2

METEORITIC MAGNETISM: IMPLICATIONS FOR PARENT BODIES OF ORIGIN

A. BRECHER

Recent progress in studying and understanding the magnetic record of meteorites is reviewed. Magnetic data are not compatible with the simple picture of a single planetary parent-body with core-mantle structure and a dynamo-generated magnetic field, as earlier envisaged by Soviet colleagues. The strong preterrestrial magnetization of iron meteorites, previously believed to have been acquired during cooling in parent-body fields of ~.6 Oe, has now been shown to be probably a spontaneous moment, directionally controlled by the octahedral Ni-Fe structure. For each class of meteorites, the magnetic record is basically in accord with conclusions based on chemical-mineralogical-petrologic characteristics. For example, the complex remanence of brecciated achondrites bears no record of their primary igneous differentiation, but only of multiple brecciation events. Similarly, the unreilites show the expected magnetic imprint of shock-metamorphism at impact. Although systematic trends were found among ordinary chondrites groups, allowing for a rudimentary magnetic classification, only very few appeared to possess a primordial remanence component, which was used to estimate parent body fields in the range 0.1 = .3 oe. Most ordinary chondrites have been magnetically affected by brecciation at formation (e.g., LL), or by metamorphism within the parent body, or individually - by shock at the breakup of the parent body. Only the carbonaceous chondrites have preserved a clear magnetic record of their formation at low-temperature ($T < 500^{o}$ K), in strong magnetic fields ($H \lesssim 1$ oe). The evidence is compatible with cold condensation and aggregation of component grains either in extended, enhanced solar wind fields, or in cometary magnetic fields.

I. INTRODUCTION

Modern paleomagnetic studies of terrestrial rocks have played a key role in reconstructing the dynamic history of the earth. They have provided the decisive evidence for continental drift and global plate tectonics and for the existence of a core generating magnetic fields possibly as early as 3.9 b.y. ago, the age of the oldest magnetized crustal rocks recovered, thus severely constraining the thermal evolution of the earth.

The exciting discovery almost two decades ago of fossil magnetism in meteorites of all types held the promise for similarly probing into the physical environment of the early solar system (see references in Stacey 1976).

Although a considerable amount of data on meteoritic magnetism has been collected to date and preliminarily interpreted, I confess at the outset that the evidence for and origin of ancient magnetic fields, as recorded in meteorites, is still ambiguous and elusive.

An earlier review of the state of art in meteoritic paleomagnetism, which I had the privilege to present in a similar forum five years ago (Brecher 1971) contains the necessary technical background for the present one. A number of more recent but by necessity incomplete reviews in the literature (Guskova 1972; Herndon *et al.* 1972; Herndon and Rowe 1974; Wasson 1974; Butler and Gose 1975; Wasilewski 1975; Stacey 1976) permit me to limit this paper to general interpretive remarks, based mainly on our own experimental results obtained over the past 5 years. The major questions to be addressed are:

First, do meteorites (all? any class?) bear a clear record of ancient preterrestrial magnetic fields? The related question of whether a certain class of meteorites are capable of retaining such a memory must also be examined and carefully separated from the question of whether they actually do. The pitfalls are well illustrated by the case of iron meteorites below. (Sec. 2).

Second, if the answer to the first question is positive, can any information on the intensity, duration, source or configuration of these fields be retrieved? If the answer is negative, then how is the chemical/thermal/mechanical/magnetic history of the meteorites reflected in their magnetic behavior? Can cogenetic groups of, or metamorphic sequences for, meteorites be identified based on magnetic properties? This aspect is best illustrated below in discussing the ordinary chondrites and brecciated meteorites. (Sec.3,4).

Third, and more technical, but crucial question regards the nature of magnetization, i.e., by what mechanism and at which stage of formation or evolution of the meteorite parent-body it was acquired? This particular question has been best answered to date in the case of the carbonaceous chondrites. (Sec. 5).

II. THE NATURE OF MAGNETIZATION IN IRON METEORITES

It is logical to discuss first the magnetic evidence pertaining to the more differentiated classes of meteorites linked to asteroidal-sized parent bodies (*e.g.*, Wood 1967; Fricker *et al.* 1970), in the framework of the "planetary origin" hypothesis proposed by Pochtarev, 1967 and Guskova and Pochtarev, 1967. From their extensive magnetic data (Guskova and Pochtarev 1969; Guskova 1972) they concluded that, since all meteorites possess an apparently preterrestrial remanence, all must have originated in a differentiated planetary body. The irons, as a once molten core, probably acquired a thermal (TRM) or thermochemical (TCRM) remanence during slow cooling in a dynamo-type magnetic field of average value ~.6 Oe; and the ordinary chondrites, as a silicate shell, experienced only ~.2 Oe fields, also in cooling through the Curie point of kamacite ($T_c \approx 770^o$ C). This interpretation had an appealing generality and simplicity and led to predictions (now largely disproven) of planetary magnetic fields (ibid). It is, however, beset with problems: inconsistencies of relative cooling rates of stony, stony-iron and iron meteorites, the large number and sizes of (differentiated) parent bodies required by various data, the fact that the iron core was long since solid at the time of cooling through T_c and could no longer generate the magnetizing field, and the general difficulty of sustaining a core-dynamo in relatively small bodies (Brecher 1971). Another puzzling fact is the high stability of NRM in such coarsely crystalline objects. An intrinsic experimental problem with laboratory simulations of the natural remanence (NRM) of iron meteorites (*e.g.*, Guskova 1965) is that the presumably complex TCRM, involving simultaneous diffusional phase-changes and slow cooling (1-500^o C/my) of Ni-Fe alloys, cannot be adequately reproduced on the short laboratory time scale. Various structural factors led us to question (Brecher 1971) and to recently probe the nature of the hard magnetization in iron meteorites. Although they generally contain magnetic carriers capable of preserving a stable paleoremanence (Brecher and Cutrera 1976), our latest experiments showed that no reliable information on their early magnetic environment can be

https://doi.org/10.1017/S0252921100070366 Published online by Cambridge University Press

retrieved from them (Brecher and Albright 1976). The natural (NRM), thermal (TRM) and spontaneous (SM) magnetization of octahedrites were found to be directionally controlled by the octahedral structure of Ni-Fe. The taenite γ{111} planes on which kamacite plates nucleated and grew, are "easy" planes of magnetization; their intersections define "easy" magnetic axes, in and along which the magnetization vectors tend to lie. Cooling from above T_c in zero-field (SM)

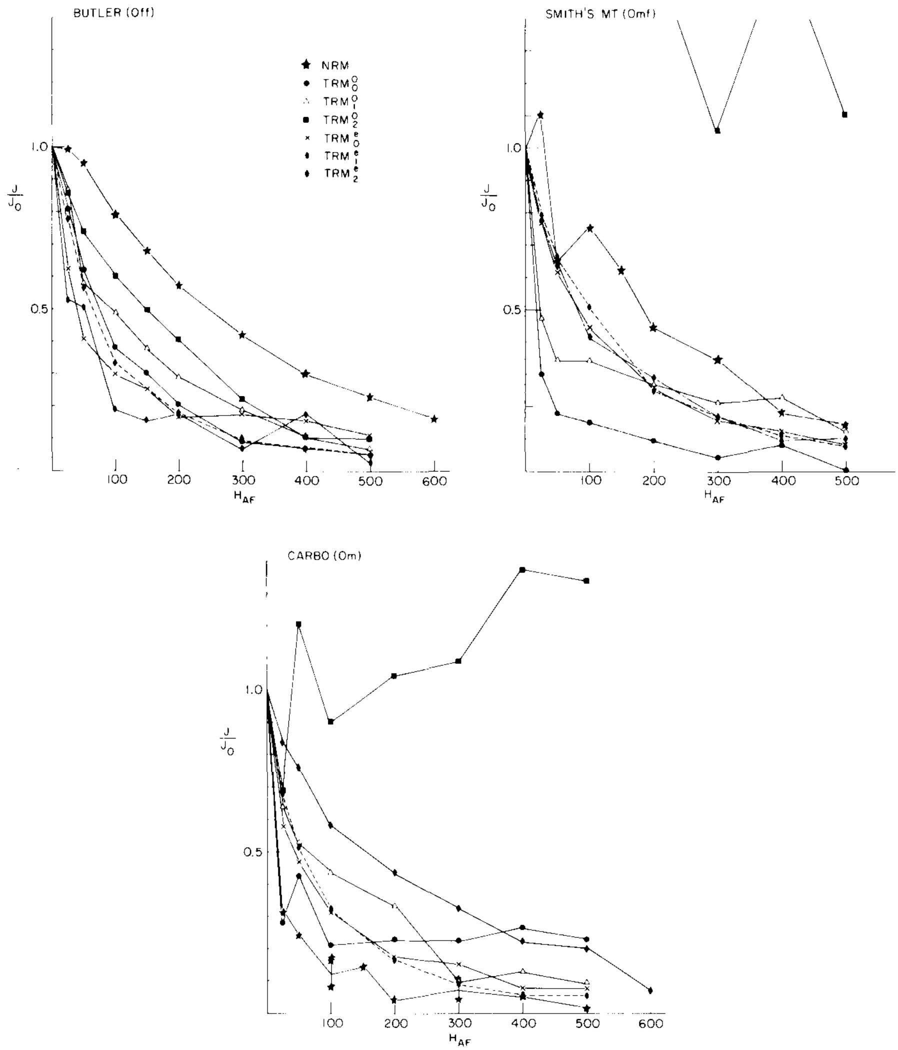

Figure 1. The coercivity spectra (normalized residual moment (J/J_o) vs. alternating field (Oe)) of natural remanent magnetization (NRM) for three octahedrites, are compared with those of spontaneous magnetization following three consecutive heatings to 800° C and zero-field coolings ($TRM^o_{0,1,2}$) and with those of thermoremanence acquired in earth's field ($TRM^e_{0,1,2}$). The relative stabilities of NRM and TRM's are quite similar, although they depend somewhat on structural class.

or in the earth's magnetic field (TRM) produces magnetic behavior, akin to that of NRM. Moreover, the intensities and stabilities of SM and TRM are comparable (Fig. 1), (though weaker than that of NRM due to loss of kamacite in heating), so that spurious apparent paleointensities of ~1 Oe are obtained even for zero-field cooling.

Thus, the earlier conclusion of Soviet colleagues that iron meteorites, as pieces of planetary cores, carry the magnetic record of core-dynamo fields of ~1 Oe, now appears doubtful. The strong and stable magnetization of iron meteorites seems to be simply a spontaneous moment, whose direction is internally controlled by the octahedral crystal structure (through a combination of magneto-crystalline anisotropy and shape anisotropy of the kamacite plates). Disappointingly, the evidence no longer requires the presence of ancient magnetic fields.

On the other hand, both the intensity and the relative stability of natural and saturation remanence were found to vary systematically with structural characteristics (cf. kamacite bandwidth), increasing as expected from the coarser- to the finer-grained classes (Fig. 2). In this manner, a magnetic classification of iron meteorites may eventually emerge.

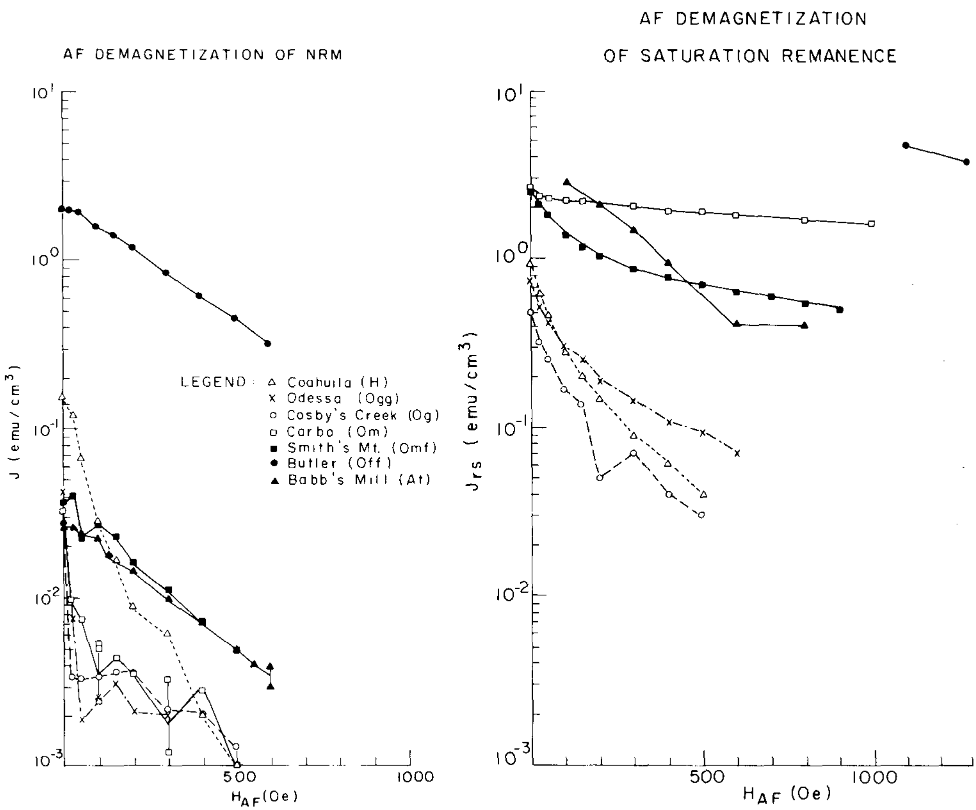

FIGURE 2. The intensity and stability of both natural (NRM) and saturation (IRM_S) remanence are seen, in a) and b) respectively, to decrease from the finest (Off) to the coarsest (Ogg) grained iron meteorites. Magnetic behavior thus reflects structural characteristics.

III. THE ORDINARY CHONDRITES

In examining the questions of whether the ordinary chondrites tell us anything about their parent-body fields, it became apparent that only a few chondrites satisfy the simultaneous magnetic criteria (of NRM hardness and directional coherence about or convergence to it in AF demagnetization) for survival of a stable paleoremanence, but most do *not*. In a recent survey study (Brecher and Ranganayaki 1975), a systematic variation of magnetic properties was found not only with the amounts of metal, but with the metal composition as well: the intensity of NRM decreased, but its relative stability and directional coherence improved from E → H → L → LL groups, as the overall content of metal decreased, whereas the Ni percentage in NiFe increased. Some criteria for recognizing the magnetic effects of shock and for simulating them in the lab have also been suggested and are currently being refined, based on better statistics.

For the few ordinary chondrites which could have a possibly primitive magnetization component, a comparison with laboratory TRM's yielded paleointensities of .01 - .3 Oe, lower than previous estimates (.1 - .9 Oe) (Guskova 1963, 1970) because only the stable NRM component was matched against the TRM. We have obtained such estimates on 10 chondrites: 1E4, 1H6, 1L4, 1L5, 2L6 and 4LL6, and there exist previous data for 14 others (Brecher and Ranganayaki 1975).

The LL-chondrites appeared, as a class, best equipped as magnetic recorders in view of their higher Ni and finer resulting metal microstructure. Recent in-depth studies showed that relatively few of these brecciated meteorites, mostly the high grade ones (*e.g.*, Dhurmsala, LL6) have a stable, well-behaved NRM (Brecher and Stein 1975; Brecher 1976). This means that it is the termal event associated with impact shock-metamorphism which homogenized the meteorite and reset the magnetic clock, possibly in the presence of magnetic fields. The paleofield value obtained for the LL6 Dhurmsala is ~.06 Oe. The problem, here as in the case of carbonaceous chondrites (Sec. 5) is that the hard NRM component which gives lower paleofield strengths, and the soft one, which yields higher values, are often unidirectional. Either the magnetization was acquired simultaneously by two discretely-sized metal grain populations, with different efficiencies; or the coarser grains carry a secondary remanence acquired in the local field of the finer grains, long after the magnetic fields responsible have decayed. The former hypothesis is better supported by observations. Most LL's and, in particular some shock-reheated members of chondrite groups, have a directionally chaotic magnetization, with typical bimodal coercivity curves (Brecher and Ranganayaki 1975; Larson *et al.* 1973). It appears that brecciated meteorites in general have not preserved any reliable record of a parent body field; their very inhomogeneous and complex magnetization is probably the direct result of brecciation and shock. Only if the temperature at shock or brecciation exceeded the highest Curie point (~770^{0} C) could a uniform magnetization be imprinted in the presence of a field. However, in view of the strong magnetic anisotropy of ordinary chondrites (Alexeyeva 1958, Stacey *et al.* 1961, Weaving 1962) and of their visibly oriented metamorphic fabric, I believe that an apparent remanence could ensue from severe shock metamorphism, even in the absence of magnetic fields (Brecher 1971, 1976), or in the presence of transient fields associated with shock-produced plasmas (Meadows 1972). This hypothesis is supported by results on the magnetic behavior of lunar and other meteoritic breccias (*e.g.*, Brecher 1976).

IV. THE BRECCIATED ACHONDRITES AND THE SHOCKED UREILITES

The achondrites are of particular current interest, in view of the fact that they are objects as old as the solar system, which have undergone early magmatic differentiation and later brecciation. They have many similarities to lunar rocks and may yet help elucidate the still unresolved problems posed by lunar magnetism. The evidence for a basaltic-achondritic surface composition of Vesta, a large main-belt asteroid (Chapman 1976) enhances the relevance of magnetic studies in constraining models of asteroidal meteorite parent-bodies. Among the various classes of brecciated or shocked achondrites studied recently, the heavily shock-textured ureilites were found to possess the stablest NRM (Brecher and Stein 1975) (Fig. 3). Their strong, uniform and coherent magnetization is undoubtedly due to the large amount of secondary, impact-reduced metal, which could have efficiently acquired a TCRM at precipitation, growth and post-shock cooling, in the presence of short-lived magnetic fields possibly generated at impact (Meadows 1972). Alternatively, this might simply indicate strong pinning of magnetization directions along a preferred axis of veining and elongation of shock-reduced or deformed metal grains (Brecher 1976). The other brecciated achondrite groups, be they monomict or polymict, show typically a large intragroup scatter in NRM intensity, stability and directional behavior under AF demagnetization. In contrast, their saturation remanence (IRMs) behavior shows much more uniform magnetic capabilities: similar amounts, compositions and grain-size distribution of metal.

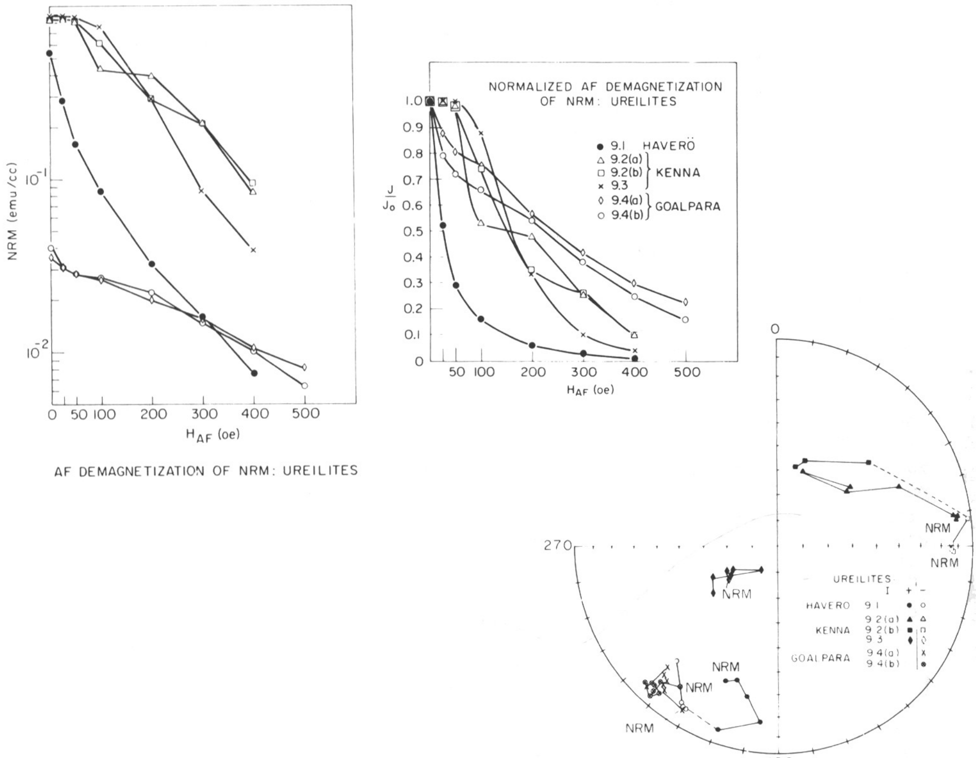

Figure 3. The ureilites have an unusually strong and stable natural remanence. The intensity of NRM is in the range ~.1 - 1 emu/cm^3 (left). The remanence is homogeneous within each meteorite (e.g., Golapara, Kenna), both in intensity (left) and in relative stability (left and center). At right, the remanence directions are plotted in projection on a steronet. These are seen to cluster tightly or converge under progressive AF cleaning. Mutually oriented samples (a,b) have similar NRM directions. This type of coercivity and directional behavior suggests that the NRM is a true paleoremanence.

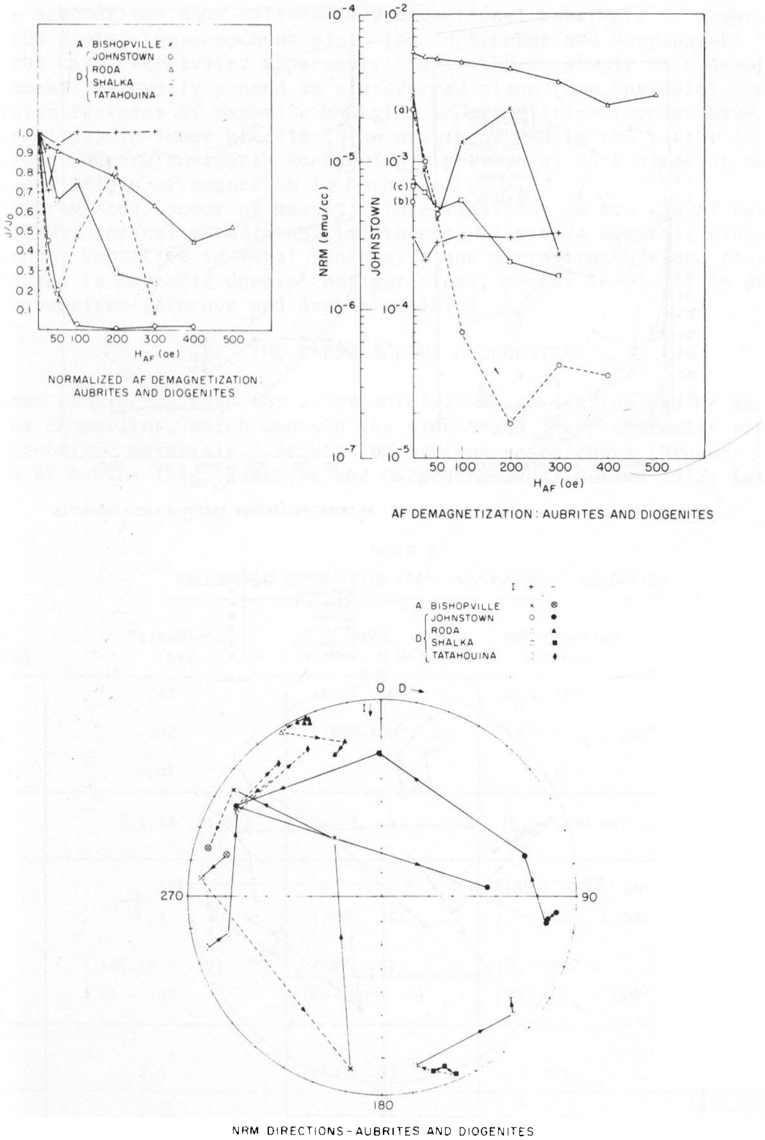

Figure 4. The NRM intensities and relative stabilities of the calcium-poor achondrites (aubrites and diogenites) show much greater intragroup variability than the ureilites (Figure 3). Similarly, scatter in remanence directions (right) corresponding to the progressive AF cleaning (shown on left and center), indicates that a primary magnetization component cannot be isolated. Brecciation has no doubt drastically modified or erased beyond the point of recognition any original remanence.

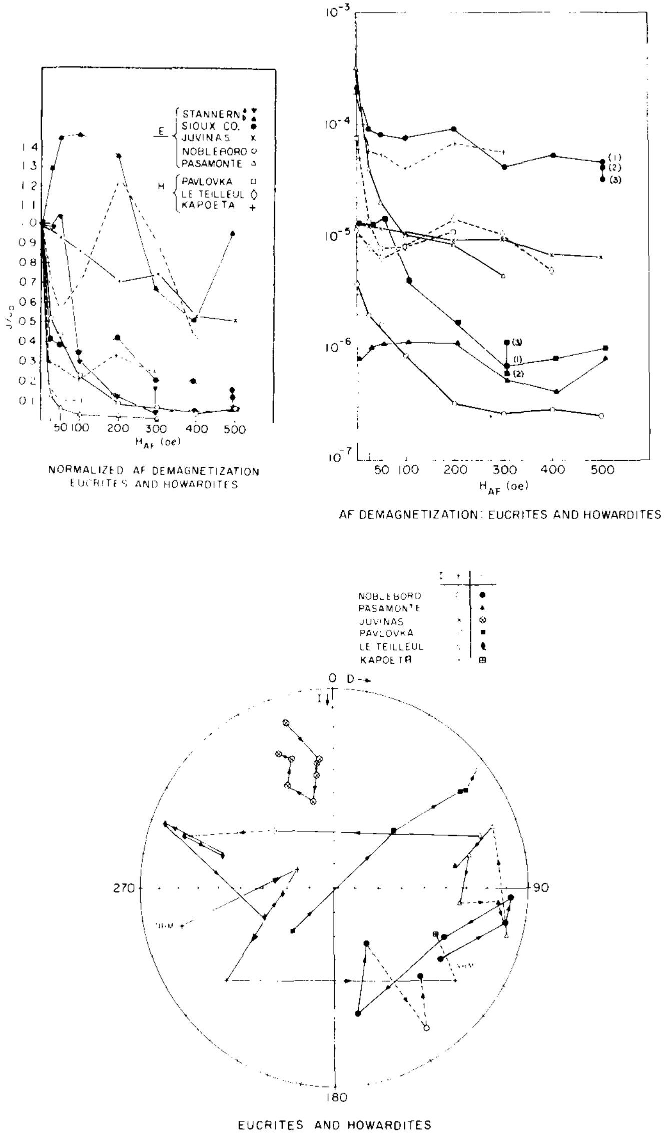

Figure 5. The calcium-rich, basaltic achondrites eucrites and howardites are also brecciated and show magnetic behavior similar to that of Figure 4. Again, no clear evidence of a primary magnetization (acquired during igneous differentiation of an asteroidal parent body) can be found.

It is clear that no clear magnetic record of a primary igneous differentiation episode within the parent body, has been preserved in the brecciated achondrites (Fig. 4, 5). On the contrary, the multi-component, inhomogeneous NRM reflects well the history of multiple brecciation indicated also by petrographic evidence.

None of the achondrites show satisfactory directional coherence of magnetization in projection plots; two-component plots (as in Brecher and Ranganayaki 1975) show that even the high-coercivity, apparently stable NRM is simply an undemagnetizable residual moment texturally pinned to a preferred plane (Brecher 1976). All these characteristic features of magnetic behavior in meteoritic breccias have corresponding parallels in lunar breccias; the origin of NRM in the latter is notoriously controversial. We are currently continuing experimental work aimed at understanding the nature and origin of magnetism in both.

A very promising aspect of magnetic investigations is the use of saturation remanence (IRMs) intensity and stability in establishing a magnetic classification. This remanence, sensitive to metal grain-size and microstructure and to shock-induced changes in magnetic domain configurations, serves very well in delineating groups of meteorites (Brecher and Arrhenius 1974)

V. THE CARBONACEOUS CHONDRITES

The most convincing case for a "primordial" magnetization can be made for the carbonaceous chondrites, which contain the oldest and least thermally reprocessed types of meteoritic materials. Results of various researchers (Brecher 1972; Brecher and Arrhenius 1974; Banerjee and Hargraves 1972; Butler 1972; Larson *et al.*

TABLE I

PALEOFIELD INTENSITIES FROM CARBONACEOUS CHONDRITES

Meteorite (Type, Subtype)	Paleofield (oe)	pTRM (T^o C, H oe)	NRM fraction matched	NRM type	Ref.
Orgueil (I, C1)	.67	(120^o, .5)	$T_B < 73^o$ C	TRM	[2]
	.02	(250^o-120^o, .5)	$120^o < T_B < 250^o$ C	CRM	[2]
Ivuna (I, CI)	~.05	------	all	CRM + DRM	[1]
Murray (II, C2)	.7 (.33 - 1.35)	(250^o, .5)	$H_{AF} > 100$ oe	non-thermal	[1]
Murchison (II, C2)	{.4	o	{$100 < H_{AF} < 300$ oe	non-thermal	[1]
	{$\gtrsim 3$	(250^o, .5)	{$H_{AF} > 300$ oe	pTRM?	
	{.18(.17 - .19)	(90^o, .5)	{$T_B < 90^o$ C	TRM or CRM	[2]
	{.01 - .02	(90-250^o, .5)	{$90^o < T_B < 150^o$ C		
Renazzo (II, C2)	2.3	(250^o, .5)	all	pTMR, TCRM	[1]
Allende (III-V, C4)	{.95	(150^o, .5)	{$H_{AF} < 500$ oe	{non-thermal	[1]
	{.25	(350^o, .05)	{$H_{AF} > 500$ oe	{pTRM	
	{.15		{$400 < H_{AF} < 600$	{non-thermal	
	1.09(.96 - 1.23)	(110-130^o, .5)	$20^o < T_B < 130^o$ C	TRM	[2]
	1.1 (.93 - 1.3)	(150^o, .59)	$30 < T_B < 150^o$ C	TRM, TCRM	[3]

Refs: [1] Brecher, 1972 and this work; [2] Banerjee and Hargraves, 1972; [3] Butler, 1972.

H_{AF} - peak alternating field value which gives microcoercivity of remanence. T_B = blocking temperature.

1973) agree on the presence of a stable paleoremanence in most of these meteorites. I illustrate with results for Ivuna (Cl) - an example of pristine magnetic record (Fig. 6) to indicate that special methods were used to ascertain that an original paleomagnetic remanence can be and has been preserved: low-T cleaning followed by progressive AF demagnetization and coercivity spectrum and directional analysis of NRM, all indicate the persistence of a single-component natural remanence (NRM). Modelling of this NRM by quite different methods has allowed the strength of the ancient fields responsible for imprinting this remanence to be estimated at ≲1 oe. I illustrate the method in the case of Renazzo and Murray (Fig. 7) and show in Table I a summary of the paleointensities obtained for several carbonaceous mete-

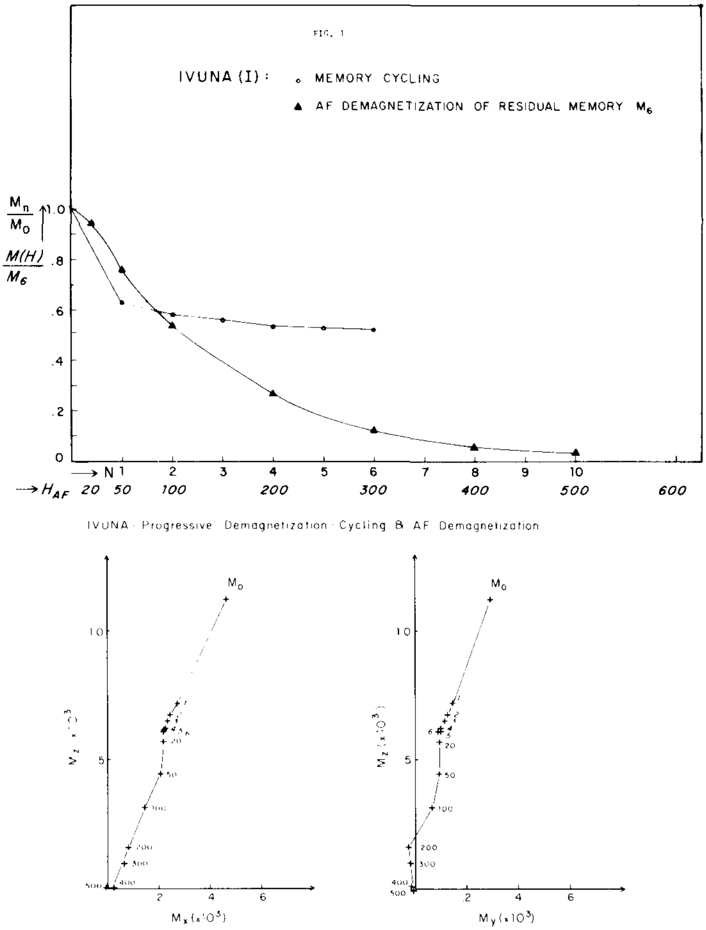

FIGURE 6. *The magnetic behavior of Ivuna, a primitive carbonaceous chondrite of type Cl indicates that a primary paleoremanence has survived due to its low-temperature history since formation. Above: repeated low-temperature cycling shows that ~60% of NRM resides in a stable fine-grained (single-domain) magnetite, and has a high stability under AF demagnetization. Below: in projecting the NRM vector onto two orthogonal planes, it can be seen that it converges smoothly towards the origin, the progressive loss of intensity entailing no directional changes. This indicates that Ivuna has a single-component, unidirectional NRM, acquired in a single magnetizing event.*

orites. The nature of this stable NRM is still controversial, although it is generally recognized that it must be a low-temperature ($T \lesssim 500^{o}$ K) magnetization, residing mostly in the most ancient, pre-irradiated, magnetite mineral fraction. It seems to me that the most satisfactory explanation involves a chemical remanence (CRM) locked during grain condensation and growth in space, combined with depositional remanence (DRM) or low-T partial thermoremanence (pTRM) acquired during aggregation of the carbonaceous meteorites or during sedimentation on a parent body, in a continuous presence of a magnetic field.

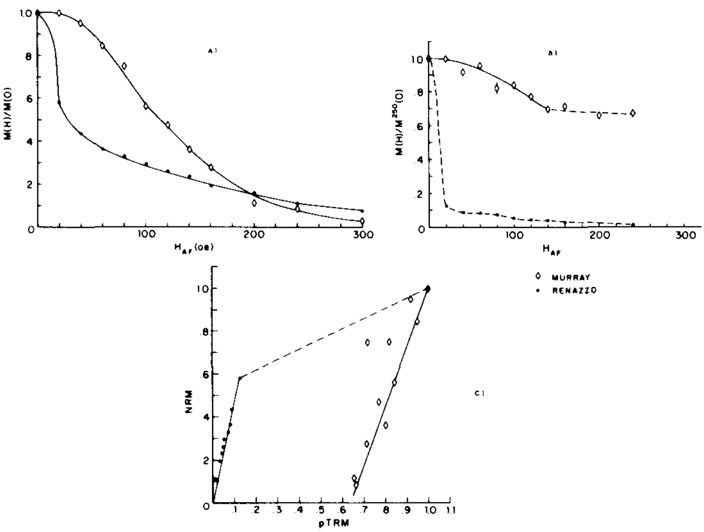

FIGURE 7. An illustration of the procedure by which paleofield strengths are estimated: a) The normalized AF demagnetization of NRM in Murray and Renazzo samples. b) The normalized AF demagnetization behavior of artificial pTRM (250^{o} C, H_O) for the same samples. c) The plot of residual NRM vs. residual pTRM for the same cleaning fields. Linearity for points representing $H_{AF} \gtrsim 100$ oe and extrapolation to the origin imply that the NRM of Renazzo behaves as a (p)TRM acquired in ~2 oe fields. Scatter and nonzero intercept for Murray plot suggest a nonthermal component probably CRM. If presumed to behave like a TRM, the average slope implies that NRM was acquired in fields of ~.7 oe.

Because of many difficulties with generating and maintaining dynamo fields in small bodies and because of the likelihood of stronger, extended, solar wind fields in the early stages of solar-planetary system formation, I favor condensation and aggregation of CC in the presence of the latter. This picture can also account for the magnetic anisotropy observed (Brecher 1972; Brecher and Arrhenius 1974). The possibility that relatively strong solar-wind-convected magnetic fields, or SW fields enhanced within asteroidal bodies by unipolar induction, are responsible, has been made more plausible by our recent results on the low-T electrical conductivity of carbonaceous chondrites. (Brecher *et al.* 1975). Coupled with observational evidence on the surface composition of asteroids (Chapman 1976), these indicate that early solar-wind induction heating of asteroids with carbonaceous surfaces is quite plausible (Sonett., in this volume) and can lead both to their partial differentiation or metamorphism, and to their magnetization. The difficulty in constraining ancient solar-wind parameters comes, not the least, from the uncertainty in the place of origin of CC.

Another very interesting possibility is "cold" magnetization by a strong

https://doi.org/10.1017/S0252921100070366 Published online by Cambridge University Press

magnetic field (10-100 gauss) in cometary nuclei, possibly implied by the weaker (10-100 γ) fields of cometary tails, which have been discussed recently by Ip and Mendis (1976).

VI. CONCLUSIONS: PROGRESS AND PROSPECTS

Recent research on lunar magnetism has rekindled interest in meteoritic paleomagnetism and in the same time broadened the geocentric horizons, changed the perspectives and sharpened the focus for further research. We now know that similar processes, such as meteoritic bombardment and associated shock, brecciation, compaction, metamorphism, degassing, etc. - have shaped the surfaces of all solar system bodies. Magnetic studies may further constrain their inferred history, if integrated with other types of pertinent evidence (chemical, mineralogical, petrological, radiochronological, noble-gas and tracks data). Recent progress has been rapid, but a coherent view of meteorites, their origin and evolution has yet to emerge.

REFERENCES

Alexeyeva, K. N. 1958, *Meteoritika, 16,* 67.
Banerjee, S. K., and Hargraves, R. B. 1972, *Earth Planet. Sci. Lett., 17,* 110.
Brecher, A. 1971, in: *Evolutionary and Physical Properties of Meteoroids* Proc. IAU Coll. #13, ed. C. L. Hemenway, P. M. Millman, and A. F. Cook (NASA SP-319), p. 311.
Brecher, A. 1972, in: *Symposium on the Origin of the Solar System,* ed. H. Reeves (Paris, CNRS), p. 260.
Brecher, A., and Arrhenius, G. 1974, *J. Geophys. Res., 79,* 2081.
Brecher, A., and Ranganayaki, R. P. 1975, *Earth Planet. Sci. Lett., 25,* 57.
Brecher, A., and Stein, J. 1975, abstr., *EOS, Trans. Amer. Geophys. Un., 56,* 1016.
Brecher, A., Briggs, P. L., and Simmons, G. 1975, *Earth Planet. Sci. Lett., 28,* 37.
Brecher, A. 1976, in: *Lunar Science VII,* (Lunar Science Institute, Houston), p. 91.
Brecher, A., and Cutrera, M. 1976, *J. Geomag. Geoelec., 28,* 31.
Brecher, A., and Albright, L. 1976, to be submitted to *Phys. Earth Planet. Int.,* and Abstracts for Fall AGU Meeting and Meteoritical Society Meeting.
Butler, R. F. 1972, *Earth Planet. Sci. Lett., 17,* 120.
Chapman, C. R. 1976, *Geochim. Cosmochim. Acta, 40,* 701.
Fricker, P. E., Goldstein, J. I., and Summers, A. L. 1970, *Geochim. Cosmochim. Acta, 34,* 475.
Gose, W. A., and Butler, R. F. 1975, *Revs. Geophys. Space Phys., 13,* 189 (and bibliography, ibid., p. 226).
Guskova, E. G., and Pochtarev, V. I. 1967, *Geomagn. and Aeron., 7,* 245.
Guskova, E. G., and Pochtarev, V. I. 1969, in: *Mereorite Research,* ed. P. M. Millman (D. Reidel Publ. Co., Dordrecht, Holland), p. 633.
Guskova, E. G. 1963, *Geomagn. Aeron., 2,* 626.
Guskova, E. G. 1965, *Geomagn. Aeron., 5,* 91.
Guskova, E. G. 1970, *Meteoritika, 30,* 74.
Guskova, E. G. 1972, *Magnetic Properties of Meteorites* (Nauka, Leningrad) (in russ.).
Herndon, J. M., Rowe, M. W., Larson, E. E., and Watson, D. E. 1972, *Meteoritics, 7,* 263.
Herndon, J. M., and Rowe, M. W. 1974, *Meteoritics, 9,* 289.
Ip, W. H., and Mendis, D. A. 1976 (in press).
Larson, E. E., Watson, D. E., Herndon, J. M., and Rowe, M. W. 1973, *J. Geomagn. Geoelectr., 25,* 331.
Meadows, A. J. 1972, *Nature, 237,* 274.
Pochtarev, V. I. 1967, *Geomagn. Aeronom., 7,* 609.
Sonett, C. P. 1976, in this volume.

Stacey, F. D., Lovering, J. F., and Parry, L. G. 1961, *J. Geophys. Res., 66,* 1523.
Stacey, F. D. 1976, in *Annual Reviews Earth and Planetary Sciences, vol. 4,* p. 147.
Wasilewski, P. J. 1974, in: *Proc. Nagata Conf.* (Univ. of Pittsburgh), p. 478.
Wasson, J. T. 1974, *Meteorites - Classification and Properties,* (Springer-Verlag, N.Y., Heidelberg, Berlin).
Weaving, B. 1961, *Geochim. Cosmochim. Acta, 26,* 451.
Wood, J. A. 1967, *Icarus, 6,* 1.

DISCUSSION

GOLD: I do not understand how, in the case of chemical magnetization, the sense of the magnetic field can be established. Each small domain would have an equal chance of magnetizing in either direction, and thus, even a small piece would have virtually no resulting field. Only if the magnetization is so intense that each forming region determines the sense of its next forming neighbor. But that cannot be operative for very weakly magnetized bodies. In that case, an external - even if very weak - organizing field is clearly required. Our work on cometary impact magnetization would indicate that fields of ~1 Gauss at the impact would be common, and that both thermal and shock magnetization on the meteorite present bodies must be expected.

BRECHER: Your point is valid: we do observe in most lunar and meteorite breccias that there is no stable direction *vector of magnetization, but a preferred plane or axis to which the magnetization is confined during progressive demagnetization. In a recent EPSL paper (Feb. 1976 issue) I proposed a theoretical model to explain this type of behavior, which does not require an external magnetic field. The preferred plane of magnetization is associated with shock-produced textural effects. "Weak organizing fields," as you call them, are ubiquitous in the solar system (in the inter-planetary space or in the planetary magnetospheres) and can easily give rise to a statistical alignment of magnetic grain moments. Your "cometary impact magnetization" looks promising, but we need more direct experimental evidence on the magnetic effects of shock. Several groups are now in the process of investigating these effects and evaluating the feasibility of this mechanism.*