MAGNETIC PROPERTIES OF LOW-PETROLOGIC GRADE NON-CARBONACEOUS CHONDRITES

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***Abstract*:** The magnetic properties and paleointensities of a number of non-carbonaceous chondrites show a considerable variation. Enstatite chondrites are far more magnetic than others and record ancient fields of 7 to 16 Oe. Abee has a high field, recorded in individual clasts and the random directions suggest the magnetization was pre-accretional. Indarch and Yamato-691 also record high fields, but have a single direction of magnetization, so we cannot infer if the magnetic record is of pre- or post-accretional origin.

A series of L and LL chondrites (Bjurbole, Yamato-74191, Mezo Madaras and Chainpur) contain plessite and it is therefore only possible to infer early magnetic fields at temperatures below 550°C, the transition temperature for plessite. Nevertheless, they have random components of magnetization and it is possible therefore that they record pre-accretional remanence. If these samples were reheated as suggested by others, we cannot explain the random directions, unless it is in some way related to tetrataenite, which is highly anisotropic. Ancient fields recorded in these samples are in the range of .1–.7 Oe.

Finally, ALHA77304 has no plessite, is an LL chondrite and records two components. The stable component may be of primary origin and if so records a field of 0.45 Oe.

1. Introduction

Paleomagnetic studies of carbonaceous chondrites (BANERJEE and HARGRAVES, 1972; BUTLER, 1972; BRECHER and ARRHENIUS, 1974) indicated that there was a substantial magnetic field associated with the formation of parent bodies of C chondrites in the early solar system. Early paleomagnetic studies of non-carbonaceous chondrites (*e.g.* BRECHER and RANGANAYAKI, 1975; GUS'KOVA, 1976; SUGIURA, 1977), however, have not yielded such definitive results, because their natural remanent magnetization (NRM) is very unstable.

Magnetic properties of low-petrologic grade, non-carbonaceous chondrites are of particular interest because: (1) their metallic grains are relatively fine-grained and could possess stable remanence and (2) they are likely to preserve the record of the magnetic field in the early solar system in the same way as that recorded in carbonaceous chondrites, because they have not been reheated to high temperatures.

Very few type 3 ordinary chondrites have been studied in detail magnetically. GUS'KOVA (1969, 1970) reported on the NRM and the initial susceptibility of Krymka (L3), Mezo Madaras (L3), Bremervorde (H3) and Panallee (LL3). BRECHER *et al.* (1977) and BRECHER and FUHRMAN (1979) studied Brownfield (H3) and Panallee (LL3),

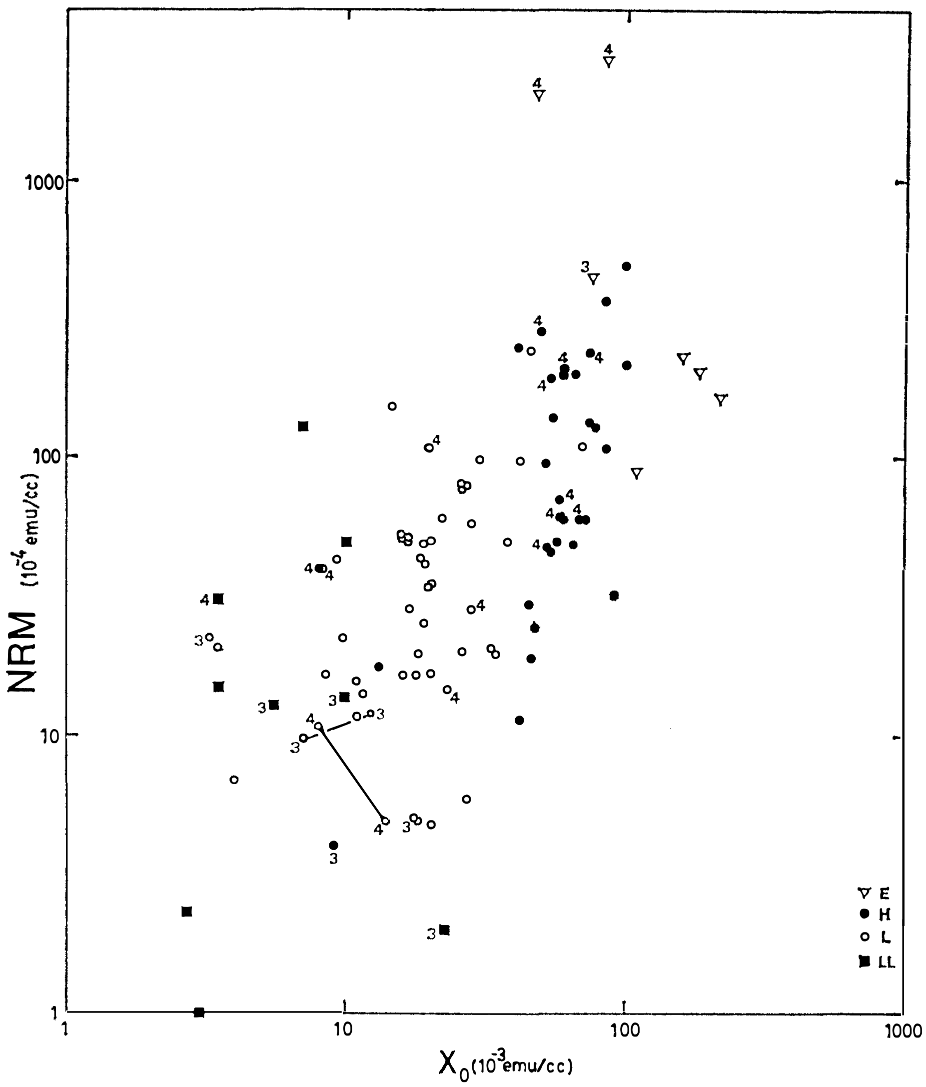

Fig. 1. NRM vs. X_0 plot for non-carbonaceous chondrites. Lines connect data for the same meteorite from different sources. Numbers (3) and (4) indicate the metamorphic grade of the chondrites.

respectively. Two Yamato meteorites (E3 and L3) were studied by NAGATA *et al.* (1975) and by SUGIURA (1977).

In Fig. 1, the NRM is plotted against the initial susceptibility (X_0) for various non-carbonaceous chondrites. The data sources are GUS'KOVA (1969, 1970, 1976), SUGIURA (unpublished), and this study. BRECHER *et al.* (1977) and BRECHER and FUHRMAN (1979) also provide many data but their X_0 is systematically larger than the X_0 of the others, so they have not been included in the figure. X_0 is a measure of the capacity of acquiring remanence and is mainly dependent on the amount of the ferromagnetic material and the grain size. In general it can be seen that the NRM becomes larger as the susceptibility increases. This effect is quite clear for all the meteorites together. However the relation within groups of meteorites appears to be quite different. The NRM and the initial susceptibility of type L3 chondrites are smaller than those of the metamorphosed L chondrites. Type H3 chondrites are only represented by one data point, but it also has a very small NRM and χ_0. E chondrites show a negative correlation between NRM and χ_0, and unequilibrated (type 3 and 4) E chondrites have larger NRM values than equilibrated E chondrites. Thus unequilibrated chondrites tend to carry more remanence than equilibrated chondrites.

2. Sample Description

In this study, we describe the magnetic properties of Chainpur (LL3), ALHA77304 (LL3), Mezo Madaras (L3), Bjurbole (L4) and Indarch (E4) in detail. Three chondrites (Yamato-74191 (L3), Yamato-691 (E3), Abee (E4)) which have been previously reported in the literature (SUGIURA, 1977; SUGIURA and STRANGWAY, 1981) are also reviewed in this discussion. Since each chondrite is different from the others, brief descriptions of the samples are given separately. Some of the important petrological and magnetic properties are summarized in Table 1.

Table 1. Petrological magnetic properties of Bjurbole, Y-74191, Mezo Madaras, Chainpur, ALHA77304, Y-691, Abee and Indarch.

	Bjurbole	Y-74191	Mezo Madaras	Chainpur	ALHA77304	Y-691	Abee	Indarch
Type	L4	L3	L3	LL3	LL3	E3	E4	E4
Friable	○	×	×	○	×	×	×	×
Chondrule rich	○	○	○	○	○	m	×	m
Breccia	×	×	○	○	○	×	○	×
Plessite	○	○	○	○	×	×	×	×
Slow cooling	○	○	○	○	m	—	×	m
Shock	×	×	m	×	×	m	×	m
Age (Ba)	4.5	?	—	—	4.5	—	4.5	—
NRM (10^{-4} emu/g)	1.5	1.5	3.7	4.3	4.3	133	800	579
J_s (emu/g)	13	21	17	11	13	48	82	66
H_c	630	30	42	89	6	12	14	15
H_p (Oe)	.25 .60	.13	.15	.74	.45	> 10?	7	15.7
χ_0(10^{-2} emu/g)	.42	.54	.37	.32	.17	21.4	24.2	14.1

m: moderate; —: unknown; H_p is paleomagnetic field intensity.

Bjurbole and Chainpur are porous and friable. All the L and LL samples in this study are rich in chondrules, suggesting that they have not been seriously mechanically disturbed since their accretion. Chainpur, Mezo Madaras, ALHA77304 and Abee have exotic clasts. Clasts in Abee are large (2–3 cm), while clasts in the other chondrites are less than 1 cm. Among ordinary chondrites, ALHA77304 is unique in that it does not have plessite (dark-etching taenite=kamacite+tetrataenite interior with a tetrataenite rim), suggesting relatively fast cooling below 320°C. Abee is interpreted to have cooled very rapidly from high temperature (HERNDON and RUDEE, 1978). None of the present samples are severely shocked, but melt pockets have been observed in Yamato-691 (OKADA, 1975) and in Indarch. Veins which were produced by a shock event which occurred after metamorphism were observed in Mezo Madaras (BINNS, 1968). ^{40}Ar–^{39}Ar plateau ages were reported (KANEOKA, 1980, 1981; BOGARD, 1980) for three samples and they are all 4.5 Ba.

The NRM intensity of E chondrites is much larger than that of L and LL chondrites. The difference is only partly explained by the amount of ferromagnetic materials (which is measured as the intensity of the saturation magnetization: J_s). The bulk coercive force (H_c) of L and LL chondrites is mainly determined by the amount of plessite (SUGIURA, 1977). Cohenite and schreibersite and their grain sizes seem to be important factors which determine the H_c of enstatite chondrites.

2.1. *Indarch*

Indarch is an E4 chondrite. The piece we received (USNM-334) has two dislocations apparently caused by a shock event. A small melt pocket was observed in a thin-section. Polycrystalline kamacite, which suggests rapid cooling, was also observed. These phases may have been produced by the shock event which produced the dislocations, although RAMDOHR (1973) did not find any evidence of shock in Indarch. This meteorite is rich in Henderson phase (a Fe–Ni–Si mineral whose structure is not well known: RAMDOHR, 1973). We do not know the magnetic properties of the Henderson phase, but there is no evidence of it in the $J_s(T)$ curve of Fig. 2, which looks like a pure kamacite signature. Cohenite (coarse grain) and schreibersite are microscopically observed minor ferromagnetic phases. A Curie point at about 130°C is seen on the $J_s(T)$ curve, which we attribute to nickel-rich cohenite. The Curie point of schreibersite can not be recognized on the $J_s(T)$ curve, but the rapid decrease of J_{rs} up to 300°C suggests that it may be one of the main carriers of the NRM.

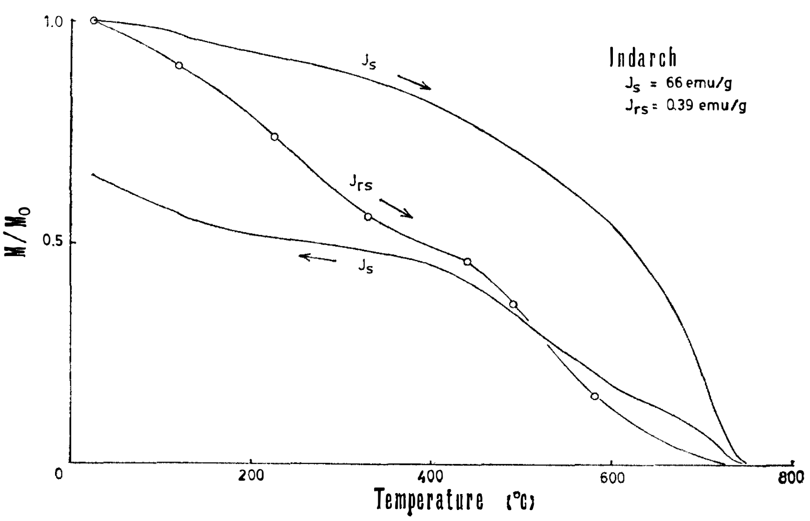

Fig. 2. $J_s(T)$ and $J_{rs}(T)$ curves for Indarch. The sample was sealed in a quartz tube under vacuum. The decrease of J_s after heating is probably due to oxidation of metallic iron.

NRM directions of seven subsamples are well-grouped (Fig. 3). Alternating field (AF) and thermal demagnetization show that the NRM is essentially single component. Compared with anhysteretic remanent magnetization (ARM) and partial thermoremanent magnetization (pTRM; $T \leq 328$°C), the NRM is deficient in high coercivity components (Fig. 4). Thermal demagnetization experiments (Figs. 5 and 6) show that

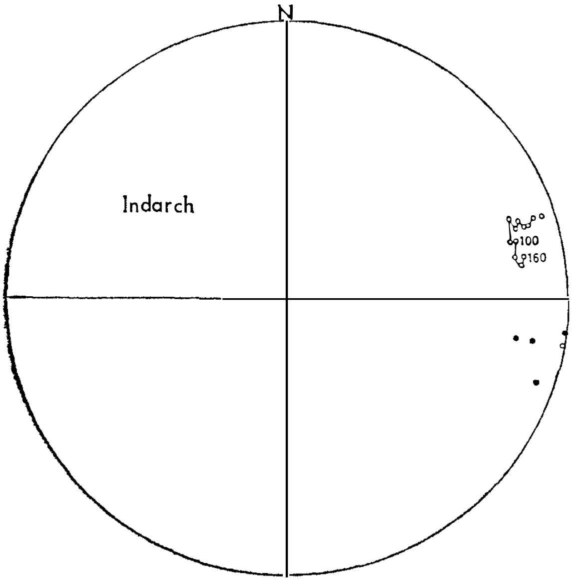

Fig. 3. NRM directions and its changes during AF and thermal demagnetization for subsamples of Indarch. The NRM direction did not change appreciably during the thermal demagnetization up to 700°C. It also does not change much during AF demagnetization up to 160 Oe.

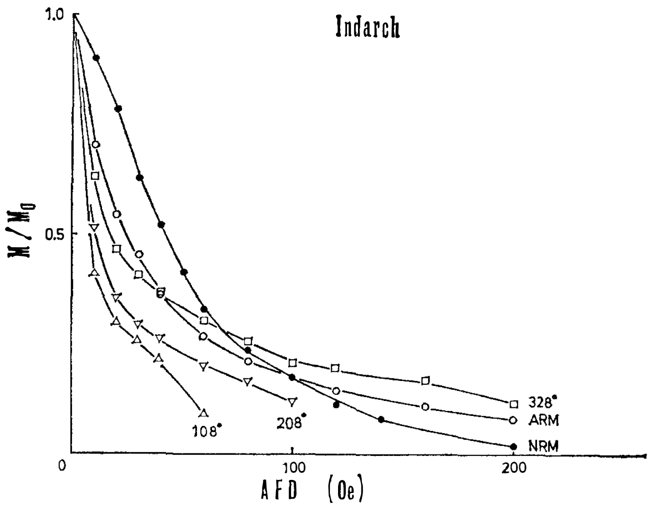

Fig. 4. Normalized AF demagnetization curves of NRM, ARM and pTRMs (T<108, 208 and 328°C). The initial intensities of these remanences are similar.

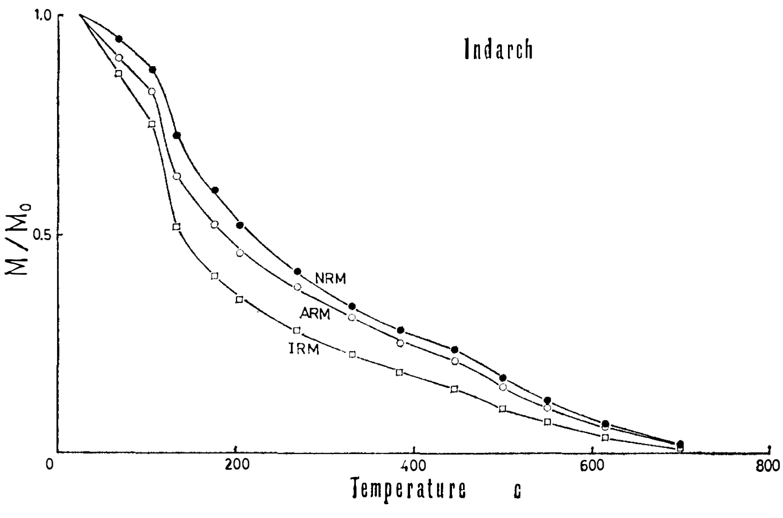

Fig. 5. Stepwise thermal demagnetization of NRM, ARM and IRM. The initial intensities of these remanences are similar.

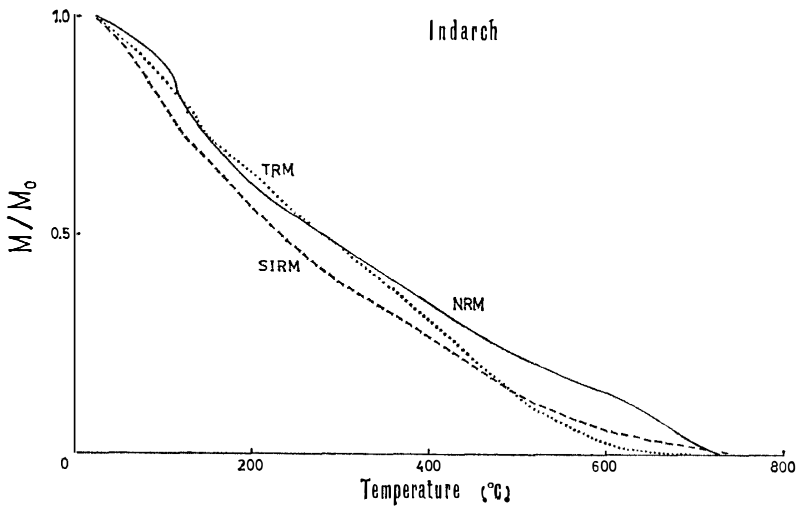

Fig. 6. Continuous thermal demagnetization of NRM, TRM and saturation IRM measured with a vibrating sample magnetometer.

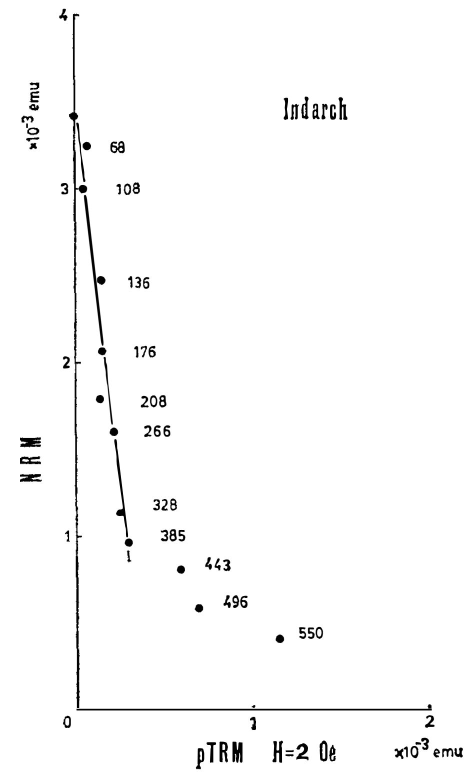

Fig. 7. Paleointensity determination by Thellier's method for Indarch.

the NRM has more high temperature component than ARM, TRM or isothermal remanent magnetization (IRM).

We do not know the origin of the NRM in Indarch, but it is possible that it was acquired during rapid cooling after metamorphism. Some kamacite (polycrystalline, probably low coercivity) was heated above its Curie point by this shock event and acquired TRM. Other kamacite (which was highly deformed by the shock, but not heated above the Curie temperature), acquired pTRM. The fact that the NRM is less stable than ARM can be explained as due to the highly deformed (and hence highly coercive) kamacite.

The magnetic field paleointensity was estimated with Thellier's method and the ARM method. Although the data are not of high quality (Fig. 7), a linear relation between NRM loss and pTRM gain can be seen up to 385°C. The breakdown of the linear relation above 400°C is due to chemical changes during heating. This is confirmed by a change in the acquisition capacity for ARM in a separate sample(not shown). The estimated paleointensity is 17.8 Oe, while the ARM method, applied at the low coercivity (<100 Oe) range, gives a paleointensity of 13.6 Oe (not shown). This field is a record of the field present when the sample last cooled below 385°C.

2.2. *ALHA77304*

ALHA77304 is a LL3 chondrite. It is a regolith (polymict) breccia, containing lithic clasts. The sample we received is homogeneous and does not contain large clasts. The sample was cut to make several subsamples whose weight is about 1 g. It contains some goethite (α FeOOH) as a weathering product.

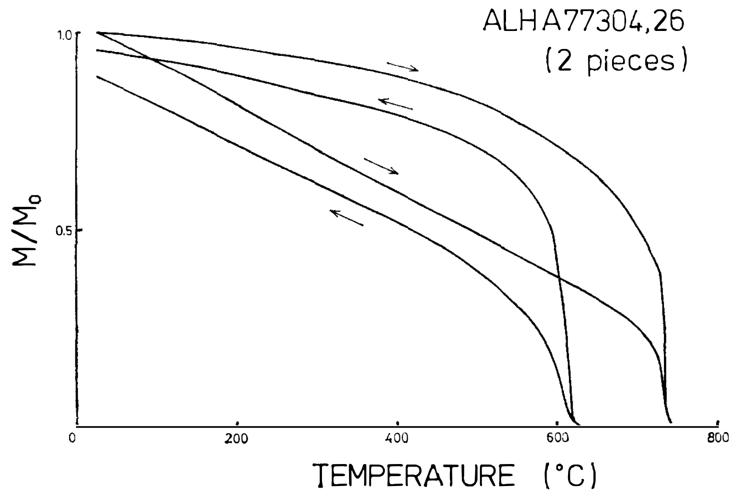

Fig. 8. $J_s(T)$ curves of 2 pieces of ALHA77304. Curie points of taenite are distributed between 550°C and room temperature. The main ferromagnetic phase is kamacite.

Thermomagnetic curves (Fig. 8) show that the main ferromagnetic minerals are kamacite and taenite (its Curie points are distributed between 550°C and room temperature). The absence of plessite (which is also indicated by the small coercivities $H_c=$ 6.0, $H_{cr}=84$ Oe) is remarkable, suggesting that the meteorite was rapidly cooled in a regolith layer of the parent body compared with the usual cooling rate 1°C/Ma.

The NRM directions of several subsamples are shown in Fig. 9, together with the directional change during AF and thermal demagnetization. The initial NRM directions are well-grouped and their intensities (Table 2) are similar for the subsamples. The NRM is made of two or three components, as indicated by the gradual change of the NRM direction during demagnetization.

The main component of the NRM is demagnetized at relatively low temperatures (<370°C) (Fig. 10). Since the NRM did not show viscous decay during a storage

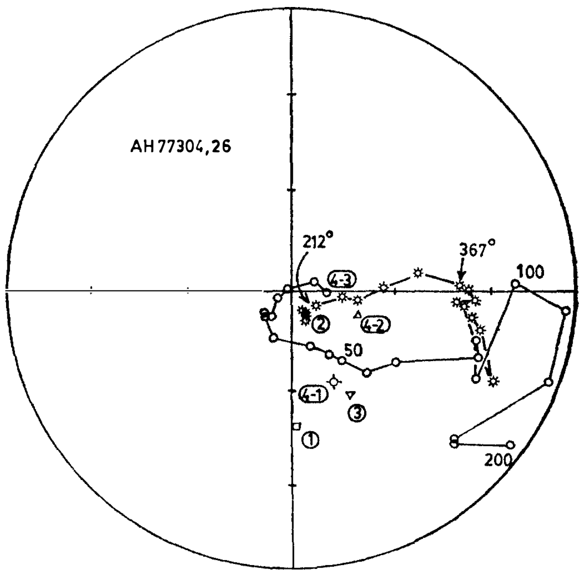

Fig. 9. NRM directions and their changes during AF (subsamples 4–3) and thermal (subsample 2) demagnetization of ALHA77304. Numbers indicate either AF field in Oe or temperature in °C.

Table 2. NRM in ALHA77304 subsamples.

	Weight (g)	NRM (10E-4 emu)	NRM/weight (10E-4 emu/g)
1	1.11	7.862	7.08
2	1.515	6.765	4.47
3	3.081	18.2	5.91
4–1	1.679	6.212	3.70
4–2	1.24	4.203	3.39
4–3	0.512	2.002	3.91

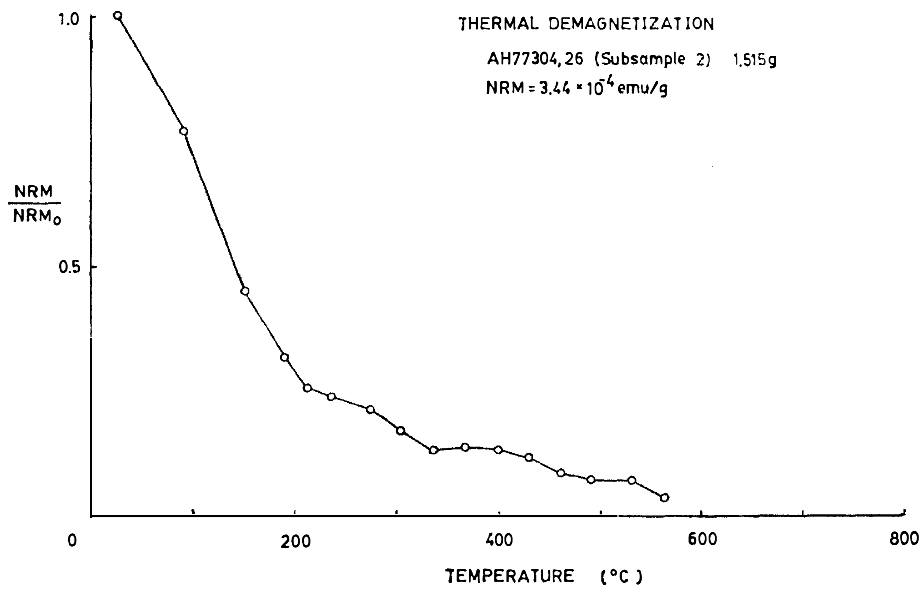

Fig. 10. NRM intensity change during thermal demagnetization of NRM.

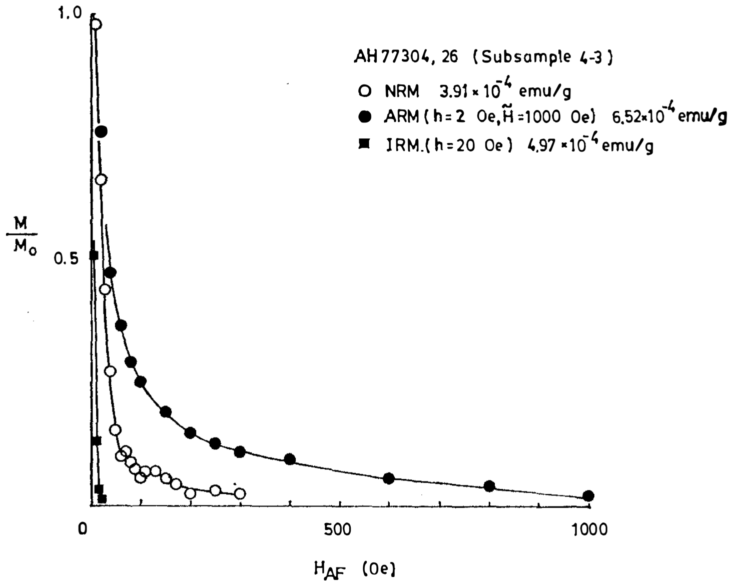

Fig. 11. Normalized AF demagnetization curves of NRM, ARM and IRM.

test, it is not believed that this main component is of viscous origin. The NRM direction and intensity became incoherent above 600°C, probably because magnetite was produced from goethite during the vacuum heating and acquired remanence.

The NRM is more stable than small field IRM, but is less stable than ARM (Fig. 11). Thus the main soft component is not likely of artificial IRM origin unless the soft component of the TRM has decayed. This soft NRM component could be a partial thermoremanence acquired during a metamorphic event. The high coercivity component (100–200 Oe) could be a thermal or depositional (accretional) remanence. Comparing the intensity of the NRM and the ARM in this coercivity range a rough estimate of the paleomagnetic intensity of 0.45 Oe is obtained.

2.3. *Bjurbole*

Bjurbole is an L4 chondrite with many chondrules which can be separated from the matrix easily. Several chondrules and matrix samples were prepared, keeping the orientation with respect to the whole rock. Some chondrules and matrix specimens whose orientation is not known have also been used to get a rough idea of the magnetic properties of the meteorite. Only those chondrules with diameters >1 mm were studied. Metallic particles sticking to the surface of chondrules were removed before the measurement. Matrix is defined as whitish, fine-grained material. The following results for matrix may not be typical, because the red colored portion which contains rusty iron was not included in the matrix sample. (STACEY *et al.* (1961) reported J_s= 13 emu/g, while the J_s of our matrix sample is only 4 emu/g.) As shown by the $J_s(T)$ curve of Fig. 12, the main magnetic minerals are plessite (transition point at 570°C) and kamacite (transition point at 765°C). Chondrules are more weakly magnetic than matrix. Their magnetic minerals are kamacite and plessite (Fig. 13); the composition of the former is variable from one chondrule to another. Hysteresis parameters of some matrix and chondrule samples are shown in Table 3. Apparently, plessite (which transforms to taenite by heating to 570°C) is the magnetically harder component. The

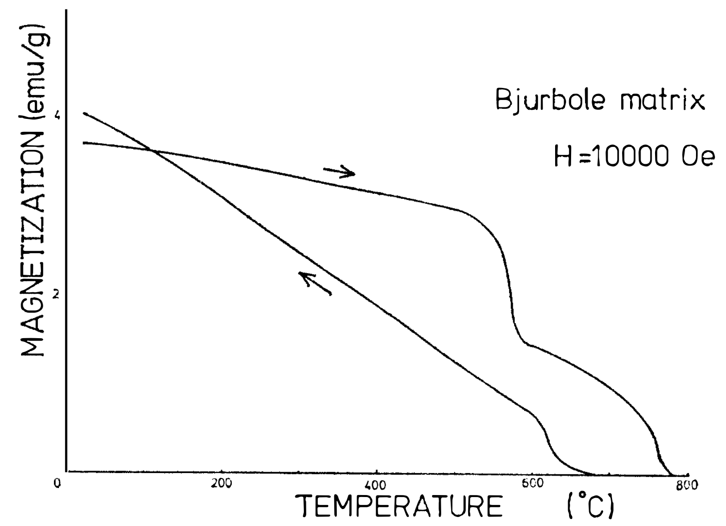

Fig. 12. $J_s(T)$ curve of Bjurbole matrix. The sharp drop of J_s at 560°C during heating is the transition point of plessite.

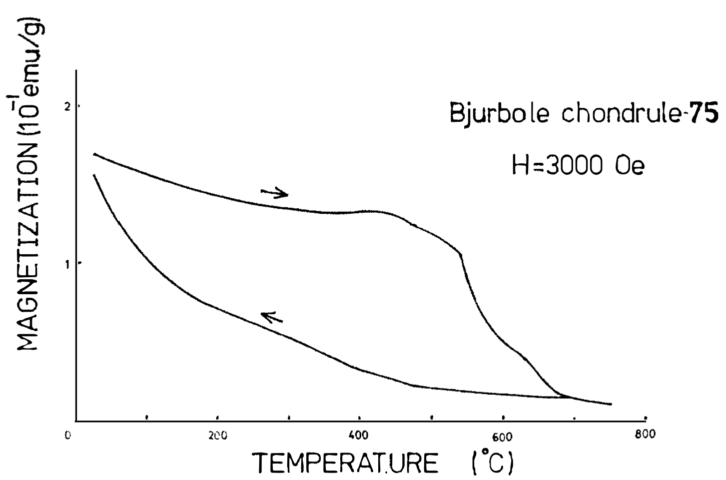

Fig. 13. $J_s(T)$ curve of a Bjurbole chondrule. Kamacite has distributed transition points between 620–680°C during heating, suggesting high nickel content.

Table 3. Magnetic properties of Bjurbole.

Sample	Weight (mg)	J_s (emu/g)	X_p (10E–5 emu/g/Oe)	J_{rs}/J_s	M_{1000}/M_0*	H_c (Oe)	H_{cr} (Oe)
Matrix							
Raw	22.3	3.2		0.127		630	4050
Annealed	22.3	3.8	4.29	0.0064		18	450
Chondrules							
No. 73	4.07	0.258	2.78	0.027	0.35	130	
No. 74	5.16	0.087	2.90	0.176	0.59	360	
No. 75	8.8	0.182	2.88	0.083	0.72	190	
No. 77	3.2	0.219	2.60	0.014	0.37	66	

* Ratio of remanence remaining after demagnetizing the saturation magnetization by 1000 Oe AF to the initial J_{rs}.

paramagnetic susceptibility (which was determined from the slope of the hysteresis curve at $10000<H<15000$ Oe) is larger than expected for L chondrites, probably because ferromagnetic materials (plessite) are not saturated in the field range. J_{rs}/J_s, H_c and M_{1000}/M_0 (see Table 3) are generally large but variable among chondrules. Since most of the remanence is carried by plessite, this is probably due to variable plessite content in chondrules.

2.4. *NRM of unoriented matrix samples*

The NRM intensities of five small (20–70 mg) matrix specimens are shown in Table 4, which agrees well with the bulk NRM intensity previously reported by BRECHER and RANGANAYAKI (1975). Although Bjurbole is generally not magnetically viscous, one sample showed marked magnetic viscosity during storage tests for seven days (VRM/NRM=0.41). Viscous magnetization in other samples is less than 5% of the initial NRM. As shown in Fig. 14, the NRM intensity monotonically decreased up to 425°C during thermal demagnetization. The NRM direction drifts gradually up to 560°C,

Table 4. NRM in unoriented matrix of Bjurbole.

	Weight (mg)	NRM (10E-4 emu)	NRM/weight (10E-4 emu/g)
1	40.3	0.103	2.51
2	73	0.308	4.22
3	25.5	0.690	27.0*
4	21.3	0.048	2.26
5	33	0.116	3.52

* Viscous.

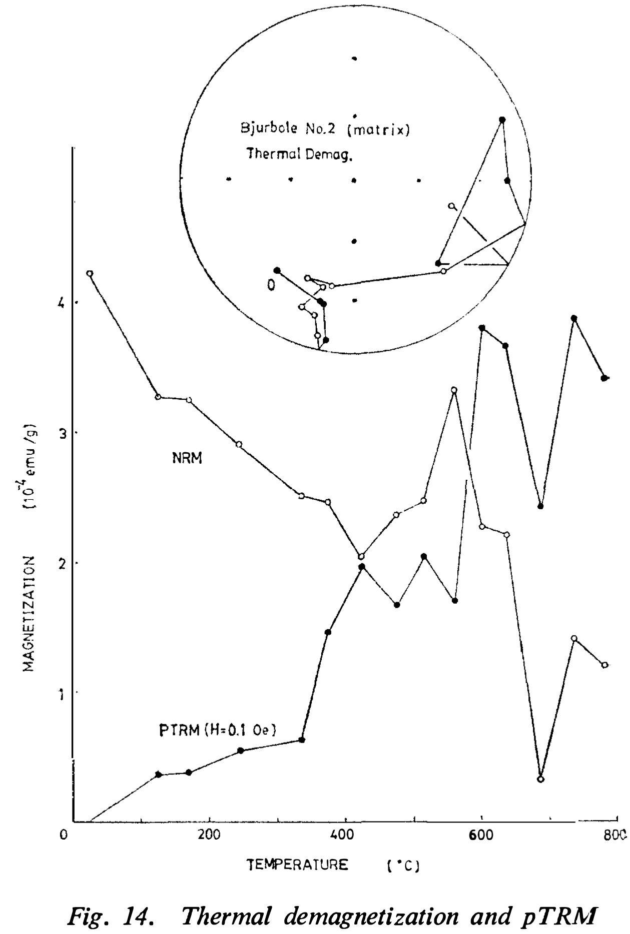

Fig. 14. Thermal demagnetization and pTRM acquisition by a matrix sample. Irregular changes above 500°C are probably due to oxidation of metal grains.

above which it becomes incoherent. It is probable that the sample was oxidized at high temperature, even though it had been sealed in a quartz tube under vacuum. A paleointensity of about 0.25 Oe was obtained by Thellier's method applied to the low temperature component of NRM. In spite of the erratic behavior of the NRM intensity during AF demagnetization, the direction of the NRM remains within 50 degrees up to 1000 Oe (Fig. 15). The remanence is probably a composite of a stable

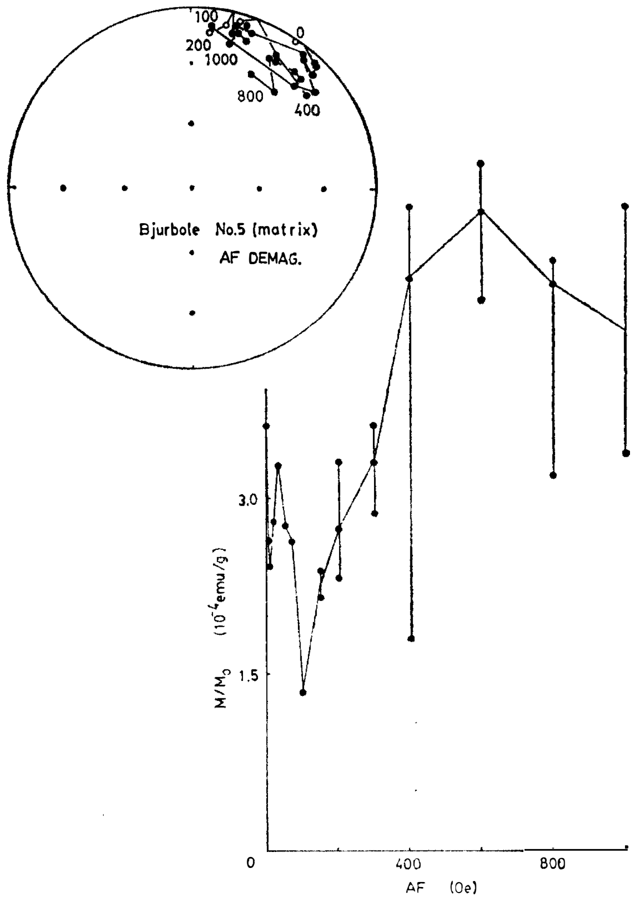

Fig. 15. AF demagnetization of the NRM in a matrix sample. The intensity changes erratically but the direction is fairly stable up to 1000 Oe.

component carried by plessite and an unstable components carried by kamacite.

2.5. *NRM of unoriented chondrules*

For measurements of the NRM of chondrules, it is important to remove metallic particles sticking on the surface of chondrules. The NRM, after removing the surface metal, is often several times smaller than before removing the metal, and the direction of the NRM is also quite different. The surface metal, if deformed, could acquire strong spurious remanence. The typical NRM intensity of seemingly clean chondrules is shown in Table 5.

2.6. *NRM of oriented samples*

The NRM directions of oriented specimens are shown in Figs. 16 and 17 (cor-

Table 5. NRM in unoriented chondrules of Bjurbole.

	Weight (mg)	NRM (10E–7 emu)	NRM/weight (10E–4 emu/g)
1	8.35	4.5	0.53
2	7.42	1.0	0.14
3	10.45	1.9	0.11
4	12.17	1.8	0.15

responding to two separate samples which were not mutually oriented). In both cases, the NRM directions of the chondrules are scattered and very different from that of the whole rock. Figure 16 indicates that they are not completely random, but are distributed on a hemisphere which include the NRM direction of the whole rock. The NRM direction of small matrix samples (NRM intensity$\cong 2\times 10$ E–5 emu) are also distributed on the same hemisphere. The random NRM is not likely due to preaccretional remanence because type 4 chondrites are thought to have been reheated to 600°C (DODD, 1969). Since the NRM intensity of chondrules is generally very small (Table 6), we deferred detailed study until we have access to a more sensitive magnetometer. Chondrule No. 24, however, has an exceptionally strong NRM, on which paleointensity study was done with Thellier's method. Figure 18 shows directional and intensity changes in the NRM during thermal demagnetization, as well as the pTRM acquisition. The NRM is very stable up to 535°C, suggesting that plessite carried the NRM. The pTRM intensity increased up to 585°C. An NRM loss *vs.* pTRM gain plot gives a paleointensity 0.6 Oe (not shown). But, if the NRM is carried by plessite, it must be of (thermo-) chemical origin. Thus the validity of using Thellier's method of paleointensity determination is questionable. The decrease of pTRM intensity at high tempera-

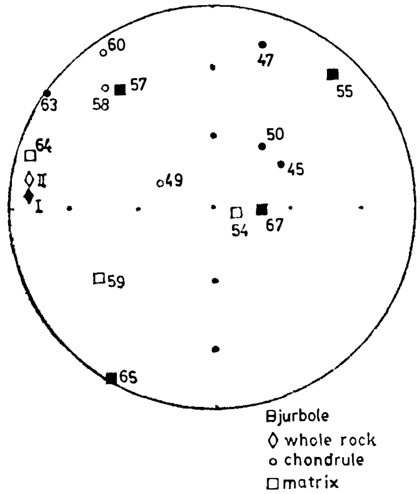

Fig. 16. The NRM directions of oriented whole rock, chondrule and matrix samples. The directions of two whole rocks are very close, but those of smaller components (chondrules and matrix) are scattered.

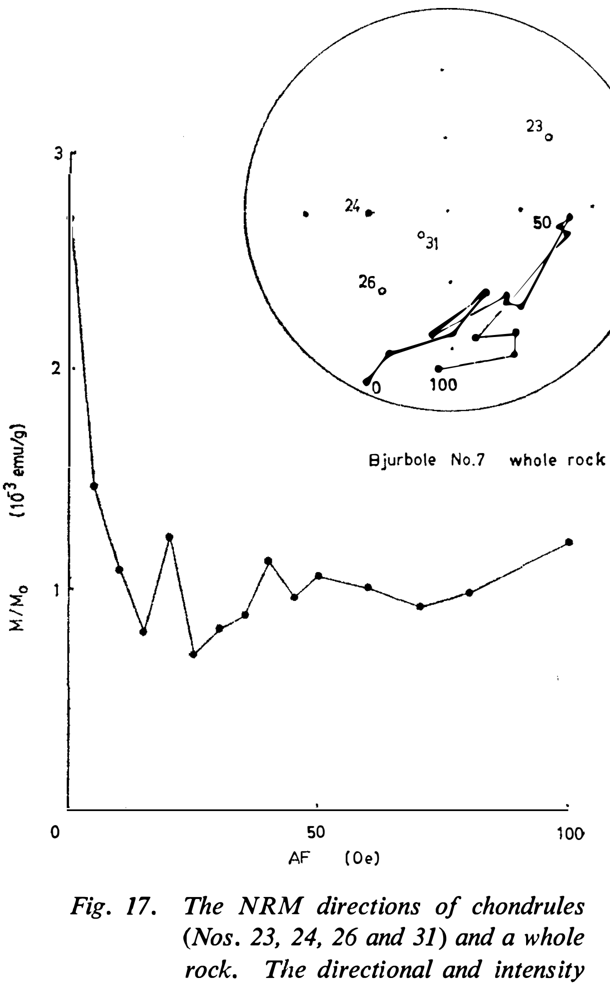

Fig. 17. The NRM directions of chondrules (Nos. 23, 24, 26 and 31) and a whole rock. The directional and intensity changes of the NRM of the whole rock are also shown.

Table 6. NRM intensity of oriented samples shown in Fig. 17.

		NRM (10E–7 emu)			NRM (10E–7 emu)
Whole rock	WR-I	3516	Matrix	54	147
	WR-II	4600		55	121
Chondrules	45	13.4		57	11
	47	8.5		64	217
	49	6.9		65	409
	50	30.5		67	297
	58	2.9			
	60	4.0			
	63	33.7			

Exact weight of these samples is unknown. Chondrules are about 10 mg. The weight of the matrix samples can be roughly estimated from the specific NRM intensity ($3 \times 10E{-}4$ emu/g) of unoriented matrix.

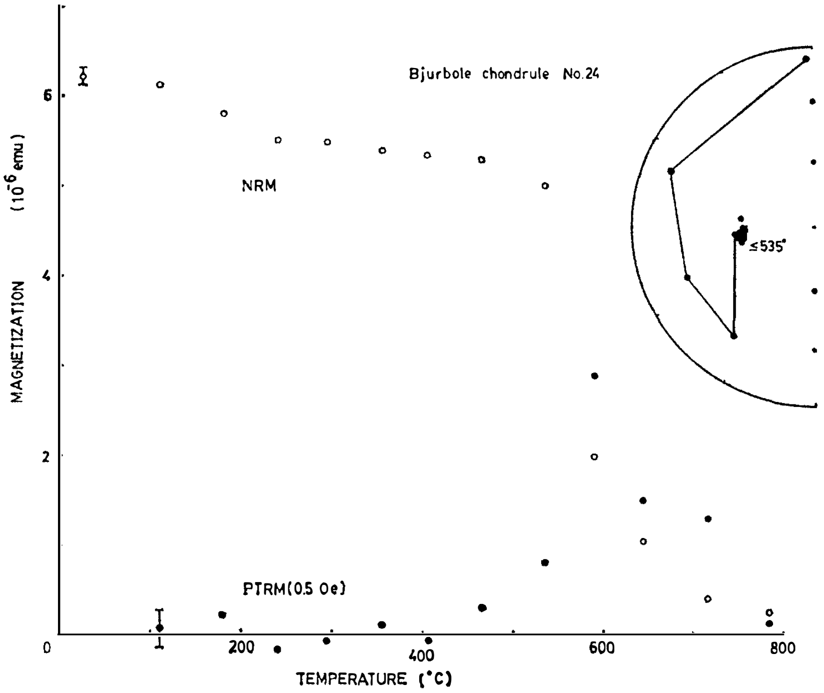

Fig. 18. Thermal demagnetization of the NRM and pTRM acquisition of a chondrule.

ture is due to disappearance of plessite (to make homogeneous taenite) and/or due to release of internal stress in kamacite by annealing.

2. 7. *Chainpur*

Ferromagnetic materials in Chainpur are plessite and kamacite (Fig. 19). The $J_{rs}(T)$ curve in the figure, clearly shows that plessite is the magnetically hard component.

Five small samples ($\sim$50 mg) were prepared keeping the orientation with respect to the whole rock (Table 7). The initial NRM directions are fairly well grouped (Fig. 20). Because of the weak intensity, further study of a chondrule sample (sample No.

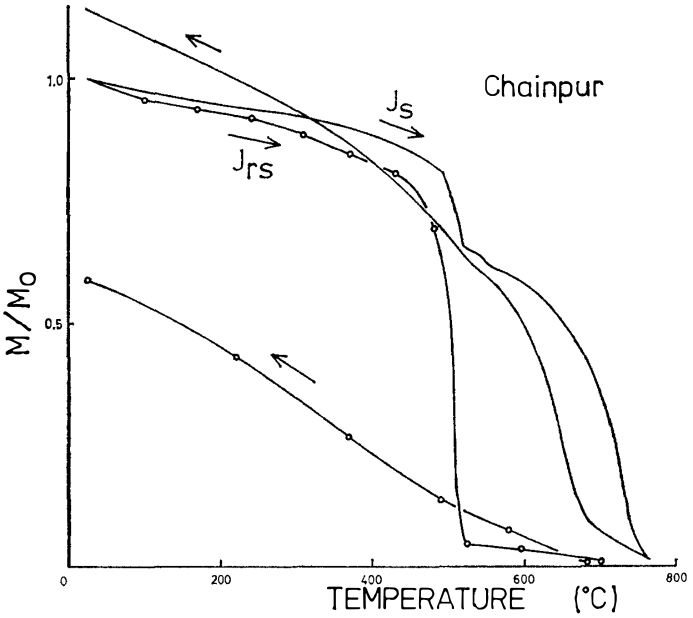

Fig. 19. *$J_s(T)$ and $J_{rs}(T)$ curves of Chainpur. The sharp drop of J_{rs} at 510°C is due to the transition of plessite.*

Table 7. NRM intensity of Chainpur subsamples.

	Weight (mg)	NRM (10E–7 emu)	Description
bulk	4×10E+3	19669	
1	25	145	Matrix+chondrules
2	50	220	Matrix+chondrules
3	10	18.6	A chondrule
4	10	339	A chondrule+metal on the surface
5	100	325	Matrix+chondrules

Weights are visual estimates.

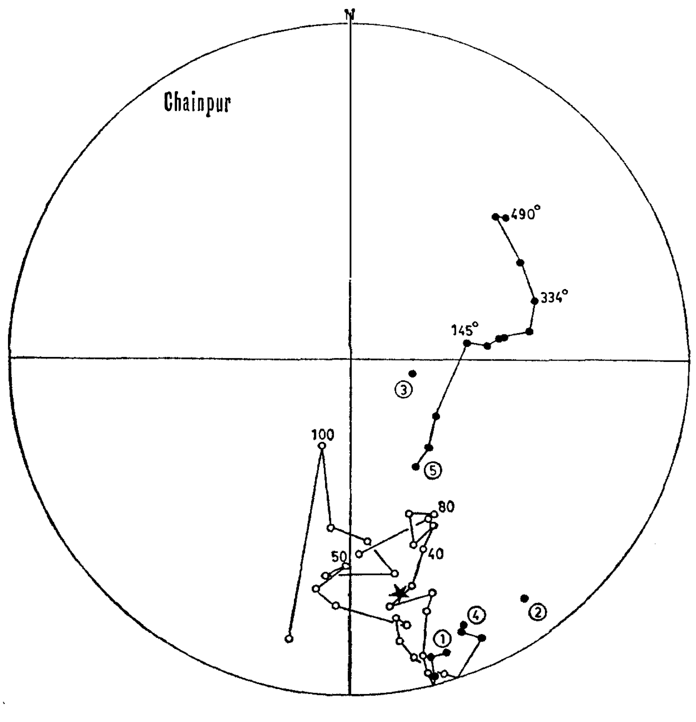

Fig. 20. The NRM directions of oriented subsamples (1–5) of Chainpur and their directional change during thermal or AF demagnetization. Solid star indicates the NRM direction of the whole rock. Numbers indicate either the AF field in Oe or the temperature in °C used for the demagnetization.

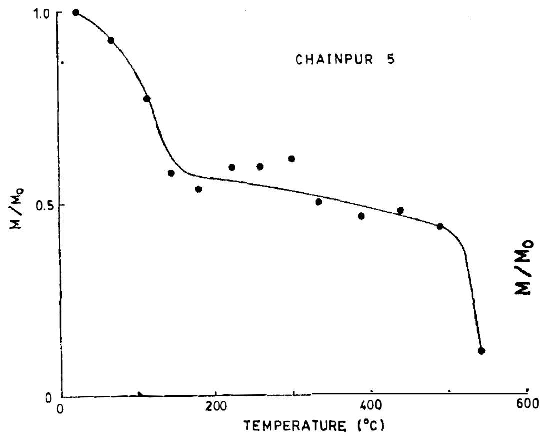

Fig. 21. Intensity change of NRM during thermal demagnetization. The main component which disappears at 530°C is carried by plessite. It is not known what carries the low temperature component.

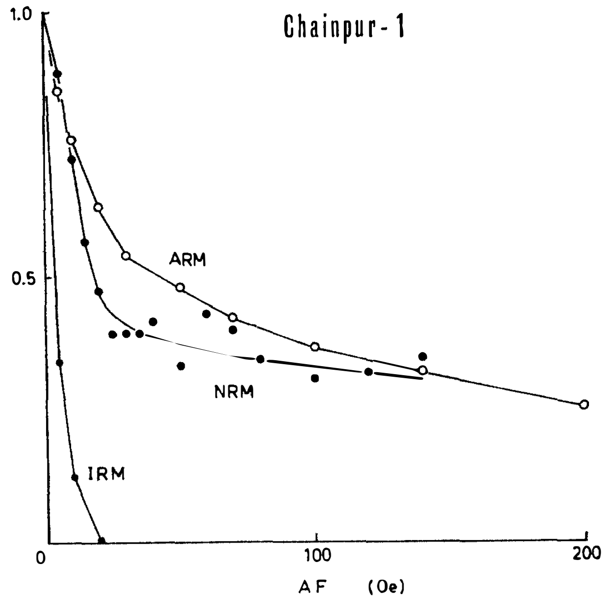

Fig. 22. AF demagnetization curves of NRM, ARM and IRM.

3) was deferred. (Other samples consist of small chondrules and the matrix.) The NRM direction of each subsample moves away from the NRM direction of the bulk sample during AF or thermal demagnetization. The stable component (which is 20–50% of the total NRM) is apparently carried by plessite (Figs. 21 and 22). The origin of the less stable component of the NRM is not clear at present. From the comparison of the intensity of the stable component and the intensity of an ARM (5 Oe, 1000 Oe), a paleointensity of 0.74 Oe is obtained (not shown). (This is an upper limit because the coercivity spectrum extends above 1000 Oe which was used to make the ARM.)

2.8. *Mezo Madaras*

Ferromagnetic material in Mezo Madaras is similar to that in Chainpur (Fig. 23). The NRM (Figs. 24, 25, 26) of Mezo Madaras is also quite similar to that of Chainpur,

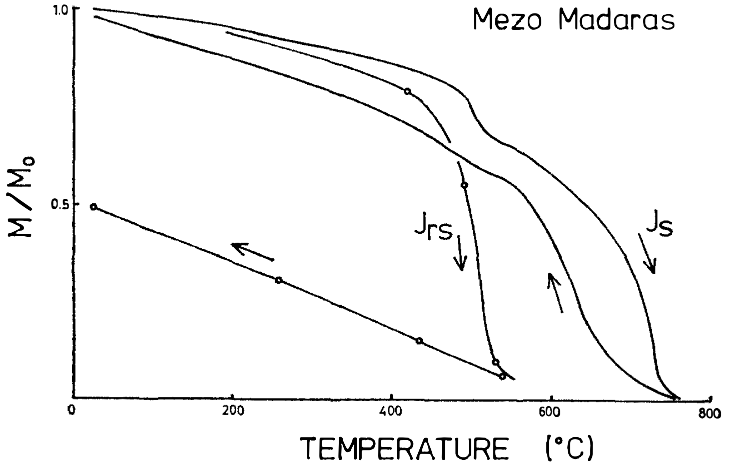

Fig. 23. $J_s(T)$ and $J_{rs}(T)$ curves of Mezo Madaras

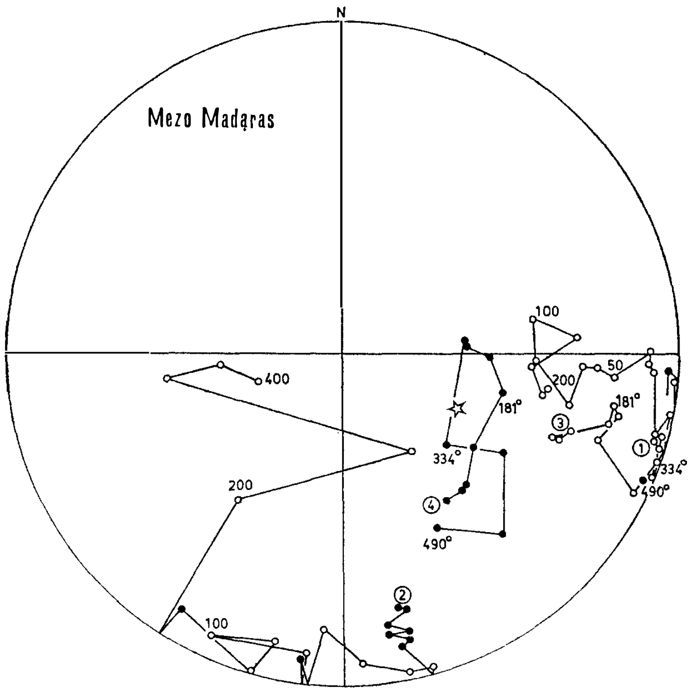

Fig. 24. The NRM directions and their changes during AF and thermal demagnetization of subsamples (1)–(4). The star indicates theNRM direction of the whole rock. Numbers indicate either the AF field in Oe or the temperature in °C used for the demagnetization.

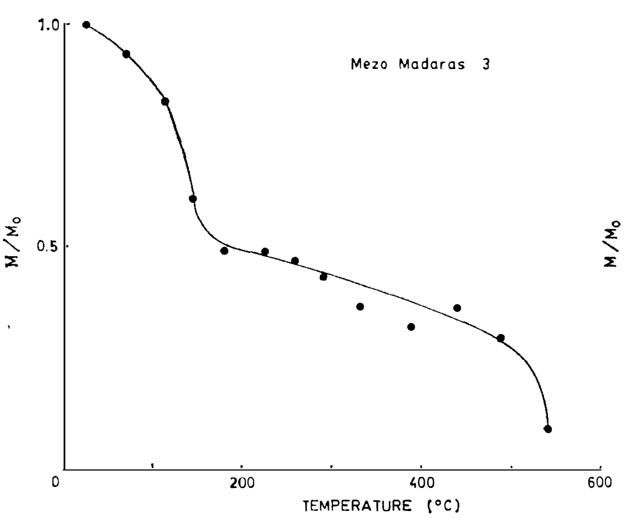

Fig. 25. Intensity change during thermal demagnetization of NRM in Mezo Madaras.

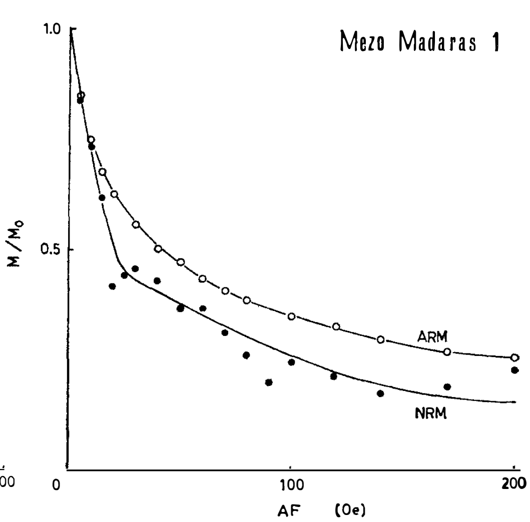

Fig. 26. Intensity change during AF demagnetization of ARM and NRM.

although Mezo Madaras' data are noisier, probably because of the higher degree of metamorphism in this meteorite (SEARS *et al.*, 1980).

Four subsamples ($\sim$100 mg) were prepared, keeping the orientation with respect to the whole rock (Table 8). The NRM directions of the subsamples are quite different from that of the whole rock (Fig. 24). The NRM in each subsample is, very roughly

Table 8. NRM intensity of Mezo Madaras subsamples.

	Weight (mg)	NRM (10E–4 emu)	NRM/weight (10E–4 emu/g)
bulk	2.079	7.739	3.72
1	0.099	0.404	4.09
2	0.244	0.893	3.98
3	0.145	0.763	5.09
4	0.225	0.892	3.96

speaking, directionally stable.

The scattered NRM directions can not be due to pre-accretional remanence because this chondrite is known to have cooled slowly through 550°C after accretion (SCOTT and RAJAN, 1981). A similar puzzling nature of NRM has been observed in Dhumsala (BRECHER *et al*, 1977).

2.9. *Yamato-74191*

The magnetic properties of Yamato-74191 were reported in the previous paper (SUGIURA, 1977). Additional data (Fig. 27) has shown that although the NRM is stable against demagnetization, the NRM directions are widely scattered.

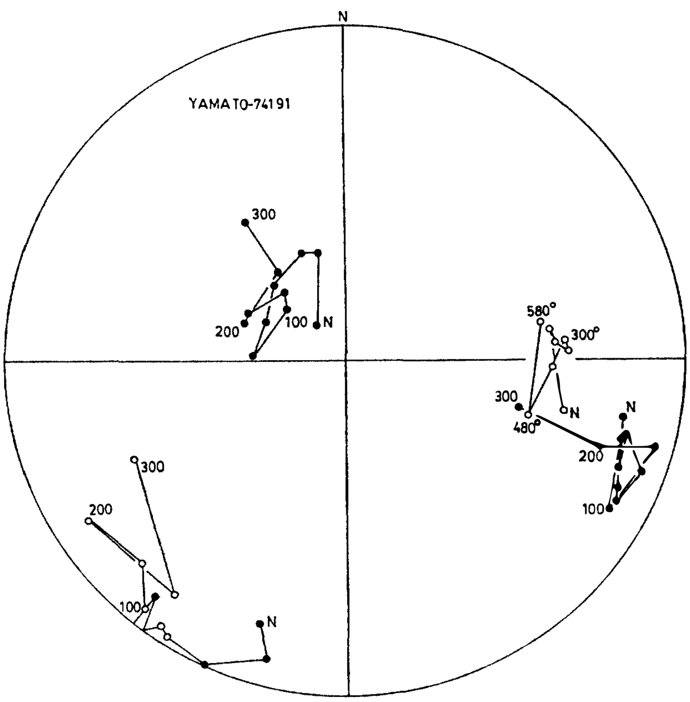

Fig. 27. NRM directions and their changes during AF and thermal demagnetization of subsamples of Yamato-74191. Numbers indicate either the AF field in Oe or the temperature used for the demagnetization.

2.10. *Yamato-691 and Abee*

Yamato-691 has an almost single component NRM (NAGATA *et al.*, 1975; SUGIURA, 1977) whose properties are quite similar to those of Indarch. The NRM in Yamato-691 is less stable than ARM. But if we assume that the hard coercivity component was produced by a mild shock event, then we obtain a very high (>10 Oe) paleointensity from comparison of the soft component of NRM and ARM.

We studied the magnetic properties of the Abee chondrite in detail (SUGIURA and STRANGWAY, 1981) and found that NRM in clasts and matrix samples were nearly random, suggesting that it has pre-accretional remanence. (The NRM directions among matrix subsamples are consistent.) Paleointensities (~7 Oe) were obtained with Thellier's method.

3. Summary

Magnetic properties of low-petrologic grade, non-carbonaceous chondrites are not simple.

Indarch and Yamato-691 have a single component NRM, which is less stable than ARM, and can be interpreted as a partial TRM acquired after a shock event. Abee's clasts seem to have acquired their remanence before the final compaction of the meteorite, while its matrix acquired NRM during or after its compaction. ALHA77304 has two components of NRM, which could be interpreted as primary TRM (or DRM) plus pTRM. Bjurbole, Chainpur, Mezo Madaras and Yamato-74191 have random (and stable) NPM components carried by plessite. The former two chondrites have a soft, overprinted NRM component. The random NRM could be pre-accretional remanence. But Bjurbole and Mezo Madaras are thought to have been reheated to >500°C after their accretion (DODD, 1969; SCOTT and RAJAN, 1981). In that case the random NRM in these chondrites could not be pre-accretional. It then becomes difficult to explain the random orientations. It may be possible to consider that highly anisotropic tetrataenite acquired random NRM whose direction is mostly controlled by the crystallographic orientation. This needs to be tested further. In the cases of Chainpur and Yamato-74191 (which were probably not reheated to high temperatures after the accretion), the random NRM component could be due to pre-accretional remanence. More studies are needed to solve this problem.

Paleointensities were estimated either with Thellier's or with ARM methods (Table 1). The paleointensities for the samples which contain plessite were estimated using the ARM method, because plessite is not thermally stable. The paleointensities are very rough estimates because the NRM is probably of thermo-chemical origin. These paleointensities are substantially larger than those obtained for ordinary chondrites by BRECHER and RANGANAYAKI (1975) and by BRECHER and LEUNG (1979). The difference is due to the difference in the method of paleointensity determination.

(1) BRECHER and colleagues obtain paleointensities by NRM-TRM comparison at high coercive force range. In the case of meteorites, this is not appropriate, because hard components are easily produced by oxidation and/or are destroyed by transformation of plessite or taenite.

(2) We use the ARM method or Thellier's method, which we believe is better, but tend to get data based on the soft component of NRM.

(3) Their samples are generally larger than our samples. If the NRM has random components, they are averaged in the sample, giving apparently small NRM intensity.

The paleointensities for E chondrites were also obtained with either Thellier's method or the ARM method. The paleointensities for E chondrites are much larger than those determined for L and LL chondrites. The NRM in primitive ordinary chondrites are not as simple as we expected. Yet they have a much more stable NRM than metamorphosed chondrites. The difference in NRM stability seems to be mainly due to the presence of coarse, well-annealed kamacite in metamorphosed chondrites. To get really reliable paleomagnetic data, relatively rapidly cooled regolith breccias like ALHA77304 (which unfortunately has two components NRM) and Abee, are most hopeful.

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