THE MAGNETIC EFFECTS OF BRECCIATION AND SHOCK IN METEORITES: III. THE ACHONDRITES

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Abstract. We present results of a magnetic survey of achondritic meteorites, representing the aubrites (A), diogenites (D), howardites (H), and eucrites (E) groups and relate their magnetic behavior to respective class characteristics and models of origin.

Magnetic susceptibility (χ) values cluster well within each group and decrease systematically between groups (from ~ 2 to 0.1×10^{-3} G Oe^{-1} cm^{-3}), with the average metal contents, (from ~ 1 to < 0.1 wt.%) in the above order. The natural remanent magnetization (NRM) values range broadly within each group, but group averages decrease roughly as above. However, the considerable within-sample and intra-group variability in NRM level and its demagnetization characteristics attest to inhomogeneous and localized brecciation effects. Although petrological-chemical studies resolve a primary component of magmatic differentiation on the planetoid of origin, no clear magnetic record of such event has been preserved. The magnetization of achondrites is mainly the product of their complex, multi-stage impact brecciation and metamorphism history, in accord with other lines of evidence.

The magnetic behavior of achondrites is remarkably similar to that characteristic of lunar breccias and impact-melt rocks and reinforces their analogous mode of genesis, as brought out by chemical and petrographic analyses.

1. Introduction

Magnetic investigations of achondritic meteorites are important for two main reasons:

First, they are of intrinsic interest, insofar as the achondrite groups are the only meteorites which bear an often complex record of early primary igneous differentiation in a primitive planetoid (e.g., Stolper, 1977) and of later metamorphism, shock and brecciation episodes on its surface (Wetherill, 1975; Birck and Allègre, 1978). Spectral evidence that some main-belt asteroids (e.g., 4 Vesta and 44 Nysa) have achondritic surface compositions (Chapman, 1976), yet coexist with thermally unprocessed carbonaceous asteroids, raises intriguing questions regarding the thermal evolution of asteroids. The role of solar-wind driven electromagnetic heating of asteroids in the early solar system might be elucidated by electrical and magnetic measurements on meteorites (Brecher *et al.*, 1975), thus constraining evolutionary models of the early Sun.

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Magnetic results could also bear on various proposed genetic connections between achondrite groups: the Ca-rich basaltic achondrites (eucrites-E and howardites-H) have been linked to the Ca-poor (A-aubrites or enstatite and D-diogenites or hypersthene) achondrites via a crystallization sequence in primary magmatic fractionation (Shimizu and Allègre, 1975); or as mechanical mixtures of end members of a liquidus fractionation sequence of the parent body (Morgan and Lovering, 1973); or as partial melts and cumulates from the same source material (Stolper, 1977). However, some authors proposed that the primary differentiation of achondritic components occurred already during a nebular condensation-accretion stage (e.g., Ahrens and Danchin, 1970; Vizgirda and Anders, 1975; Morgan *et al.*, 1978).

The resolution of these multiple alternatives provides the link to the second principal reason for studying the magnetic record in achondrites, namely that they are recognized as the closest known natural analog to lunar rocks (e.g., Bunch, 1975). Comparative research on lunar and meteoritic samples is of broader scope and greater promise for separating the general from the particular processes which have affected solar system objects. Thus, chemical modelling of the eucrite parent body brought out its remarkable similarities to the Moon, whose origin can no longer be ascribed to unique circumstances (Vizgirda and Anders, 1975; Consolmagno and Drake, 1976). Oxygen-isotope data placed the formation of the Earth, Moon and the differentiated meteorite classes in the same nebular neighborhood (Clayton and Mayeda, 1975). Radiometric chronology indicated that, like their lunar counterparts, the achondrite mineral phases participated in the sharp-isochronism of nebular condensation and primary differentiation approximately 4.55 b.y. ago, but underwent complex metamorphic partial resetting due to shock or brecciation high-temperature events, long thereafter (Wetherill, 1975; Birck and Allègre, 1978).

Further, like most lunar rocks, the achondrites have been brecciated and shocked to various degrees, by impacts on the surface of their parent bodies. A complex sequence of fragmentation, compaction, recrystallization, shock metamorphism and impact-melting is apparent from extensive textural petrologic and chemical studies (Wahl, 1952; Fredriksson and Keil, 1963; Duke and Silver, 1967; Reid, 1974; Bunch, 1975; Prinz *et al.*, 1974; Dymek *et al.*, 1976; Wilkening, 1976; Gooley and Moore, 1976) and from noble-gas and fossil particle track data which testify to a regolith-origin (Wilkening *et al.*, 1971; Poupeau *et al.*, 1974). Most eucrites are recognized as monomict breccias derived from a primary magma, with the exception of a few unbrecciated cumulates (such as Ibitira, Moama, Moore Co. and Serra de Magé) (Stolper, 1977; Hostetler and Drake, 1978). All eucrites selected for the purpose of our study (Table I) are typical brecciated eucrites. Follow-up work is planned on the eucritic adcumulate rocks, which are the most likely candidates for the preservation of a primary magnetization. The howardites are identified with polymict surface breccias, with a great diversity in metamorphic grade of component fragments and clasts (Bunch, 1975). All diogenites studied are also breccias, with the exception of Tatahouina (Gooley and Moore, 1976). The aubrites too are surface-breccias (Wahl, 1952; Poupeau *et al.*, 1974).

TABLE I
Magnetic data on achondrites

Group/Meteorite[a]	$\chi \times 10^{-3}$ $\frac{\text{emu}}{\text{cm}^3}$	NRM $\frac{\text{emu}}{\text{cm}^3}$	IRM_S $\frac{\text{emu}}{\text{cm}^3}$	Q	IRM_S/NRM	Reference
AUBRITES						
Bishopville	3.84	2.83×10^{-5}	1.16×10^{-2}	7×10^{-3}	400	[1]
Bishopville	1	2×10^{-4}	–	2×10^{-4}		[2]
Staroe Pensyanoe	1	2×10^{-4}	–	2×10^{-4}		[2]
Norton County	0.5	2×10^{-4}	–	4×10^{-4}		[2]
DIOGENITES						
Roda	1.33	5.54×10^{-5}	1.14×10^{-2}	4×10^{-2}	200	[1]
Shalka	1.04	0.73×10^{-5}	0.223×10^{-2}	7×10^{-3}	300	[1]
Tatahouina	0.94	30×10^{-5}	1.2	0.32	40	[1]
Johnstown a.	4.14	2.24×10^{-5}	0.68	5×10^{-3}	300	[1]
b.	2.97	0.5×10^{-5}	–	2×10^{-3}		[1]
c.	2.61	0.7×10^{-5}	–	2×10^{-3}		[1]
HOWARDITES						
Pavlovka	1.9	7.76×10^{-5}	4×10^{-3}	4×10^{-2}	51	[1]
Pavlovka	2.8	1.4×10^{-3}	–	5×10^{-3}		[2]
Le Teilleul	1.74	1.1×10^{-5}	8.64×10^{-3}	6×10^{-3}	750	[1]
Kapoeta	0.644	2×10^{-4}	2×10^{-2}	0.3	100	[1]
Yurtuk	2	1.6×10^{-3}	–	0.8		[2]
Luotolax	{2.6 2	{1.7×10^{-3} 1×10^{-3}	–	0.65		[2]
EUCRITES						
Juvinas	0.96, 0.53	1.28×10^{-5}	3.92×10^{-3}	0.1	300	[1]
Juvinas	2.3	8×10^{-4}	–	0.34		[2]
Nobleboro	1.1	3.76×10^{-5}	2.23×10^{-4}	3×10^{-2}	6	[1]
Pasamonte	2.17	3.21×10^{-4}	5.41×10^{-3}	0.15	17	[1]
Stannern	–	0.8×10^{-6}	0.6×10^{-3}		750	[1]
Stannern	0.6	0.4×10^{-3}	–	0.66		[2]
Sioux County		1×10^{-5}	1×10^{-3}		100	[1]

[a] Order of groups corresponds to decreasing average metal contents (% wt.): A ~ 1; D $\lesssim$ 1; H $\lesssim$ 0.3; E $\lesssim$ 0.1.
References: [1] this work; [2] Guskova (1972).

This set of remarkable textural and mineralogical similarities of achondrites to lunar surface breccias imply germane modes of formation. Therefore, the magnetic properties of achondrites may help clarify, by analogy, still obscure or controversial aspects of the nature of lunar magnetism (Fuller, 1974; Brecher, 1976a, 1976b). This paper is the third in a series devoted to the identification and comparison of magnetic indicators of shock and brecciation effects in meteorites (Brecher *et al.*, 1977 and Brecher and Fuhrman, 1978 – hereafter referred to as Papers I and II). Some of the most significant results have been presented in a preliminary form by Brecher and Stein, 1975, emphasizing similarities of meteoritic and lunar breccias, and the importance of textural magnetic effects (Brecher, 1976a, 1976b, 1976c).

2. Meterorite Samples and Initial Magnetic Measurements

Large samples (several grams) of thirteen well-studied achondrites (1A, 4D, 3H, 5E) (Table I) were obtained for magnetic studies from Dr E. Olsen (Chicago Field Museum) and from Professor H. Wänke (Max Planck Institut, Mainz). From examinations under a petrographic microscope, our samples appeared to be texturally and petrographically representative of the meteorites, judging by the literature descriptions (e.g., Wahl, 1952; Duke and Silver, 1967; Bunch, 1975).

Whenever possible the samples were dry-cut into mutually oriented subsamples (e.g., Juvinas, Le Teilleul, Stannern and Johnstown), to test the small-scale magnetic coherence. The larger-scale magnetic coherence could also sometimes be assessed by comparison with other magnetic data in existing literature (Table I). These include measurements of natural magnetic remanence (NRM) intensity and bulk magnetic susceptibility (χ) on seven achondrites (3A, 3H, 2E) (Guskova, 1972) and more exhaustive information on a new Antarctic achondrite Yamato (b) (Nagata *et al.*, 1975). The data in Table I allow for a comparison among achondrite groups, which are listed roughly in order of decreasing metal content (Section 4), as well as between members within each group, based on listed magnetic parameter values:

(1) *The bulk susceptibilities* (χ) were measured with a Bison 3101 system, with a dynamic range 10^{-6}–10^{-1} emu in 0.5 Oe applied fields. The bulk susceptibility (χ) values are a rough measure of metal abundance – assuming similar grain size distributions and metal compositions, which is not realistic (e.g., Gooley and Moore, 1976). These values cluster in a narrow range (0.5–5×10^{-3} emu cm^{-3}) for all achondrite groups (A, D, H, E).

The magnetic moments were measured with a Schonstedt SSM-1A Spinner Magnetometer interfaced to a Hewlett Packard 9815 programmable calculator, with on-line data reduction and display capabilities.

(2) *The natural remanence* (NRM) intensities reflect to some extent the efficiency of the magnetization process, if normalized to variable metal contents, composition and grain sizes (see below). The range of NRM values (in emu cm^{-3}) for each achondrite group (Table I) are: A (2×10^{-4}–2×10^{-5}); D (5×10^{-4}–5×10^{-6}); H (10^{-3}–10^{-5}); E (10^{-3}–10^{-6}); and are typically spread broadly over two to three decades. The scatter of values within each group, and between samples and subsamples of individual meteorites does not favor a uniform magnetization mechanism.

(3) *The Koenigsberger ratio* ($Q = \mathrm{NRM}/(\chi \cdot \mathrm{H})$) of remanent to induced magnetization is used in terrestrial rock magnetism as an approximate indicator of the nature and efficiency of the magnetizing mechanism (i.e., high for stable thermal (TRM) or chemical (CRM) remanence in igneous rocks, but low for depositional remanence (DRM) in sedimentary rocks); or as an indicator of magnetic grain sizes and domain structure (high for fine-grained or single-domain carriers, low for coarse or multidomain grains). Since the

value of Q depends on the inducing or magnetizing field, which could be of order ~ 1 Oe (e.g., Brecher, 1972, 1977, Paper II) according to data on carbonaceous chondrites and ureilites, or as low as ~ 0.01 Oe for the ordinary chondrites (Brecher and Ranganayaki, 1975), only the relative Q values for groups are of significance here. Normalizing **H** to 1 Oe, the values of Q range from $(0.2–7) \times 10^{-3}$ for A; $(2–320) \times 10^{-3}$ for D; $(5–800) \times 10^{-3}$ for H; and $(10–600) \times 10^{-3}$ for E. The ureilite achondrites had, by far, the highest Q values (0.08 to 82) (Paper II), suggesting that they possess both a much more efficient and a stabler type of remanence. In contrast, these four achondrite groups are quite similar in their low Q values, which increase slightly as the metal contents decrease (A→D→H~E) and possibly due also to progressively finer-grained metal. The absolute Q values could be two orders of magnitude higher if the ancient external fields were ~ 0.01 Oe, and if their NRM were considered to be of thermal origin (TRM) (Section 4, 5).

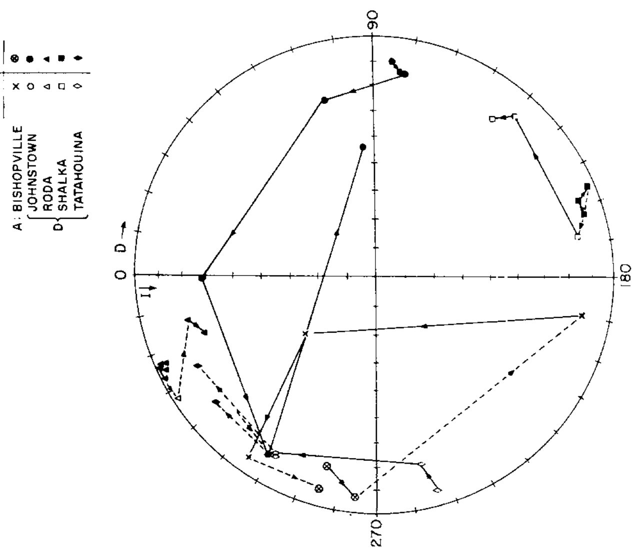
(4) *The saturation remanence* (IRM_s) levels (Table I), represent an upper limit to the capability of the meteorite samples for retaining a magnetization (see Section 4). Although the samples were saturated by exposure to high (8 kOe) fields after complete alternating field (AF) demagnetization of NRM (Section 3), the IRM_s values are important as 'initial' magnetic characteristics because the derived ratio, IRM_s/NRM is a rough index of domain structure, degree of undersaturation and even for paleofield intensities, if normalizable (e.g., Fuller, 1974). In the A, D, and H groups, IRM_s values range roughly over one decade (10^{-3}–10^{-2} emu cm^{-3}) and the lowest are E group values which extend below it ($0.2–5 \times 10^{-3}$ emu cm^{-3}).

Overall, the groups appear much more homogeneous based on remanent capability, as the narrow intragroup spreads in IRM_s intensity imply, than from the NRM group scatter. This suggests that achondritic material with similar potential for magnetization was subjected to diverse brecciation and shock events in local impact events on their parent planetoid.

The IRM_s/NRM values for achondrites are both higher (order 10 – a few × 100) and more scattered within each group than those reported for ureilites (1–10) mainly because of discrepant NRM values. These ratios indicate severe undersaturation of remanence, due to a less efficient or locally variable process or by a coarser metal grain population than in the ureilites (Paper II).

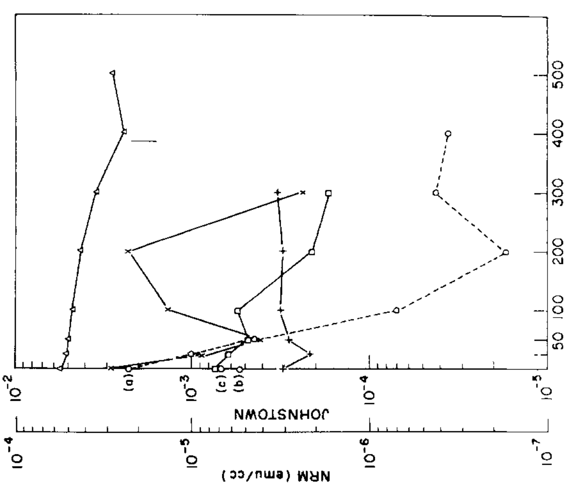
3. AF Demagnetization Behavior of Natural (NRM) and Saturation (IRM_s) Remanence

3.1. *The A and D groups* are poorer in Ca and richer in metal than the E, H groups, and will be discussed collectively. The relative intensity and stability of remanence in the aubrite Bishopville and in the diogenites Johnstown, Roda, Shalka and Tatahouina are illustrated in Figure 1. Note the spread in NRM values (Figure 1a) over 3 decades and the inhomogeneity in distribution of metal and/or magnetization level shown by three Johnstown subsamples. The most remarkable feature of Figures 1a and 1c is the diversity of NRM demagnetization curves, from the very strong and hard remanence in Roda to the



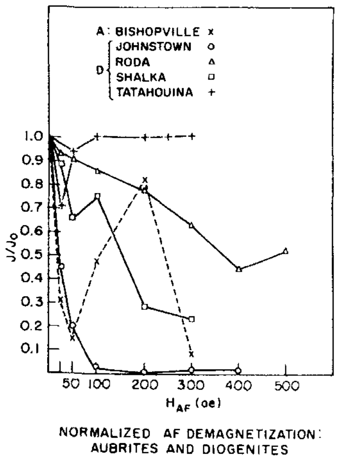
NRM DIRECTIONS - AUBRITES AND DIOGENITES

b

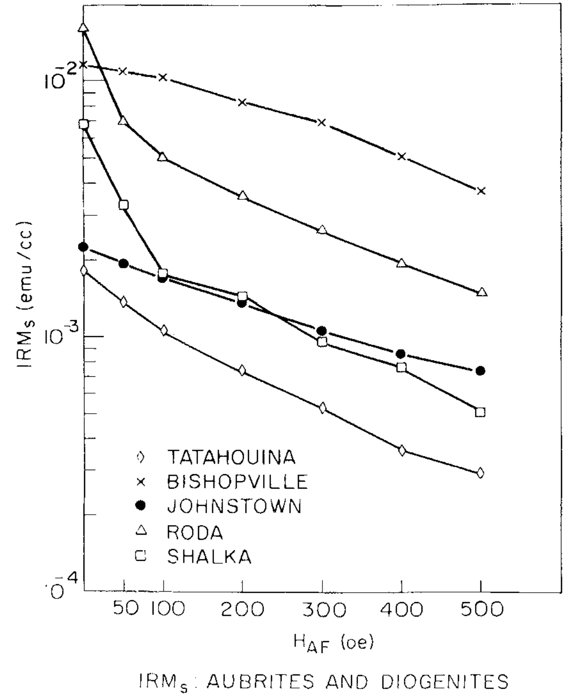


AF DEMAGNETIZATION: AUBRITES AND DIOGENITES

a



c



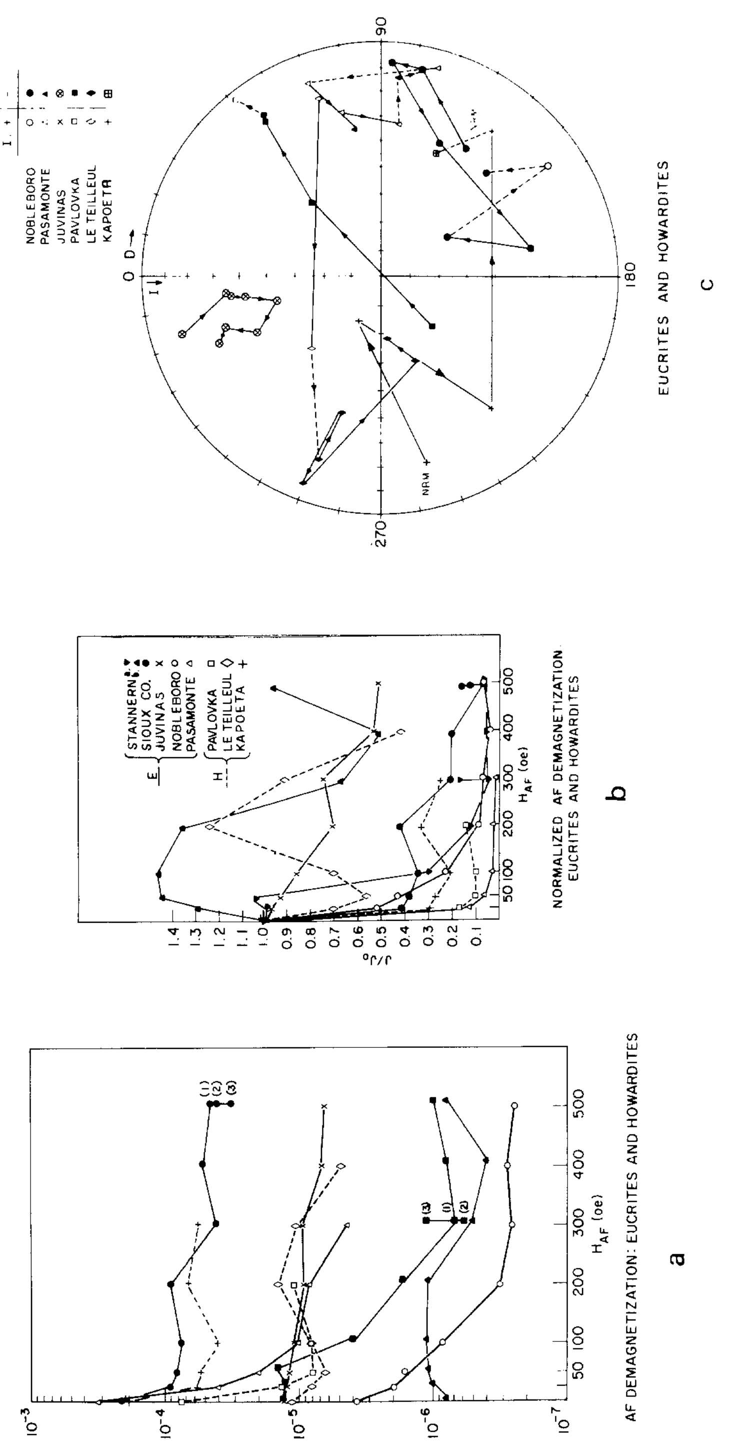
d

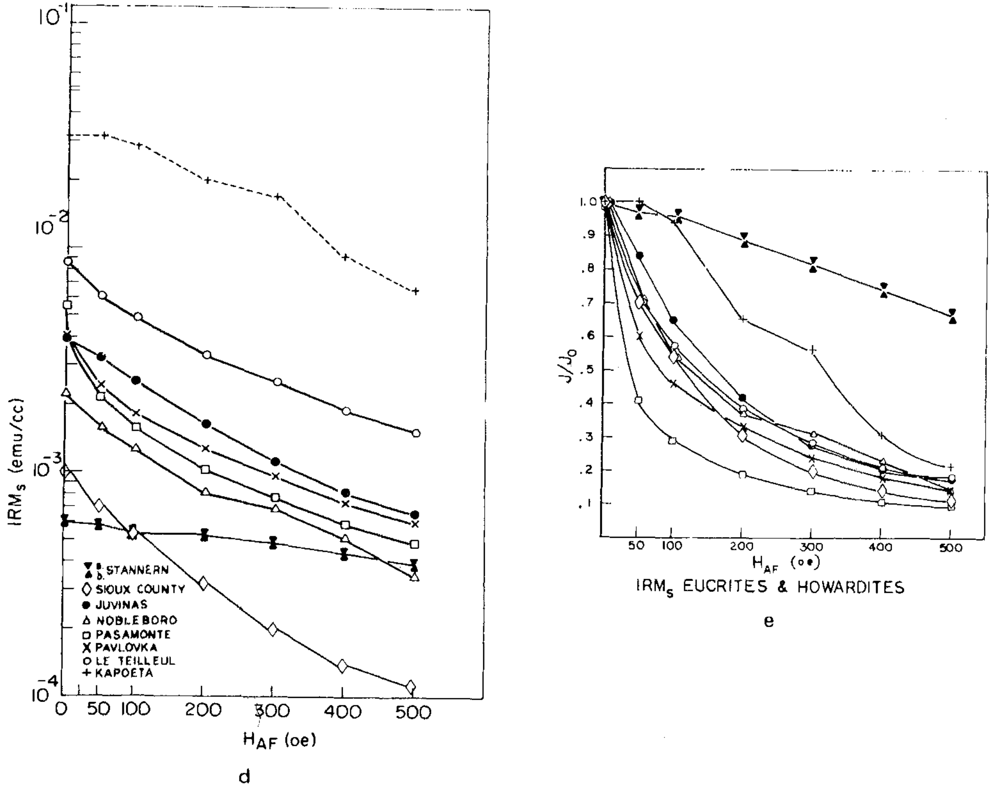
Figs. 1a–1d. (1a) presents the intensity of NRM in Ca-poor achondrites and the NRM losses with progressively larger alternating field (AF) cleaning on an absolute scale. Johnstown (dotted) has the scale at left.

(1b) shows the corresponding directional changes in NRM with AF demagnetization.

(1c) is a normalized replotting of data shown in (1a) which allows a comparison of relative magnetic hardness.

(1d) shows the distribution and behavior of saturation remanence (IRM_S) with AF cleaning. A comparison with (1a) shows that the achondrites are capable of carrying, but do not carry, a stable remanence.


AF DEMAGNETIZATION: EUCRITES AND HOWARDITES
a
NORMALIZED AF DEMAGNETIZATION
EUCRITES AND HOWARDITES
b
EUCRITES AND HOWARDITES
c
STANNERN
SIOUX CO.
JUVINAS
NOBLEBORO
PASAMONTE
PAVLOVKA
LE TEILLEUL
KAPOETA
NRM



Figs. 2a–2e. The NRM characteristics of eucrites (solid) and howardites (dotted) are shown in Figures (2a) on an absolute intensity scale and normalized to the initial moment in Figure (2b). Figure (2c) is a stereonet projection of the NRM vector changes in direction for each value of the AF in Figs. (2a) and (2b). Note the scattered, incoherent changes in directions and polarity typical of achondrites (Figures (1b) and (2c)). Figures (2d) and (2e) illustrate the absolute and relative stability of IRM_s for these achondrites. Note the similarity in range and coercivity of IRM_s to that shown in Figure (1d).

extremely soft moment of Johnstown. The directional changes in NRM vector for Johnstown, Shalka and Bishopville (Figure 1b) show planar migration and reversal patterns typical of lunar and meteoritic breccias, in which the magnetization seems controlled by textural effects (Brecher and Stein, 1975; Brecher, 1976a, 1976b, 1976c; Brecher, 1977; Brecher *et al.*, 1977). These achondrites also display the typically jagged AF demagnetization profiles (Figures 1a, 1c) indicative of undemagnetizable, pinned magnetic moments. Roda shows the best directional coherence and stability of NRM, and might therefore have preserved a primary NRM. Detailed 2-component projection analysis of its NRM vector directional changes with progressive magnetic cleaning (e.g., Brecher and Ranganayaki, 1975; Papers I, II) reveals, however, at least 3 distinct NRM components. The NRM in other A, D-meteorites changes polarity repeatedly, while Bishopville and Tatahouine show large directional excursions in preferred planes. In contrast, the saturation remanence (IRM_s) intensity levels and stability spectra are quite similar (Figure 1d). Roda has undoubtedly the hardest IRM_s spectrum and finest magnetic carriers. The order of decreasing magnetic hardness of IRM_s and hence of an increasing fraction of coarse metal grains is: Roda, Shalka, Tatahouina, Bishopville, and Johnstown (Figure 1d), but a continuum is evident.

3.2. *The Eucrites* (*E*) *and Howardites* (*H*), representing the Ca-rich and metal-poor achondrites, are groups in Figure 2. They behave collectively in a similar manner to that described above. The range and diversity of NRM stability to AF demagnetization is evident from Figure 2a (on an absolute intensity scale) and even more striking in Figure 2b, when normalized to the initial moments. There seems to be no difference between the magnetization of eucrites studied (solid lines) which are monomict breccias and that of Howardites (dashed lines) which are polymict surface breccias in either intensity or in magnetic stability. Similarly, most E, H-achondrites show very large directional excursions and repeated reversals upon AF cleaning (Figure 2c). Pronounced planar pinning of NRM directions is evident in Pavlovka (notice the great circle path in Figure 2c), Nobleboro, Kapoeta, and others. The Stannern and Sioux County samples have particularly nonuniform moments and unstable NRM directions, with evidence of random oscillation in some preferred textural plane. The eucrites Pasamonte and Juvinas show the best directional coherence of this group, but two-component projection plots of NRM directional migration revealed that they too possess a typical achondritic chaotic and multicomponent magnetization. Pavlovka appeared, however, to have only two distinct directional NRM components (Figure 3c), in spite of its relatively weak and soft NRM (Figures 3a, 3b). Therefore a paleointensity determination experiment was carried out (e.g., Papers I, II) as summarized in Figure 3. Not only did thermally-induced mineralogical changes occur on heating as indicated by the increase in saturation remanence level and stability, but the laboratory thermoremanence (TRM) did not resemble at all the NRM intensity and coercivity (Figures 4a, 4b, 4c). Hence no paleointensity determination was warranted or possible (Figure 3d).

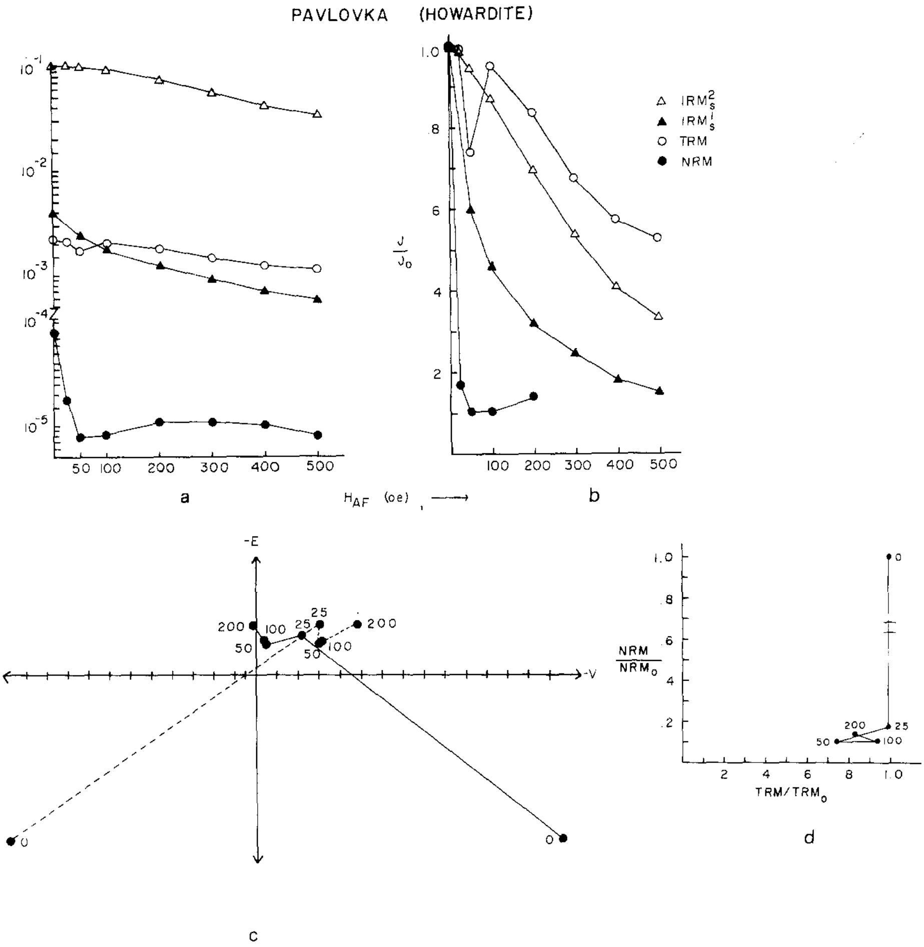


Fig. 3. This figure presents a paleointensity determination experiment on the howardite Pavlovka. (3a) contrasts the weak and soft NRM to the much stronger and harder laboratory thermoremanence (TRM), which is comparable to the initial IRM_s^1. Irreversible changes occurred during heating to 800 °C leading to a stronger and harder IRM_s^2. (3b) is a normalized set of demagnetization curves. (3c) shows that the NRM of Pavlovka, when projected on a set of two orthogonal planes, consists of two directional components, the largest of which is exceedingly soft (lost in 25–50 Oe). In (3d) a plot of NRM vs. TRM loss at each step in the demagnetization process is clearly nonlinear and no paleofield estimate is warranted.

4. Discussion of Results

4.1. The explanation for the observed magnetic behavior characteristics of A and D achondrites (Section 3.1) can be readily analyzed in terms of their metal carriers and petrographic features. Wasson and Wai (1970) describe the metallic phases of enstatite achondrites: Bishopville contains large Ni–Fe metal grains with ~ 5.7%Ni in kamacite. Gooley and Moore (1976) note that all diogenites contain < 1% wt. metal grains typically distributed in planar arrays which decorate old, healed sets of fractures. Johnstown is particularly poor in metal (~ .33 wt.%) and has a notably broad range of grain sizes (< 1 μm to 1 mm) – which explains directly its weaker and unusually unstable NRM (Figures 1a, 1c). Metal grains of 2–20 μm in size have a typical planar distribution, thus producing the great circle planar migration pattern noted for NRM (Figure 1b). At the other extreme Roda contains both irregularly-shaped and planarly-distributed metal grains, with a bimodal composition. Some have the typical meteoritic 2–5% wt. Ni, found also in Johnstown metal, whereas others are extremely rich in Ni (> 50% wt.) and Co (up to 27% wt.). These latter finer carriers may account for the high coercivity of NRM in Roda. The two types of metal may be of distinct origins and be related to distinct NRM components. Shalka contains mostly large, irregularly-shaped and Ni-poor (< 0.1–1.5 wt.%) kamacite grains. The relatively hard and flat demagnetization curve of NRM in Tatahouina, which is directionally confined to a low-inclination plane (Figure 1) is easily understood as due to the fact that this unbrecciated achondrite has a banded distribution of opaques and metal, with < 1% Ni (Gooley and Moore, 1976).

4.2. The chaotic and relatively weak NRM's in achondrites are thus not of thermal nature, as vividly illustrated for Pavlovka (Figure 3). Indeed, at least the gas-rich achondrites such as Kapoeta (Wilkening *et al.*, 1971; Wilkening, 1973) and the aubritic breccias (Poupeau *et al.*, 1974) have been cataclastically brecciated at low temperatures, as the irradiated regolith fragments and the gas contents in these assemblages testify. In this sense they do not satisfy the 'conglomerate test' for the coherence of their resultant magnetization, each lithic fragment having possibly preserved a memory of a previous magnetic event, which is lacking in the random final assemblage. All have pronounced metamorphic or cumulate fabrics, due to impact-brecciation or to settling. The most recent radiochronological study on eucrites (Birck and Allègre, 1978) includes Juvinas, Sioux County, Stannern and Pasamonte, in order of decreasing metamorphic ages (4.52, 4.19, 3.1, and 2.6 b.y.a., respectively), all of which may have undergone a primary differentiation from a magma at 4.57 b.y.a. Indeed, Juvinas, whose age is least disturbed by metamorphism, has one of the hardest and directionally most coherent NRM. Sioux County, which is a coarsely-grained breccia, has a relatively soft saturation spectrum and a texturally-planar, pinned, softer NRM. Stannern, which is strongly brecciated, has a very nonuniform and incoherent NRM, but a very uniform distribution of fine-grained carriers, as indicated by the hardest IRM_s spectrum in Figure 2e. Pasamonte, which is a typical brecciated eucrite with the youngest age of metamorphism, has the softest NRM, but a typical metal grain distribution – as seen from Figure 2e.

The metal phases in H and E have been described well in Duke (1965), whereas some important petrographic features and similarities with lunar breccias are discussed by Prinz *et al.* (1974), Bunch (1975), and Wilkening (1977). Most have scarce Ni–Fe metal (in the range 0.1–1% wt.), which is Ni-poor (0.1–0.5% Ni) (e.g., Fredriksson and Keil, 1963; Duke, 1965). Specifically, Kapoeta has up to 4–5% Ni in kamacite and ~ 38% in taenite grains – which would explain its unusually hard NRM and IRM_s (the more Ni, the finer the ferromagnetic kamacite grains). Juvinas, which contains ~ 0.04% wt. metal, with ~ 0.02% Ni, and Stannern ~ 0.04% wt. metal are metal-poor members. Both have relatively weak NRM and IRM_s, as a result. Pasamonte has metal unusually poor in Ni (< 0.1%), which explains the softeness of its NRM and IRM_s microcoercivity spectra.

4.3. The achondrites are remarkably similar to lunar rocks in several respects: First, they incorporate end-products of primary igneous differentiation of a planetoid, possibly originating in a common reservoir and linked by an evolutionary sequence. Second, most achondrites appear to be surface breccias, be they monomict (e.g., Diogenites, Eucrites) or polymict (e.g., howardites). A complex brecciation and shock history and probable formation in the regolith layer of their parent body makes the achondrites the closest available analog to lunar breccias. Third, the similarity extends to metal abundances, structure and alloy composition as well, since the achondrites are metal-poor (typically < 2 wt.%).

The morphology and implied provenance of some metal components are also inviting comparison between the formation of lunar breccias and poikilitic (impact-melt) rocks on the Moon and that of achondrites (Gooley and Moore, 1976). The similarities between achondrites and lunar breccias and impact-melt rocks extends also to metal contents and composition: such lunar rocks typically contain ≲ 2 wt.% metal, with ~ 5–7 wt.% Ni, and ≲ 2 wt.% Co, as Ni–Co–Fe alloy phases. However, an almost pure Fe component (low in Ni, but sometimes high in Co) is often present in lunar breccias and is ascribed a secondary origin by shock-reduction *in situ*. A similar metal component was also reported for some achondrites (e.g., the Binda howardite, with 0.44–2% Ni, 1.4–2.2% Co in Fe and in most eucrites and ureilites) (e.g., Fredriksson and Keil, 1963; Lovering, 1964; Duke, 1965).

The same variety and inhomogeneity in the amounts, composition, texture, grain sizes and morphologies of metal phases is typical of the achondrite groups and of lunar rocks. Roughly, the abundance of metal, present largely as kamacite, decreases in the order A, D, H, E, with a range of ~ 0.3–6 wt.% in the ureilites, ~ 0.1–1 in A and D, and mostly < 0.5 in H and E, with a few exceptions (Duke, 1965).

5. Summary and Conclusions

5.1. The metal-poor achondrites (≲ 1% wt.) group tightly in magnetic susceptibility (χ) values and in remanent magnetic capability (IRM_s values and stability), but range broadly in NRM values (from ~ 2×10^{-3} emu cm^{-3} in the diogenite Johnstown to ~ 2×10^{-6} emu cm^{-3} in the eucrite Nobleboro), overlapping at the high end with LL- and L-chondrites.

5.2. The stability of NRM to alternating field (AF) demagnetization varies, from the remarkably hard and relatively strong NRM of the howardite Le Teilleul and diogenite Roda, to the extremely soft NRM of the diogenite Johnstown, whose value dropped 3 decades in cleaning to 200 Oe.

The shapes of the microcoercivity curves were similarly diverse, from the smooth, well-behaved profiles displayed by the eucrites Pasamonte and Nobleboro, to the irregular intensity changes typified by the diogenite Tatahouina, aubrite Bishopville, and howardite Le Teilleul. A general feature is the presence of several directional components of NRM. In agreement with the complex history inferred for achondritic meteorites from petrographic analysis (e.g., Duke and Silver, 1967; Prinz *et al.*, 1974; Bunch, 1975), these magnetic data confirm that no pristine NRM component has survived the brecciation episode and that no coherent magnetization has been acquired during cooling, following impact-metamorphism. This is analogous to magnetic behavior patterns observed in lunar breccias (e.g., Brecher, 1976) and in the brecciated LL-chondrites (Paper I).

5.3. The saturation remanence intensity and stability is very well clustered for all achondrites. The continuum of metal grain sizes inferred from magnetic data is in accord with the continuum of degrees of metamorphic recrystallization due to the impact event and to the wide range of temperatures experienced by fragments incorporated in the same breccia inferred from petrographic evidence (e.g., Bunch, 1975).

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References

Ahrens, L. H. and Danchin, R. V.: 1970, *Phys. Chem. Earth* **8**, 267.
Birck, J. L. and Allègre, C. J.: 1978, *Earth Planet. Sci. Letters* **39**, 37.
Brecher, A.: 1972, *Proc. CNRS Symp. on the Origin of the Solar System*, p. 260.
Brecher, A. and Arrhenius, G.: 1974, *J. Geophys. Res.* **79**, 2081.
Brecher, A. and Ranganayaki, R. P.: 1975, *Earth Planet. Sci. Letters* **25**, 57.
Brecher, A. and Stein, J.: 1975, *EOS Trans. AGU* **56**, 1016.
Brecher, A., Briggs, P. L., and Simmons, G.: 1975, *Earth Planet. Sci. Letters* **28**, 37.
Brecher, A.: 1976a, *Lunar Sci.* **VII**, 91.
Brecher, A.: 1976b, in A. H. Delsemme (ed.), *Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins*, Univ. of Toledo, p. 415.
Brecher, A.: 1976c, *Earth Planet. Sci. Letters* **29**, 131.
Brecher, A. Stein, J., and Fuhrman, M.: 1977, *The Moon* **17**, 205.
Brecher, A. and Fuhrman, M.: 1979, *The Moon and the Planets* **18**, 251.
Bunch, T. E.: 1975, *Proc. Lunar Sci. Conf. 6th*, 469.
Chapman, C. R.: 1976, *Geochim. Cosmochim. Acta* **40**, 701.
Clayton, R. N. and Mayeda, T. K.: 1975, *Proc. Lunar Sci. Conf. 6th*, 1761.
Consolmagno, G. J. and Drake, M. J.: 1976, *Meteoritics* **11**, 265 (abstract).
Duke, M. B. and Silver, L. T.: 1967, *Geochim. Cosmochim. Acta* **31**, 1637.
Dymek, R. F., Albee, A. L., Chodos, A. A., and Wasserburg, G. J.: 1976, *Geochim. Cosmochim. Acta* **40**, 1115.

Fredriksson, K. and Keil, K.: 1963, *Geochim. Cosmochim. Acta* **27**, 717.
Fuller, M.: 1974, *Rev. Geophys. Space Phys.* **12**, 23.
Gooley, R. and Moore, C. B.: 1976, *Am. Mineral.* **61**, 373.
Guskova, Ye. G.: 1972, *The Magnetic Properties of Meteorites*, Nauka Press, Leningrad (108 pp.) and NASA Technical Transl. NASA-TT-F-792.
Hostetler, C. J. and Drake, M. J.: 1978, *Geochim. Cosmochim. Acta* **42**, 512.
Larson, E. E., Watson, D. E., Herndon, J. M., and Rowe, M. W.: 1973, *J. Geomag. Geolec.* **25**, 331.
Lugmair, G. W., and Scheinin, N. B.: 1975, *Meteoritics* **10**, 447 (abstract).
McCarthy, T. S., Erlank, A. J., and Willis, J. P.: 1973, *Earth Planet. Sci. Letters* **18**, 433.
Morgan, J. W., Higuchi, H., Takahashi, H., and Hertogen, J.: 1978, *Geochim. Cosmochim. Acta* **42**, 27.
Morgan, J. W. and Lovering, J. F.: 1973, *Geochim. Cosmochim. Acta* **37**, 1697.
Nagata, T., Sugiura, N., and Schwerer, F. C.: 1975, Notes on the Properties of the Yamato Meteorites.
Poupeau, G., Kirsten, T., Steinbrunn, F., and Storzer, D.: 1974, *Earth Planet. Sci. Letters* **24**, 229.
Prinz, M., Fodor, R. V., and Keil, K.: 1974, Proc. Soviet-American Conf. Cosmochem. Moon and Planets.
Reid, A. M.: 1974, *Meteoritics* **9**, 398 (abstract).
Shimizu, N. and Allègre, C. J.: 1975, *Meteoritics* **10**, 488 (abstract).
Stolper, E.: 1975, *Nature* **258**, 220.
Stolper, E.: 1977, *Geochim. Cosmochim. Acta* **41**, 587.
Tatsumoto, M. and Unruh, D. M.: 1975, *Meteoritics* **10**, 500 (abstract).
Vizgirda, J. and Anders, E.: 1976, *Lunar Sci.* **VII**, 898.
Wahl, W.: 1952, *Geochim. Cosmochim. Acta* **2**, 91.
Wasson, J. T. and Wai, C. M.: 1970, *Geochim. Cosmochim. Acta* **34**, 169.
Wetherill, G. W.: 1975, *Ann. Rev. Nuclear Sci.* **25**, 283.
Wilkening, L. L., Lal, D., and Reid, A. M.: 1971, *Earth Planet. Sci. Letters* **10**, 334.
Wilkening, L. L.: 1973, *Geochim. Cosmochim. Acta* **37**, 1985.
Wilkening, L. L., Herman, G. F., and Anders, E.: 1973, *Geochim. et Cosmochim. Acta* **37**, 1803.
Wilkening, L. L. and Anders, E.: 1976, *Geochim. Cosmochim. Acta* **39**, 1205.
Wilkening, L L.: 1977, in A. H. Delsemme (ed.), *Comets, Asteroids, Meteorites: Interrelations, Evolution and Origins*, Univ. of Toledo, p. 389.