Ancient stable magnetism of the Richardton H5 chondrite

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Abstract

Investigating mineral magnetic properties of meteorites is essential to understanding the formation and evolution of planetary bodies in the solar system. In order to decipher ancient magnetic records, demagnetization experiments were carried out for the ~4550 Ma Richardton H5 chondrite. Alternating-field demagnetization revealed a soft fraction as well as a hard fraction. Conventional thermal demagnetization in air showed severe alterations. But, a few thermal demagnetizations in vacuum were successful in isolating a stable paleomagnetic record. On the basis of microscopic analysis, we found that fine-grained clinopyroxene-hosted kamacite is abundant, responsible for the stable and permanent magnetic record of Richardton. The experimental data imply a thermal or thermochemical origin for the stable paleomagnetic record of Richardton. However, the possibility of pressure (re)magnetization cannot be evaluated because the effect of pressure on magnetization for the Fe–Ni system is unknown.

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1. Introduction

As the most common type of meteorites, chondrites originate from debris of the solar nebula (e.g., Hutchison, 2004; Zanda, 2004). Due to their unique origin, chondrites are regarded as the sole witness for the formation of the early solar system. Despite such importance in unraveling the history of the early solar system, intensive scientific investigation on meteorites has been limited mainly because of the scarcity of the available samples and because meteorites are easily altered when reheated (e.g., Pellis and Storzer, 1981; Clayton, 1993). For instance, samples are hardly recyclable in other scientific investigation once they were heat-treated.Paleomagnetic analysis of meteorites is of particular interest because it provides basic information on the evolution of planetary material (e.g., Nagata, 1979, 1980; Wasilewski and Dickinson, 2000; Weiss et al., 2000; Antretter et al., 2003). In particular, deciphering the origin of natural remanent magnetization (NRM) of chondrites bears broad implications for asteroidal differentiation and collision. Perhaps the biggest challenge of meteoritic research is the fact that extraterrestrial materials display unstable magnetic behavior under heating (e.g., Fuller, 1974; Cisowski, 1986; Pearce et al., 1976; Yu and Gee, 2005). To date, the best well-known experimental design that may minimize mineralogical alteration during heating is the double-buffering approach (Taylor, 1979). In addition to thermal instability, the effect of shock demagnetization/remagnetization needs to be considered in analyzing extraterrestrial NRM. According to recent tests (e.g., Funaki et al., 2000; Gattacceca et al., 2006, 2008a,b; Gilder et al., 2006; Bazaeva et al., 2007a), terrestrial iron-oxides are easily influenced by mild shocks of < 2 GPa. It is also noteworthy that the shock-induced remanence is about an order less intense than the thermoremanent magnetization (TRM).

As an equilibrated ordinary chondrite (H5) (van Schmus and Wood, 1967), the Richardton meteorite fell on Earth on July 21, 1919 (Quirke, 1919). A total of ~90 kg of stony meteorite material was retrieved at Richardton, North Dakota, USA (Quirke, 1919). Richardton was classified as an S2 meteorite which corresponds to a shock pressure of 5–10 GPa on the Stöffler et al. (1991) scale (Grady, 2000). A Pb–Pb isochron dates the Richardton meteorite at 4550 ± 2.6 Ma using multiple phosphate fractions (Amelin et al., 2005). Compared to finds, falls may represent fresher and less weathered meteorite although both falls and finds are not free from artificial magnetic contamination (Wasilewski and Dickinson, 2000).

In the present study, we use NRM to determine the stable paleomagnetic record of the Richardton chondrite. In addition to conventional alternating-field (AF) demagnetization and thermal demagnetization in air, thermal demagnetization on vacuum-sealed samples was also carried out. A number of rock magnetic tests such as low-temperature cycling of isothermal remanent magnetization (IRM) and demagnetization of saturation isothermal remanent magnetization (SIRM) were also included.

2. Experiments and results

Fourteen individual chondrite samples (287–619 mg) of Richardton were used in this study. Stepwise AF demagnetization
Fig. 1. Alternating-field (AF) demagnetization of Richardton chondrite samples. (a) Intensity variations of R1 and R2. Nearly half of natural remanent magnetization (NRM) remained undemagnetized even at 100 mT. (b) Directional stability of NRM for R1 during AF demagnetization in vector projection. Solid and open squares represent up versus east and up versus north, respectively. Grey arrows show a linear extrapolation of NRM trending towards the origin. was carried out using a Molspin AF demagnetizer. AF demagnetization showed that Richardton has a stable remanence with (at least) two components. A low-coercivity component (less resistant to AF demagnetization), reflecting ~10% of the NRM, was eliminated at 30 mT (Fig. 1a). On the other hand, a high-coercivity fraction (more resistant to AF demagnetization) represented substantial fractions of the NRM. These high-coercivity fractions were unaffected even at the highest available AF (Fig. 1a), although a linear extrapolation of NRM trended towards the origin (Fig. 1b).

To overcome such incomplete demagnetization, a stepwise thermal demagnetization was carried out using independent AF-untreated samples. At first, conventional thermal demagnetization (in air) was carried out for two samples to examine the effect of alteration. Throughout all heat treatments, temperatures were reproducible within ±1.6 °C. The residual field in the furnace during the entire heating-cooling processes was <120 nT. As anticipated, thermal demagnetization in air showed unstable demagnetization behavior (Fig. 2a). On stereo projections, NRM directions migrated substantially during demagnetization for 30–500 °C (more than 30° in declination and 20° in inclination) (Fig. 2b). From 500 to 700 °C, NRM declination remained relatively constant while inclination alternated between 37° and 52° (Fig. 2b). It is apparent that Richardton contained unstable material when heated in air (Fig. 2). Unfortunately, we were unable to extend thermal demagnetization beyond 700 °C due to the temperature limit of the commercial oven.

To minimize the effect of thermal alteration, the remaining ten chondrite samples were treated as suggested by Taylor (1979). Each sample was tightly wrapped with quartz wool and placed inside quartz capsules. Double-buffered-encapsulation was adopted, after which the samples were vacuum-sealed (Taylor, 1979). Thermal demagnetization results for seven samples showed unstable NRM behavior during heating. Fortunately, three samples (R7, R10, and R12) yielded fairly stable thermal demagnetization data (Fig. 3).

Perhaps the most convincing evidence for the presence of a stable remanence for Richardton is the fact that intensity variation curves for the three samples are similar (Fig. 3a–c). In these samples, higher unblocking temperature fractions (400–700 °C) all converge towards the origin in vector projections (Fig. 3d–f). Unfortunately, comparing quantitative directional similarity between/among samples is impractical because unoriented chips were used. As a result, a rigorous test of the uniform magnetization within the meteorite was not available. In fact, two conflicting scenarios are possible at this stage. If an identical direction for the higher unblocking temperature fractions for all samples is assumed, it is trivial to show that lower unblocking fractions were oriented in different directions in each chondrite sample (Fig. 3). A similar scattered distribution of the soft fraction of NRM was also observed from

Fig. 2. Thermal demagnetization of R3 in air. (a) Intensity variation and (b) directional changes on a stereo plot show unstable NRM behavior due to alteration.
the 4.0–4.5 Ga Martian meteorite ALH 84001 (e.g., Antretter and Fuller, 2002). On the other hand, if an identical direction for the lower unblocking temperature fractions for all samples is assumed, higher unblocking temperature fractions are oriented in different directions in each chondrite sample. This is analogous with a randomly oriented high-coercivity fraction observed from the Bensour LL6 meteorite (e.g., Gattacceca et al., 2003). Indeed, observing mm-scale NRM heterogeneity is surprisingly common in meteorites (e.g., Morden and Collinson, 1992; Collinson and Morden, 1994; Gattacceca et al., 2003).

As most magnetic material in terrestrial rocks displays characteristic low-temperature variation, it is important to determine the temperature dependence of IRM at low-temperatures (10–300 K). In the present study, all low-temperature experiments were carried out using a Quantum Design MPMS at the Institute for Rock Magnetism, University of Minnesota. Warming of low-temperature IRM (generated at 10 K in a field of 2 T) showed a continuous decay of magnetization (Fig. 4a). In particular, the maximum variation of remanence was observed ∼50 K (grey line in Fig. 4a), suggesting the possible presence of Cr-spinel or kamacite (Kohout et al., 2007). In Richardton, it is likely that kamacite is responsible for the remanence drop at ∼50 K because Cr-spinel is absent (see Section 3).

Continuous measurement of room-temperature IRM (2 T was applied at 300 K) during zero-field cooling (300–10 K) and warming (10–300 K) was also monitored (Fig. 4b). The results were somewhat reversible at <150 K but irreversible at >150 K. Warming recovered ∼85% of initial remanence (Fig. 4b). In general, such high memory
ratio indicates the presence of fine-grained iron-oxides in terrestrial rocks (e.g., Özdemir et al., 2002).

3. Microscopy, rock magnetic analysis, and NRM/SIRM ratio

Previous studies have shown that isolating stable paleomagnetic information from meteorites is extremely difficult due to the easy of alteration during magnetic treatment at ambient temperatures (e.g., Fuller, 1974; Cisowski, 1986; Pearce et al., 1976). Such intrinsic difficulty is of nature and derived from the different crystallization environment (e.g., oxygen fugacity and temperature) compared with the laboratory heating. In the present study, relatively stable decay of NRM on thermal demagnetization was observed from the three (out of ten) samples that were double-buffered-encapsulated. Then, what is responsible for such a stable remanence? We failed to completely demagnetize the entire NRM due to inherent limitation of the highest available heating temperature in the commercial oven used. Thus, ~7–12% of NRM still remained undemagnetized at 700 °C for R7, R10, and R12 (Fig. 3). Applying a simple linear extrapolation for R7, R10, and R12 yielded maximum unblocking temperatures ($T_{UBmax}$) of ~710 °C, ~720 °C, and ~750 °C, respectively (Fig. 3a–c). It is apparent that R7 displayed the best quality data with no kink at ~600 °C (Fig. 3a). It can be interpreted that higher $T_{UBmax}$ of ~720 °C and ~750 °C for R10 and R12 resulted from slight alteration as evidenced by the small kink at ~600 °C (Fig. 3b–c).

A high Curie point of >700 °C may be explained by the composition of kamacite in the Fe–Ni system. To confirm this, the composition of the opaque phase in the Richardton was determined using a scanning electron microprobe JEOL JXA-8600. Daughter samples of R3 and R7 were analyzed. It should be noted that R3 and R7 showed the most and least alteration during heating, respectively. Both samples contain abundant elongate kamacite with grain sizes of 5–20 μm in length within clinopyroxene (Fig. 5a). Silicate-hosted Fe–Ni phases have been documented in other meteorites (e.g., Uehara and Nakamura, 2006), and are analogous to iron-oxides within silicates in terrestrial Precambrian rocks (e.g., Selkin et al., 2000; Yu and Dunlop, 2001; Renne et al., 2002). However, kamacite in the altered R3 sample (Fig. 2) is dominantly distributed along clinopyroxene boundaries (Fig. 5b). In this altered R3 sample, two interesting features exist. First, kamacite is massive with grain size over 100 μm in length (Fig. 5b). Second, kamacite was zoned to oxidized margins (Fig. 5b). The mineralogy of the chondrite will be described elsewhere.

To determine the possibility of potential artificial contamination of NRM during initial sample collection and curation, it is necessary to compare the demagnetization characteristics between NRM and SIRM. SIRM was applied using an ASC Scientific IM-10 impulse mag-
netizer, with a maximum applied field of 1 T. SIRM was two orders of magnitude larger than the NRM or NRM*. NRM* was calculated by projecting the low-coercivity or lower unblocking fractions towards the direction of high-coercivity or higher unblocking remanences, respectively. AF and thermal demagnetization trends for NRM (and NRM*) and SIRM are significantly different both in raw scale and in a normalized scheme (Figs. 6 and 7). Considering the distinctively different decay trends and magnitude contrast, artificial contamination of Richardton can be ruled out.

Comparison of NRM (or NRM*) over SIRM as a function of demagnetization field provides the variation of REM ratio (Wasilewski and Dickinson, 2000). Both NRM/SIRM and NRM*/SIRM increased as the AF increased (Fig. 8). For magnetite, this trend simply reflects the presence of a fine-grained phase (Yu, 2006). It is true that REM alone cannot provide a precise estimate of ancient planetary magnetic field intensity (Yu, 2006). The biggest ambiguity originates from the types of NRM, as REM was calibrated mostly by the ratio between TRM and IRMs. Unfortunately, meteoritic NRM can be of non-TRM origin, including shock-induced and chemical remanences. Furthermore, anisotropy originating from grain shape is another source of uncertainty in using REM (Yu et al., 2007). Nevertheless, REM is still useful in meteoritic research because it avoids heating and therefore provides a crude estimate of the strength of the planetary paleomagnetic field (e.g., Gattacceca and Rochette, 2004; Kletetschka et al., 2004). An empirical scaling law for various magnetic materials was provided by Kletetschka et al. (2004). Although experimental data for kamacite (Fe$_{95}$Ni$_5$) is unavailable, an approximation of the paleofield for Fe and the Fe–Ni system is 35–300 $\mu$T (Kletetschka et al., 2004, 2006). It remains to be confirmed whether this estimation is valid using the Thellier-type double heating paleointensity technique.

4. Discussion

The mean composition of the magnetically stable kamacite in Richardton is Fe$_{95}$Ni$_5$ (Table 1). The theoretical Curie point of Fe$_{95}$Ni$_5$ based on the phase diagram by Yang et al. (1997) is ~720 °C, agrees well with the estimated $T_{UB}^{\text{max}}$. Rock magnetic analysis is consistent with the presence of fine-grained kamacite being the dominant magnetic phase. It is worth noting that AF demagnetization of NRM (or NRM*) showed a sigmoidal hump (Fig. 6) and thermal demagnetization revealed a sharp remanence drop near the maximum unblocking temperature ranges (Fig. 7). Contrary to such NRM demagnetization characteristics, more widely distributed coercivity spectra (Fig. 6) and unblocking temperature spectra for SIRM (Fig. 7) are observed, commonly referred as a Lowrie–Fuller test (Lowrie and Fuller, 1971). These contrasts in demagnetization characteristics between NRM and SIRM are generally regarded as an indication of fine-grained remanence carriers in rocks (e.g., Dunlop and West, 1969; Lowrie and Fuller, 1971). In addition, the presence of a fine-grained NRM carrier was also inferred from the low-temperature data (Fig. 4) and from an increasing REM trend (Fig. 8) based on analogy between the Fe–Ni system and iron-oxides. Overall, such rock magnetic results agree well with the presence of 5–20 $\mu$m kamacite grains. In Richardton, such

![Fig. 7](image1.png)

**Fig. 7.** (a) Thermal demagnetization of natural remanent magnetization (NRM) and saturation isothermal remanent magnetization (SIRM). NRM* was calculated by projecting the lower unblocking fractions towards the direction of higher unblocking remanences. (b) Same data as in (a) but presented as curves normalized to the initial NRM, NRM*, or SIRM.

![Fig. 8](image2.png)

**Fig. 8.** The NRM/SIRM and NRM*/SIRM ratio as a function of alternating-field (AF). The ratio increases together with the AF.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>EPMA analyses and mean composition (wt%) of ten kamacite grains in the Richardton chondrite.</th>
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<tbody>
<tr>
<td>Element</td>
<td>Range</td>
</tr>
<tr>
<td>Fe</td>
<td>91.62–96.35</td>
</tr>
<tr>
<td>Ni</td>
<td>3.45–7.38</td>
</tr>
<tr>
<td>Si</td>
<td>0.00–0.73</td>
</tr>
<tr>
<td>Mg</td>
<td>0.00–0.16</td>
</tr>
<tr>
<td>Ca</td>
<td>0.00–0.18</td>
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<td>Co</td>
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grain sizes probably reflect pseudo-single-domain (PSD) kamacite because the critical single-domain (SD) size of Fe is less than 23 nm (Kneller and Luborsky, 1963).

While the observed thermal demagnetization results indicated that kamacite (Fe50Ni50) is responsible for the stable remanent magnetization in Richardton, little is known about the ancient NRM acquiring mechanism and environment. The most extreme idea would be that the NRM of thermal origin was acquired at ~4550 Ma. The best experimental evidence that favors our proposition is the stable remanent magnetization carried by fine-grained kamacite within silicates. Survival of ancient magnetization from later disturbance such as intensive viscous contamination (e.g., Nagata, 1980) or shock-induced remagnetization (e.g., Funaki et al., 2000; Bazaeva et al., 2007a) is possible because kamacite was embedded within clinopyroxene. Furthermore, such silicate-hosted NRM carriers also explain stable NRM decay on heating.

However, to validate NRM of possible thermal origin, there are three points to be clarified. First, although kamacite with a Ni content <30% is known to be stable, it easily transforms to taenite on heating (Yang et al., 1997). Furthermore, such transformation (kamacite to taenite) and restoration (taenite to kamacite) can both occur (sometimes reversible but not always). Thus, we cannot rule out the possibility of a thermo-chemical remanent magnetization (TCRM) origin of NRM. Second, although the thermal evolution model suggests a thermal equilibrium at high temperatures around 5 Ma since the onset of asteroidal accretion (Amelin, 2005), such a model does not necessarily indicate NRM of thermal origin. For instance, an estimated slow-cooling rate of 26 K/Myr (Amelin, 2005) is better suited to the TCRM model than TRM. A third problem is whether TRM or TCRM, or both assumed the presence of magnetic field in the parental asteroid body, although shock-induced demagnetization/remagnetization may completely reset the pre-existing remanence at a later time.

Contrary to the suggestion of primary NRM recording an ancient solar system field, three important arguments that favor shock-related reset of magnetization should be noted (e.g., Funaki et al., 2000; Bazaeva et al., 2007a). First, it is necessary to consider whether shock pressure on Richardton in the past was large enough to reset its magnetic history. As mentioned earlier, Richardton was classified as an S2 chondrite with an estimated shock pressure of 5–10 GPa (Stöffler et al., 1991). According to Wasilewski (1976), pure iron becomes antiferromagnetic at 13 GPa and ferromagnetism is restored on pressure decrease. The transition pressure (from ferromagnetism to antiferromagnetism) is decreased with increasing Ni content (Wasilewski, 1976). Pressure of 5–10 GPa can definitely reset the magnetization of Fe50Ni50, but may not affect a composition of Fe50Ni50. Second, preliminary data on pressure demagnetization for various chondrites indicate a substantial remanence loss (Bazaeva et al., 2007b). For instance, a typical H chondrite lost 30% of NRM at 1 GPa (Bazaeva et al., 2007b). Third, shock-induced remanence could significantly modify (and sometimes completely reset) the pre-existing NRM. According to Gattacceca et al. (2006, 2008a,b), terrestrial iron-oxides would not survive mild shocks of <2.0 GPa.

In magnetic analysis on meteorites, an empirical relation for the Fe–Ni system on the effect of pressure in acquiring and losing magnetization as known for iron-oxides (e.g., Rochette et al., 2003; Gilder et al., 2006; Bazaeva et al., 2007a) is urgently required. Without such information, stating an affirmative description on the origin of NRM would be premature.

5. Conclusions

1. The Richardton chondrite possesses an ancient stable magnetization of high-coercivity that cannot be completely erased with nominal alternating-field demagnetizations.

2. Thermal demagnetization in air showed severe alterations, whereas thermal demagnetization under vacuum condition yielded stable magnetizations.

3. The stable paleomagnetic record of Richardton resides in clinopyroxene-hosted kamacite (Fe50Ni50).

4. A possible interpretation of the NRM of Richardton is a thermal or thermochemical origin acquired ~4550 Ma. In order to validate such a proposition, an empirical relation between the NRM and the effect of pressure for the Fe–Ni system is urgently required.

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