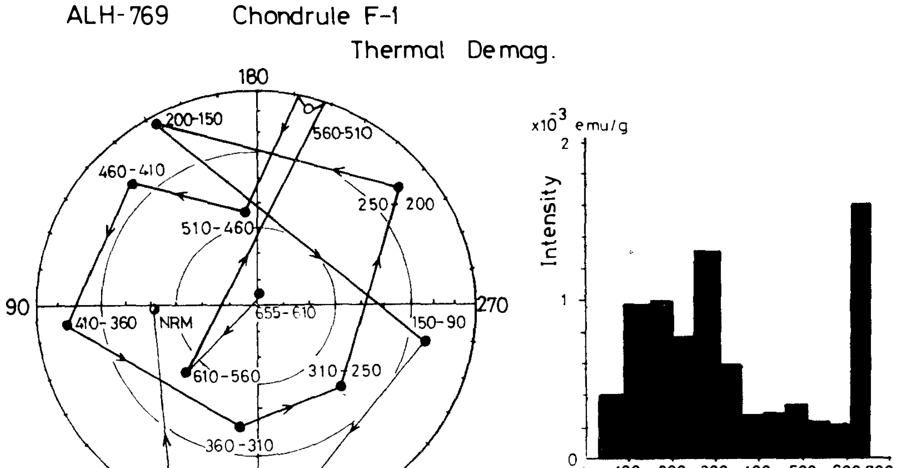

Fig. 14. Partial thermal demagnetization of one chondrule of ALH-769.
Left: Direction of partially thermal demagnetized magnetization.
Right: Magnitude of partically thermal demagnetized magnetization.

among the residual remanent magnetizations after the thermal demagnetization to T_i and T_{i-1} (where $T_{i-1}<T_i$), *i.e.* $\Delta I_i=I(T_{i-1})-I(T_i)$, are illustrated in Fig. 14. The direction of ΔI_i shown on the left and the intensity of ΔI_i on the right in Fig. 14 can be indentified to the direction and the intensity respectively of the partial TRM acquired during the cooling process through the (i) temperature range. In Fig. 14,

the direction of ΔI_i makes a complete circular rotation from the 460–410°C vector to the 200–150°C one. The tendency of a rotation of $I(T_i)$ vector, shown in Fig. 13, also could be interpreted as representing a similar characteristic of ΔI_i vector. These results of the thermal demagnetization characteristics of NRM may suggest that the chondrules made a precessional motion during the course of their acquisition of TRM while being cooled in the presence of a certain magnetic field.

4. Summary of NRM Characteristics

In Fig. 15, the NRM intensity is plotted against H_c for individual specimens of chondrule, matrix and metallic grain in ALH-769. As shown in Fig. 15, the three groups occupy the respective separate domains in the H_c versus NRM intensity diagram; namely, the metallic grain domain is characterized by a high NRM intensity (average intensity $=6\times10^{-3}$ emu/g) and a low value of H_c, and the chondrule domain by a low NRM intensity (average intensity$=1\times10^{-4}$ emu/g) and comparatively large value of H_c, while the matrix domain is located between the metallic grain and the chondrule domains. As the metallic grains occupy 5.5 wt% of the bulk composition of the ALH-769 chondrite, the apparently unstable characteristics of bulk NRM of ALH-769 should be largely due to the relatively strong and unstable NRM of the metallic grains.

Summarizing all experimental results of NRM characteristics of individual elements obtained in the present study and the current interpretation of the formation process of chondrites for the ALH-769 (L6) chondrite, serious contradictory problems

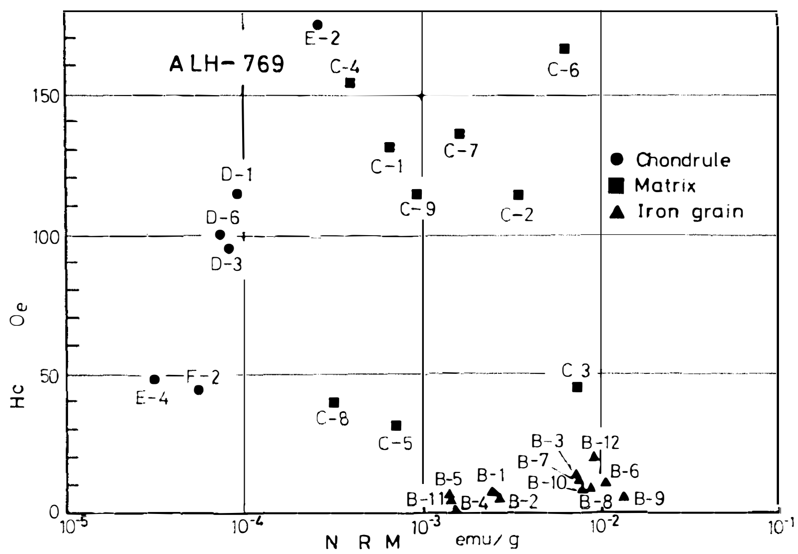

Fig. 15. Relationship of coercive force and NRM of matrix materials, metallic grains and chondrules.

could be pointed out. It is believed currently (*e.g.* WASSON, 1974) that an L6 chondrite was severely metamorphosed at temperatures of 700$\sim$900°C, probably within a parent planet or planetesimal. If the thermal metamorphism took place in the last stage of formation of chondritic materials, and the whole metamorphosed materials were then cooled down in the presence of a magnetic field, all chondrules, matrix and metallic grains should have possessed TRM of the same uniform direction. If the hypothetical thermal metamorphism was strong and long enough to cancel the whole previous magnetic history of individual magnetic elements, and if there were no magnetic field during the process of their cooling in the extraterrestrial space, the chondrite in the final stage would possess no stable remanent magnetization except unstable remanent magnetization such as IRM and VRM which may be acquired near or on the earth's surface. (The effect of geomagnetic field, has been studied in fair detail (*e.g.* NANATA, 1979a). Results of these studies have indicated that only the surface part of less than 1 mm in thickness is abnormally magnetized by the heating effect in the geomagnetic field, the interior keeping a relatively weak and uniform NRM.)

In the ALH-769 (L6) chondrite, however, individual chondrules have reasonably stable NRM which is probably acquired as TRM or pTRM while the chondrules are making a slow precessional motion, but the NRM direction of individual chondrules is widely dispersed, almost at random, within the bulk chondrite. On the other hand, the matrix NRM appears to be stable against AF demagnetization only up to about 150 Oe peak, but the NRM directions of individual matrix materials are clustered within a hemisphere as indicated by $\alpha_{95}=27°$, suggesting a possibility of a statistical alignment of fine metallic grains in the matrix, such as in DRM. The metallic grain NRM is not stable against AF demagnetization, but the NRM direction of metallic grains is widely dispersed, as in the case of chondrules, so that the unstable NRM of metallic grains may not be simply interpreted as a result of their acquisition of VRM and/or IRM in the geomagnetic field.

As far as the NRM characteristics of chondrules, matrix and metallic grains of the ALH-769 (L6) chondrite are concerned, the simplest possible overall interpretation will be as follows:

First, the individual chondrules acquired TRM or pTRM, while making a slow precessional rotation in a magnetic field. Then, the chondrules accreted together with the matrix materials and metallic grains to form the bulk chondrite structure in a weak magnetic field which was strong enough to result in a partial statistical alignment along the field direction for the fine metallic grains of matrix, but was too weak to align the chondrules having the weak NRM and the metallic grains having a relatively weak specific intensity of remanent magnetization. In the hypothetical process, it is assumed that the matrix contained a number of the single-domain metallic grains possessing the strong spontaneous magnetization (*i.e.* about 2×10^{-2} emu/g), whereas the remanent magnetization of the multi-domain metallic grains was $\leq10^{-2}$ emu/g in intensity.

From the petrological viewpoint, however, the hypothetical process for the formation of the ALH-769 L6 chondrite mentioned above is hardly acceptable, because this chondrite belongs to L6 or at least L5 of the classified chondrite type. The key point to be able to solve the contradictory problem will be a relation between the NRM behavior of individual chondrules and that of closely neighboring parts of the matrix. Such a problem will have to be experimentally solved by future investigations.

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(Received May 11, 1981; Revised manuscript received August 19, 1981)