The Thermoremanence Hypothesis and the Origin of Magnetization in Iron Meteorites

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Iron meteorites are macroscopic single-crystals of Ni-Fe alloy (ave. 10% Ni), segregated into strongly ferro-magnetic (α) and weakly magnetic (γ) phases, intergrown in the octahedral system. Given their probable origin as molten metal cores or pods, slowly cooled (at rates ~1-100°C/my) in asteroidal bodies, they seem ideally suited to record ancient magnetic fields as thermal (TRM) or thermochemical (TCRM) remanent magnetization. To test this hypothesis, we investigated the intensity, relative stability and directional behavior in AF demagnetization of the natural (NRM), saturation (IRMₐ), thermal (TRM) and spontaneous (SM) magnetization in several iron meteorites spanning the compositional-structural spectrum. The main results are: 1) The remanence intensity and relative stability increase systematically from the coarser to the finer-grained classes. The latter are capable of carrying a stable paleoremanence. 2) The NRM coercivity spectra, which are considerably harder than laboratory TRM's in the finest structured groups, gradually soften as grain-size coarsens. 3) All magnetization directions (NRM, TRM, SM) in octahedrites appear to be preferentially associated with the octahedral γ{111} crystallographic planes on which α{110} plates nucleated and grew, and/or aligned with their intersections. The finer the structure, the clearer the link of magnetization directions to 'easy' crystallographic planes and axes. 4) A direct comparison of NRM and TRM demagnetization curves yields paleointensities in the range 0.3-3 Oe. However, the similarity of SM's (following zero-field cooling) to TRM's, implies fictitious ambient field values of 2-5 Oe. The extent to which SM mimics the TRM and NRM characteristics severely limits attempts to establish that the stable NRM in iron meteorites is an ancient TRM acquired in extraterrestrial fields of ~1 Oe. It is evident that the combined effect of magnetocrystalline and shape-anisotropy of the crystallographically ordered ferromagnetic kamacite (α)-phase had an overriding importance in producing the observed magnetic remanence characteristics of iron meteorites. Therefore, no reliable information regarding the presence, strength and sources of ancient solar-system fields can be retrieved from iron meteorites.

1. Introduction

Laboratory studies of available extraterrestrial materials offer the opportunity both to test the ideas and advance the knowledge derived from years of terrestrial experience. In unraveling and interpreting the magnetic record of lunar rocks and meteorites, it is particularly important to become aware of any geocentric biases and
to actually test assumptions which are often implicit in terrestrial rock magnetism (Fuller, 1974; Brecher, 1971, 1976a). The still unresolved issue of the origin of lunar magnetism has alerted many to the need for probing deeper and wider in the search for various magnetizing mechanisms operating on planetary surfaces, in planetary interiors and in space, rather than presuming a thermoremanence (TRM) (e.g., Wasilewski, 1973; Fuller, 1974; Dyal et al., 1974). The present work grew out of this new awareness: the iron meteorites as a group of well-characterized extraterrestrial objects apparently preserving a primary TRM (e.g., Guskova, 1972) seemed ideally suited to serve as a case study for verifying the validity of the TRM hypothesis, for identifying potentially important structural magnetic effects (Brecher, 1971) or unconventional mechanisms of magnetization (Brecher, 1976a). A brief background and justification follow:

The iron meteorites are typically gigantic single crystals of Ni-Fe alloy (5–20% Ni), which segregated on a macroscopic scale into ferromagnetic (α, BCC) Ni-poor kamacite and para- or (weakly ferro-) magnetic (γ, FCC) Ni-rich taenite. These phases are intergrown in a characteristically ordered octahedral structure: the α{110} planes nucleated epitactically on the γ{111} faces and grew at the expense of the γ-host, by subsolidus diffusional equilibration during extremely slow cooling (~1–100°C/my) of initially molten cores or pods of Ni-Fe in differentiated asteroids. The basis for the prevalent structural classification and the accepted views on the thermal history and origin of iron meteorites can be found in several exhaustive references (e.g., Goldstein and Short, 1967; Scott and Wasson, 1975; Buchwald, 1975).

For the compositional range of interest (5–20% Ni) at least 80% of the octahedral structure formed in the temperature interval (780 to 620°C) just below the γ→α transformation on the Ni-Fe phase equilibrium diagram (Goldstein and Ogilvie, 1965). This happens to coincide with the temperature range below the Curie point of the ferromagnetic α-phase (e.g., Hansen, 1958), in which a TRM could most effectively be blocked in the presence of a magnetic field. Since alloy phase separation and kamacite growth proceed simultaneously on cooling, a thermochemical remanence (TCRM) is a more correct assumption (Guskova, 1965a, b). However, studies on growth-CRM in alloys and transformation-CRM in terrestrial rocks and oceanic basalts have indicated that a TCRM cooling has similar characteristics to that of TRM, if acquired during an initial cooling (Kobayashi, 1959; Marshall and Cox, 1971; Merrill, 1975). Thus, upon finding that a hard NRM component is generally present in iron meteorites (which is surprising in view of their coarsely crystalline structure), Soviet workers reasonably concluded that this NRM is probably a paleo-TRM or TCRM (Guskova, 1965a, b; 1972, 1974). By comparing AF coercivity spectra and the thermal demagnetization of laboratory TRM's and of NRM, the Soviet scientists estimated that parent-body fields of 0.22–1 Oe (ave. 0.47 Oe) were needed during cooling below $T_c$ to imprint the NRM as a TRM/TCRM (e.g., Guskova, 1972, App. 1). Based on similar magnetic evidence from other classes of meteorites (stony, stony-irons), Guskova and Pochtarev (1967) suggested that all meteorites originated in a core-mantle differentiated planetary body, capable of sus-
taining core-dynamo magnetic fields of 0.4–0.9 Oe.

In attempting to establish the nature and origin of magnetization in the iron meteorites each assumption must be explicitly stated and logically distinct aspects must be separated. In the present work we have first tried to examine if these objects are capable of preserving a stable NRM. Previous Russian studies on modelling of NRM (see GUSKOVA, 1972) suggested that some can. Our own study of magnetic domain structure in iron meteorites identified the microkamacite grains in the fine-grained plessite \((\alpha+\gamma)\) intergrowths as a very high-coercivity (SD) grain fraction, certainly capable of retaining a primary magnetic memory (BRECHER and CUTRERA, 1976). The plessite fields occur typically at the centers of the narrow residual \(\gamma\) bands, which decompose to an ordered \((\alpha+\gamma)\) intergrowth during the late stage of primary cooling \((T<500^\circ\text{C})\). They may also form upon mild reheating, by a two-stage diffusionless transformation \(\gamma\rightarrow\alpha_s\rightarrow\alpha+\gamma\) (BUCHWALD, 1975, vol. 1, p. 95 et seq.).

Further evidence of the capability to carry a stable remanence is adduced in Sec. 3.1 below. However, the validity of the common assumption that ‘if they can, they do’ is tested experimentally. The pitfalls are well-illustrated in Sec. 3.2. Another important question is whether any laboratory simulation can adequately model the NRM acquisition. The major drawback in trying to simulate in the laboratory the magnetization processes, is that the slow cooling over periods of maybe 0.5 to 50 million years, in cores of planetary bodies tens to hundreds of km in size, cannot be possibly duplicated. This intrinsic limitation may not be as severe as it seems; on the contrary it is best to minimally modify the structure of the meteorites under study (Sec. 3.3) while otherwise assessing the relative importance of structure for magnetics, as described below. Our primary objective was to determine if the NRM of iron meteorites is clearly a record of ancient magnetic fields, or is in any way an artifact of their characteristic crystallographic structure. Both Fe and Ni have magnetocrystalline anisotropy, their easy axes—[100] and [111], respectively—depending on the sign of the anisotropy constant \(K_1\) (positive and negative, respectively) (CHIKAZUMI, 1964). For an alloy in the range of 0–20% Ni-Fe, \(K_1\) is always positive, so kamacite should have three ‘easy’ [100] magnetization axes, along which the internal magnetization would stabilize in zero-field cooling (CHIKAZUMI, 1964). This was confirmed by FONTON (1960) who showed that in the iron meteorite Boguslavka (hexahedrite, 5.46% Ni)—a single crystal of kamacite—[100] is the easiest magnetic axis and [111] the hardest. Both the [100]\(\alpha\) and the [111]\(\gamma\) axes are contained in the \(\alpha\{110\}\) set of planes, which coincide with the octahedral \(\gamma\{111\}\) planes of the host taenite. These can be traced on an oriented meteorite section, as described in Sec. 2, and then related to the magnetization directions. Another possibly important factor is the shape anisotropy of the kamacite plates. The finer the meteorite structural class (based on kamacite bandwidth), the larger the expected contribution from shape anisotropy.
Table 1

<table>
<thead>
<tr>
<th>Meteorite sample</th>
<th>Ni ( ^{1} )</th>
<th>B.W. ( ^{1} )</th>
<th>Cooling rate ( ^{2} ) (^{°}\text{C/my} )</th>
<th>NRM ( ^{3} ) (emu/cm(^2))</th>
<th>MDF ( ^{4} ) (Oe)</th>
<th>% NRM at 100 Oe</th>
<th>IRM_{s} ( ^{5} ) (emu/cm(^2))</th>
<th>IRM_{s}/NRM</th>
<th>Meteorite control</th>
<th>NRM ( ^{6} ) (emu/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babb's Mill (A) (Anom)</td>
<td>17.5</td>
<td>30 ( \mu \text{m} )</td>
<td>—</td>
<td>0.0285</td>
<td>210</td>
<td>85</td>
<td>&gt;3.81</td>
<td>&gt;13.3</td>
<td>Babb's Mill</td>
<td>0.0720</td>
</tr>
<tr>
<td>Butler, Off, (An)</td>
<td>15.72</td>
<td>0.15</td>
<td>0.4</td>
<td>2.06</td>
<td>245</td>
<td>79</td>
<td>&gt;5.41</td>
<td>&gt;2.6</td>
<td>Butler</td>
<td>3.22</td>
</tr>
<tr>
<td>Smith's Mt, (Omf) (HIB)</td>
<td>9.56</td>
<td>0.63</td>
<td>0.8-2</td>
<td>0.363</td>
<td>185</td>
<td>74</td>
<td>2.48</td>
<td>6.83</td>
<td>Smith's Mt, Carbo</td>
<td>0.0620</td>
</tr>
<tr>
<td>Carbo (Om) (IID)</td>
<td>10.15</td>
<td>0.85</td>
<td>1</td>
<td>0.327</td>
<td>18</td>
<td>14</td>
<td>2.58</td>
<td>7.89</td>
<td>Carbo</td>
<td>0.0234</td>
</tr>
<tr>
<td>Cosby's Creek (Og) (IA)</td>
<td>6.67</td>
<td>2.5</td>
<td>1-3</td>
<td>0.0274</td>
<td>15</td>
<td>12</td>
<td>0.48</td>
<td>17.5</td>
<td>Cosby's Creek</td>
<td>0.0265</td>
</tr>
<tr>
<td>Odessa (Ogg) (IA)</td>
<td>7.35</td>
<td>1.7</td>
<td>3</td>
<td>0.0434</td>
<td>15</td>
<td>6</td>
<td>0.747</td>
<td>5.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Coahuila (H) (IIA)</td>
<td>5.59</td>
<td>H ( ^{3} )</td>
<td>5( ^{6} )</td>
<td>0.144</td>
<td>45</td>
<td>19</td>
<td>0.93</td>
<td>6.4</td>
<td>Coahuila</td>
<td>0.138</td>
</tr>
</tbody>
</table>

1) Taken from Handbook of Iron Meteorites, 1975 (Buchwald); B.W.: Kamacite bandwidth.
2) Single kamacite crystal.
3) Determined by Goldstein and Short's (1967) rapid method.
4) Mean destructive field; alternating field value at which 1/2 NRM has been removed.
5) Saturation magnetization.

Fig. 1. (a) Fraction of NRM remaining as function of AF peak demagnetization field.
(b) NRM, total moment (emu/cm\(^3\)) as a function of demagnetizing field.
2. Experimental Methods

Samples of seven iron meteorites, representing a broad range of compositions and structures (Table 1) were obtained from the Harvard Museum (courtesy Prof. C. Frondel). Two adjacent cubes (~1 cm³) of each, were cut with a bandsaw, preserving their mutual orientation. The magnetic moments were measured with a SSM-1A Schonstedt Spinner Magnetometer. Control samples were stored in zero-field and periodically remeasured. The other samples were progressively AF demagnetized in up to ~1,000 Oe peak field, using an instrument equipped with a 3-axis tumbler and with 3 sets of Helmholtz coils nulling the DC field at the sample. Absolute and relative intensities and directional changes of NRM were recorded (Figs. 1 and 2). The samples were then given a saturation remanence (IRMₕ) in a 10 kOe field and

Fig. 2. NRM directions of samples under AF demagnetization and of the controls (C). Positive inclination indicates lower-hemisphere vector. Three directions for Carbo at 100 Oe are two measurements 24 hours apart (directions close) and recleaning. Two directions at 300 Oe are two measurements of initial cleaning 24 hours apart.
the AF cleaning process repeated (Fig. 3). Two orthogonal faces of each cubic specimen were ground, polished and etched to reveal the octahedral (Widmanstätten) pattern (Fig. 4). To infer the crystal orientation of each specimen, we used the surface-trace-analysis method on macrophotographs of etched faces (Barrett and Massalski, 1966) (Fig. 4): One cube face is used as the plane of projection (A) on

Fig. 3. (a)IRMₘ microcoercivity spectra of five iron meteorites. Absolute saturation remanence unknown for Babb’s Mill and Butler (>5 emu which is limit of spinner). (b) Absolute scale IRMₘ values (emu/cm³) vs. applied peak alternating field. A trend towards increasing single domain stability characteristics with decreasing kamacite bandwidth is indicated.

Fig. 4a. Method of orienting kamacite planes in host taenite. Plane A is the plane of projection on the stereonet. Great circle connecting a tracing on each surface is the projection of the corresponding γ{111} plane.
Fig. 4b. Macrophotographs of Butler (sample). A and B are tracings or kamacite planes which could be followed around the cube edge.
Fig. 5. Demagnetization characteristics of NRM, TRM, and TRM$_{h}$ for (a) Butler, (b) Smith's Mill. TRM$_{h}$'s are listed in order of heating for (a)–(c). In (d), zero-field and earth's field cooling were staggered; cross-hatched area shows that the TRM$_{h}$'s are remarkably similar so that no systematic changes in TRM$_{h}$ coercivity curves, although error limits are acceptable. Within each group of TRM$_{h}$'s (i.e., spontaneous and true) hardness increases with number of heatings.
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A stereonet. The intersection of A with the orthogonal etched cube face B is the reference NS axis. The tracing of the kamacite plates on A with respect to this edge give declination markings on the perimeter of the stereonet. The angles which kamacite plates on face B make with this edge correspond to inclinations with respect to face A. The great circle connecting the traces of the same kamacite plate on both A and B is the projection of its plane on the stereonet (Fig. 4). This method was successfully applied to the fine to medium-grained (Off, Omf, Om) octahedrites with evident octahedral etch patterns (Wasson, 1974). Ambiguities in tracing \( \gamma \{111\} \) planes were minimized by comparing the kamacite traces on the mutually oriented adjacent cubic samples of each meteorite. Traces identified on both polished cube

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>( \text{TRM}_0^0/\text{NRM} )</th>
<th>( \text{TRM}_0^1/\text{NRM} )</th>
<th>( \text{TRM}_2^1/\text{NRM} )</th>
<th>( \text{TRM}_3^1/\text{NRM} )</th>
<th>( \text{TRM}_1^1/\text{NRM} )</th>
<th>( \text{TRM}_2^2/\text{NRM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babb's Mill (A)</td>
<td>0.011</td>
<td>0.004</td>
<td>0.021</td>
<td>0.28</td>
<td>0.238</td>
<td>0.26</td>
</tr>
<tr>
<td>Butler (Off)</td>
<td>0.016</td>
<td>0.015</td>
<td>0.005</td>
<td>0.002</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Smith's Mt. (Omf)</td>
<td>0.112</td>
<td>0.037</td>
<td>0.028</td>
<td>0.277</td>
<td>0.312</td>
<td>0.311</td>
</tr>
<tr>
<td>Carbo (Om)</td>
<td>0.068</td>
<td>0.125</td>
<td>0.007</td>
<td>0.198</td>
<td>0.210</td>
<td>0.096</td>
</tr>
</tbody>
</table>

Fig. 6. (a) NRM and oriented kamacite planes in Butler (control). Solid lines are upper-hemisphere planes, dotted lines the lower-hemisphere complements. (b) NRM, TRM's and oriented kamacite planes in sample. Superscripts e, 0 indicate earth's- or zero-field for cooling; subscript indicates orientation of sample in space during cooling. "C" are high confidence planes mentioned in the text. NRM and all TRM's adhere to the kamacite planes.
faces are labeled ‘C’, for high-confidence planes in Figs. 6–8, whereas identifications based on different kamacite plates on each face yielded other possible sets of \( \gamma \{111 \} \) planes. By applying cubic symmetry as a constraint for angles between \( \gamma \{111 \} \) sets, we estimated our observational errors to always be <20°, whereas the errors in preserving the mutual alignment of the twin-cut cubic specimens were \( \simeq 10° \). The structureless ataxite (A, Ni-rich) and hexahedrite (H, all kamacite) specimens, as well as the very coarse octahedrite (Ogg) Odessa specimen could not be absolutely oriented relative to principal cubic crystal axes. The polishing, etching and absolute orientation of specimens were performed after initial NRM, IRM, and AF demagnetization measurements (Figs. 1–3), but prior to heating experiments. Then, they underwent a sequence of six brief (5 minutes) heatings at 800°C in a Schonstedt Thermal Demagnetizer (TSD-1). In the first three, they were cooled in zero field \( (<10\gamma) \) and in the last three, in known fields \( (\simeq 1 \text{ Oe}) \), each in a different orientation with respect to the ambient field. To separate thermal effects from field effects, this sequence was altered only for the ataxite (Table 2), by alternating zero-field and field-coolings (Sec. 3.2). The sixth heating and cooling were carried out in the refractory chamber, to prolong the cooling intervals from 10–20 minutes to \( \sim 45 \) minutes. All these times are too short to allow for diffusional phase changes although

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**Fig. 7.** (a) NRM and oriented kamacite planes in Smith’s Mt. (control). Plane of projection is different from that in Fig. 3 because previous plane was not a polished cube face. (b) NRM, TRM’s and oriented kamacite planes in the sample. See Fig. 6 for explanation of scripts. All except NRM and \( \text{TRM}_2^2 \) show some adherence to \( \gamma \{111 \} \), or equivalently, \( a \{110 \} \) kamacite planes.
diffusionless massive transformation is possible (Sec. 3.3). Only negligible surficial oxidation occurred during heatings in air. After each cooling, the moments were measured and fully AF demagnetized (Figs. 5–8). Following thermal treatments, the samples were again saturated and AF cleaned to assess magnetic-structural modifications (Fig. 9). Finally, Van Zijl's method (Cor and Grommé, 1973) was used to estimate paleointensities, by comparing the coercivity spectra of NRM, TRM and SM (Fig. 10).

Fig. 8. (a) NRM and oriented kamacite planes in Carbo (control). (b), (c) and (d) NRM and TRM's plotted with projections of kamacite planes. NRM, TRM₀, TRM₁ and TRM₂ show adherence to γ{111} planes.
3. Experimental Results and Analysis

3.1 *NRM and IRM*$_s$

The initial magnetic characteristics of the 7 iron meteorites under study are summarized in Table 1, together with their composition (Ni% contents), structural class cf. kamagate bandwidth (BW in mm) and metallographically inferred cooling rate (°C/my). Table 1 includes the NRM intensities for experimental and control samples. The NRM values are quite large and well clustered in the range $\sim 10^{-3}$–$1$ emu/cm$^3$. Differences in NRM moments between subsamples of the same meteorite may be as large as a factor of ten and attest to nonuniform magnetization. The relative NRM stability to AF cleaning is expressed both as mean destructive field (MDF) and as fraction surviving $\sim 100$ Oe cleaning (T.1). To better characterize the magnetic structure, the IRM$_s$ moments and IRM$_s$/NRM ratios are also listed in Table 1.

During daily NRM measurements, over an 8-day period for the controls stored in zero-field, the NRM remained stable in both magnitude and direction (Fig. 2).
Fig. 10

(a) BUTLER (OFF)
\( \times \) NRM vs TRM_0^0
\( + \) NRM vs TRM_1^0
\( \bullet \) NRM vs TRM_2^0

(b) 
\( \alpha \) exp.
--- 1
--- 66
--- 15
\( \times \) TRM_0^0 vs TRM_1^0
\( + \) TRM_1^0 vs TRM_2^0
\( \bullet \) TRM_2^0 vs TRM_0^0

(c) 
\( \times \) TRM_0^0 vs TRM_0^0
\( + \) TRM_1^0 vs TRM_1^0
\( \bullet \) TRM_2^0 vs TRM_2^0

(d) 
\( \times \) TRM_0^0 vs TRM_1^0
\( + \) TRM_1^0 vs TRM_2^0
\( \bullet \) TRM_2^0 vs TRM_0^0

(e) 
\( \square \) NRM vs TRM_0^0
\( \Delta \) NRM vs TRM_1^0
\( \bigcirc \) NRM vs TRM_2^0
For the samples group, the absolute NRM values and AF coercivity spectra are displayed in Fig. 1, with the corresponding directional changes shown in Fig. 2.

Two groups are resolved in Fig. 1, according to NRM stability: The harder group A is comprised of the ataxite (A), the finest (Off) and medium-fine (Omf) grained octahedrites. Group B shows a large soft NRM component and includes the coarser-grained meteorites: a medium (Om), coarse (Og) and coarsest (Ogg) octahedrite and the hexahedrite (H). Although the NRM stability clearly correlates with structural class, its intensity is a tradeoff between the grain-size of kamagate (coarsest in Off) and amount of kamagate (largest in H, which consists almost exclusively of α-phase, and smallest in A, which has little, though fine-grained, spindles of kamagate).

The same two magnetic groups are clearly resolved in the set of IRM$_s$ demagnetization spectra (Fig. 2), though the Om meteorite is now seen to belong to the magnetically harder group A. The IRM$_s$ spectra give clues to the capability for carrying a stable remanence, which again is clearly related to structural class, i.e., to the (effective) grain-size of the ferromagnetic kamagate. The IRM$_s$ values are roughly an order of magnitude larger than the NRM, confirming the predominance of multi-domain (MD) carriers. The evident trend is that both the intensity and the relative stability of NRM and IRM$_s$ increase from the coarser to the finer end of the kamagate-bandwidth spectrum.

With regard to the relative NRM directional coherence and stability, Fig. 1 shows it to also improve from the coarser-(H) to the finer (Off)-grained irons, excepting the ataxite (A). Several directional features are noteworthy: The NRM directions of sample and control coincide in the Off; have only similar inclinations in the H, Og, Om, and A; and are of opposite polarities in Omf. Sample and control NRM's lie in the same or in conjugate planes (small circles). Cleaned NRM directions may either cluster (as in Off, Omf and Og), or describe great-circle arcs (as for A and H), suggesting some type of planar confinement. The directional behavior does not correspond simply to the coercivity groups: The soft NRM components of Fig. 1 are apparently not secondary, as the directional clustering for H and Og indicate. Both soft and hard NRM components in Ogg and Om (Fig. 1) lack directional coherence (Fig. 2). The Off and Omf samples show high-coercivity and good directional convergence of NRM, so they may be assumed to carry a primary NRM. Further clues to the NRM directional behavior of octahedrites are obtained by reference to the principal crystallographic planes (Figs. 6–8): In the finest octahedrite (Off) Butler,
the NRM directions of both control and sample coincide and line up with the lower hemisphere intersection of two \( \gamma \{111\} \) octahedral planes (Fig. 6), to which they stay pinned during AF cleaning. In the medium-fine octahedrite (Omf) Smith’s Mountain the NRM directions of both sample and control cluster well, near the midpoint of the three nearest lower hemisphere intersections of \( \gamma \{111\} \) planes (Fig. 7). In Carbo (Om), the control NRM lies on one \( \gamma \{111\} \) plane, in the lower hemisphere; while the sample NRM falls on a different \( \gamma \{111\} \) lower-hemispheric trace. Under AF cleaning, the sample NRM changes polarity twice, but always stays close to the same \( \gamma \{111\} \) plane (Fig. 8). This behavior suggests that this \( \gamma \{111\} \) plane is an easy plane of magnetization, but lacks an easy axis.

3.2 Spontaneous (SM) and thermoremanent (TRM) magnetizations and their directional analysis

Four meteorites, deemed capable of having preserved a stable paleoremanence, were subjected to thermal and magnetic cycling (Sec. 2). The first three beatings, followed by zero-field cooling, produced spontaneous moments (SM) labeled TRM\(^0\),\(^1\),\(^2\) in Table 2 and Figs. 5–8. The next sequence entailed cooling in laboratory fields of 0.5–0.85 Oe to imprint a thermoremanence TRMe\(^0\),\(^1\),\(^2\). Only in the ataxite the sequence of zero- and field-coolings was staggered; results (Fig. 5d) showed that the order of the heating experiments is unimportant. However, the presence of an external field seems to influence the intensity of magnetization, although the moments do not vary in proportion to the applied field strength at cooling: The TRM\(^e\) values are typically 1/3–1/5 of the NRM intensity, whereas the SM values are one to two orders of magnitude smaller than the NRM (Table 2). However, note that for Butler (Off) the TRM\(^e\) and SM values are comparably low (1–0.1% of NRM). Moreover, for any two consecutive coolings in the same ambient field, the TRM may not change (e.g., in Omf and Om) or may decrease (e.g., in Off, Om and A). If the ambient field is varied from 0.5 to 0.85 Oe, the TRM value may stay the same (e.g., in Omf and Off) or even decrease (in A). Therefore, the field-proportionality assumption, crucial for the TRM hypothesis, is clearly not obeyed in these iron meteorites. The NRM is harder in AF demagnetization than all TRMe’s for the A, Off, and Omf irons, but considerably softer for Om. Within each group of TRM’s (i.e., spontaneous and true), magnetic hardness increases with each consecutive heating cycle. The spontaneous magnetization coercivity spectra also become more jagged and apparently undemagnetizable (Fig. 5) (Brecher, 1976a). As will be shown below, this is only an apparent magnetic hardening, possibly due to planar pinning of SM dictated by internal magnetic anisotropy, since the IRM\(_s\) following the heating cycles are actually softer (Fig. 9).

The corresponding directional behavior of TRM\(^0\) and TRM\(^e\)’s (Figs. 6–8) is more revealing of the underlying magnetization mechanism than the AF coercivity spectra. Of the three octahedrites, whose magnetization directions are plotted relative to the observed traces of \( \gamma \{111\} \) planes (Figs. 6–8), Butler (Off) shows most clearly significant results. Its three spontaneous moments (TRM\(^0\),\(^1\),\(^2\)) cluster along the upper hemisphere
intersections of pairs of $\gamma_{[111]}$ planes. Their directional coherence is preserved in stepwise AF cleaning, just like that of NRM. By comparison, the TRM$_{0,1,2}^e$ show considerable directional scatter. The TRM$^e$ polarity (in 2 out of 3 cases) differs from that of the ambient field at cooling, although initially they are roughly aligned with the field axis. With AF cleaning, the TRM$^e$'s either oscillate near the $\gamma_{[111]}$ plane closest to the direction of the ambient field or move about in a $\gamma_{[111]}$ plane.

In the case of Smith's Mt. (Omf) (Fig. 7), all moments show some degree of association with a $\gamma_{[111]}$ plane: they are directionally pinned to or migrating towards one. Now, the true TRM's show better directional coherence than the SM; upon repeated heatings the latter directions scatter increasingly and even change polarities and $\gamma_{[111]}$ plane affiliation. Only one TRM$^e$ direction coincides with that of the external field; the other two TRM$^e$ cluster on the $\gamma_{[111]}$ plane trace closest to the field direction, but with the proper polarity.

In Carbo (Om) all TRM's show greater directional scatter; only half (TRM$_{0,0,0,0,1,2}^e$) seem to be associated with a traced $\gamma_{[111]}$ plane. TRM$^e$ directions and polarities differ from those of the applied fields. However, just as for NRM, TRM reversals seem to take place within the same $\gamma_{[111]}$ plane.

The overall trend evident from an analysis of directional change patterns is that the finer the structural class, i.e., the narrower the kamacite bands, the better defined is the planar confinement of magnetization to the $\gamma_{[111]}$ planes, or to corresponding kamacite plates. This suggests that diminishing shape-anisotropy of kamacite plates relaxes the planar pinning of magnetization directions. Although not shown, all TRM's in the fine-grained ataxite are close to the same two conjugate great circles probably tracing $\gamma_{[111]}$ planes, within which the NRM's of both sample and control lie in Fig. 2.

Both the intrinsic anisotropy and the external field direction influence the directionality of magnetization, the former clearly dominating in the fine-grained meteorites. In the Off, the smooth coercivity spectra and the better directional stability of SM’s relative to true TRM’s are due presumably to stronger magnetization pinning to the kamacite plates. According to standard stability criteria, the SM’s produced in zero-field cooling of Butler (Off) mimic better the NRM than any of the TRM$^e$'s. In the coarser-structured meteorites, increasingly harder and more jagged AF demagnetization profiles (Fig. 5) do not correspond to worse directional scatter, but are the effect of planar pinning and resistance to randomization of grain moments by alternating fields. This is supported by the data of Fig. 9, which indicate the net changes in the IRM$_a$ coercivity spectra—and hence in effective magnetic grainsizes—produced by the six heating cycles.

### 3.3 Thermally induced changes

The changes in intensity of magnetization upon repeated heating (Table 2) might reflect loss of $\alpha$-phase by $\alpha \rightarrow \gamma$ transformation on heating, followed by metastable survival of $\gamma$ or by $\gamma \rightarrow \alpha$ transformation on cooling.

The IRM$_a$ intensity has decreased somewhat in all heated Group A iron meteorites.
and their AF coercivity spectra are softer (Figs. 3 and 9). The finer-grained specimens (A, Off) have undergone only modest changes, whereas the coarser (Omf, Om) have lost a substantial fraction of high coercivity magnetic carriers ($H_{AF} > 100$ Oe). The lower the Ni-content and coarser the structure (Table 1), the larger are thermally-induced changes in the magnetic size-spectra. This trend could either be interpreted in terms of magneto-textural changes, such as annealing (e.g., of Neumann bands in kamacite) and grain growth (e.g., of microkamacite in plessite) upon repeated thermal cycling; or as loss of $\alpha$-carriers related to the Ni-Fe phase transformations (Goldstein and Ogilvie, 1965; Goldstein and Short, 1967; Buchwald, 1975). Heating of kamacite to 800°C, into the $\gamma$-region, followed by rapid cooling probably leads to the formation of metastable martensite (a$_{2}$), whose magnetic properties are unknown. This supersaturated solution has the same chemical composition as the parent $\gamma$-phase (i.e., Ni-rich), so that it would have a lower magnetization than the original $\alpha$-phase. Since the BCCa$_{2}$-plates have the same crystal habit as the BCC kamacite, the directional association of magnetization with these planes would probably not be affected. It is possible to explain the loss of the high-coercivity magnetic carriers, if we assume that the microkamacite in the Ni-rich plessite ($\alpha + \gamma$) regions transforms to $\gamma$-phase on heating, which survives metastably on cooling, thus no longer contributing to the IRM$_{a}$ spectra. Indeed, Buchwald (1975, vol. 1, p. 94) shows that 10 minutes at 800°C suffice to homogenize submicroscopic ($\alpha + \gamma$) mixtures to taenite. All effects could account for the lower magnetization intensities upon heating (Table 2 and Fig. 9).

3.4 Paleointensity estimates: how meaningful?

In this paper, we have adopted the Van Zijl method for estimating paleointensities, in which the residual NRM fraction is compared to the respective TRM residual at each step of the AF cleaning process (Coé and Grommé, 1973). This method has been successfully applied earlier to derive paleofield strengths for other types of meteorites with an apparently stable and primary NRM component (Brecher, 1972; Brecher and Ranganayaki, 1975). The complete procedure is illustrated for Butler (Off) in Fig. 10. The paleofield values are obtained from the slopes (a) of the linear segments of normalized NRM vs. true TRM, assuming that the customary proportionality relation NRM/TRM=H$_{\text{anis}}$/H$_{\text{lab}}$ holds (Table 3). For the coarser Omf and Om irons, the average paleofields (1 and 0.34 Oe, respectively) are within the range

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>TRM$_{0}$ (Oe)</th>
<th>TRM$_{1}^a$</th>
<th>TRM$_{2}^a$</th>
<th>Avg.</th>
<th>TRM$_{3}^a$</th>
<th>TRM$_{4}^a$</th>
<th>TRM$_{5}^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babb's Mill (A)</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Butler (Off)</td>
<td>2</td>
<td>*</td>
<td>2.8</td>
<td>2.4</td>
<td>1.8</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Smith's Mt. (Omf)</td>
<td>1.1</td>
<td>1.1</td>
<td>0.8</td>
<td>1.0</td>
<td>5</td>
<td>2</td>
<td>*</td>
</tr>
<tr>
<td>Carbo (Om)</td>
<td>0.34</td>
<td>0.34</td>
<td>0.52</td>
<td>0.43</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Unable to obtain estimates for $H$, because of scatter and/or nonlinearity.
of Guskova's (1965a, b) values. For the finer-grained A and Off, however, stronger fields (1.7 and 2.4 Oe, respectively) are obtained, in view of the higher AF stability of NRM relative to laboratory TRM's (Fig. 5). These estimates cannot be taken at face value because of the evidence discussed in Sec. 3.2, which suggests that the external magnetic fields do not simply determine either the intensity, direction, or the AF stability behavior of TRM, although the TRM intensity relative to NRM and TRM may reflect the presence of a field (Table 2). Fictitious values for the ambient field are obtained even for zero-field cooling, if one solves for \( H_{\text{inh}} \) using \( H_{\text{anc}}/H_{\text{inh}} = \text{NRM/TRM}^0 \) (Table 3): these range from \( \sim 2 \) Oe to \( \sim 5 \) Oe for Butler (Off) (Fig. 10(e)). The internal consistency of these results, predicated on the existence of roughly linear segments in plots such as Fig. 10, is fair: Fig. 10(b) shows that the observed TRM slopes for paired TRM's follow roughly the expected slopes, within a tolerance factor of 1.5. Paired spontaneous moments TRM also follow the expected slope (Fig. 10(d)). Finally, 10(c) and 10(e) confirm that apparent 'paleofields' for zero-field coolings exceed the values of both applied laboratory fields and of the estimated ancient fields (Table 3).

4. Concluding Remarks

Magnetic fields are known to permeate space; be they of internal (planetary) or of external (solar) origin, they seem to have left some imprint on both terrestrial and extraterrestrial (lunar and meteoritic) rocks. Earlier work on deciphering the magnetic record locked in the most primitive meteorites available (the carbonaceous chondrites) indicated that relatively strong magnetic fields (\( \sim 1 \) Oe), comparable to earth's field, were present when they formed as the solar system was coming into being (Brecher, 1972; Butler, 1972; Banerjee and Hargraves, 1972). In the present work we have carefully separated the two logically distinct questions of whether the iron meteorites are capable of preserving such a paleoremanence and whether they actually do. By standard reliability criteria used in terrestrial paleomagnetism, a 'prima facies' case could be made that iron meteorites carry an original paleoremanence of TRM/TCRM type. Upon careful probing, this hypothesis however plausible, is shown to be invalid. Our results show that, in fact, no reliable information on their early magnetic environments can be retrieved from iron meteorites. The natural (NRM), thermal (TRM) and spontaneous (SM) magnetization in iron meteorites are directionally influenced by the octahedral structure. The \( \gamma \{111\} \) planes of the host taenite, on which the \( \alpha \{110\} \) oriented plates of kamacite have nucleated and grown, are 'easy' preferred planes of magnetization, whose intersections define 'easy' magnetic axes. All the above types of magnetization tend to align with any one of these axes and to be confined ('pinned') to one or several of the preferred planes during progressive demagnetization. The laboratory thermoremanence (TRM) can align with an external magnetic field direction only if the field lies in or close to an octahedral plane, and diverges upon AF cleaning. The finer the crystalline structure, the stronger is its control of magnetization directions. Moreover, the relative stability of mag-
netization, whether acquired in cooling below the Curie point in zero-field (SM) or in earth's magnetic field (TRM), is comparable. Thus, spurious apparent paleofield intensities of $\sim 1$ Oe are obtained even for zero-field cooling. However, the magnitudes of true TRM are up to an order of magnitude higher than those of SM, excepting Butler (Off). TRM values are, in turn, considerably below the NRM levels. Therefore, even if the NRM intensity may be taken to indicate the presence of an external field during primary cooling, it is difficult to extricate any information on its strength and direction. Hence, the earlier conclusion of Soviet colleagues that iron meteorites, as pieces of planetary cores, carry the magnetic record of core-dynamo fields now appears doubtful. The strong and stable magnetization of iron meteorites may conceivably be merely spontaneous ferromagnetism, which has been directionally stabilized along and in energetically favorable 'easy' axes and planes defined crystallographically, through a combination of magnetocrystalline anisotropy and shape anisotropy of the kamacite needles and plates. These preferred directions may not necessarily be coherent on a larger scale (magnetic directions may differ in two adjacent cut cubes of an iron meteorite), so that asteroidal chunks of meteoritic iron may not be uniformly magnetized. However, the finer the metallographic structure, the stronger and more coherent the natural magnetization seems to become. The trend of increasing apparent paleointensity with decreasing kamacite bandwidth (Table 3) might be attributed to the higher spontaneous moments of finer grains and to more pronounced planar pinning.

There is some evidence that anisotropy effects associated with Ni-Fe carriers may be important in chondritic meteorites and in lunar rocks as well. Stacey et al. (1961) had noted a remarkable 'memory effect' for the stable, high-$T$ (600–800°C) NRM component in chondrites, which reappeared, after repeated demagnetizations, with the same intensity and direction upon cooling from $T_c$. This is probably related to the pronounced anisotropy ($K_{max}/K_{min} \sim 1.4–2.1$) found in chondrites (ibid., Wearing, 1961). A similar memory effect and a strong magnetization following zero-field cooling from 800°C were reported in the lunar soil breccia 14301 by Dunn and Fuller (1972). Together with evidence for appreciable magnetic anisotropy and for texture-related directional confinement of NRM in a variety of lunar rocks (Brecher, 1976a, 1977), it seems probable that any extraterrestrial TRM may have been considerably modified or distorted by anisotropy effects.

Although it is disappointing that magnetic evidence from iron meteorites cannot be used with confidence to extract information on any ancient magnetic fields, it promises to provide a useful classification tool and may serve to confirm cogenetic groups of iron meteorites. Also, since these strong and ductile natural alloys are representative of an important class of man-made permanent-magnet materials, namely the diffusion-hardened alloys, it is possible to gain insight into the types and importance of magnetic anisotropy energies which control magnetic-field annealing of such alloys.
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