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A linear field dependence of thermoremanence in low magnetic fields

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Abstract

We tested a linear field-dependence of thermoremanent magnetization (TRM) to saturation isothermal remanent magnetization (SIRM) ratio for magnetite-containing natural samples. The TRM/SIRM shows a linear field-dependence to very low field ranges (<1 μT). This observation is at odds with a claim of limited sensitivity at low fields in TRM acquisition documented in previous studies. We attribute the difference to poor field control in the ovens used in previous studies. The TRM/SIRM ratio shows a grain-size dependence. For magnetite-containing samples with insignificant anisotropy, the TRM/SIRM is most efficient in pseudo-single-domain magnetites. These results suggest that while the TRM/SIRM ratio is linear at low field strengths, the ratio provides only a crude estimation on the actual paleo-field within two orders of magnitude, suggesting that a careful sample characterization is necessary in applying the TRM/SIRM as a paleointensity proxy.

Keywords: Thermoremanent magnetization (TRM); Saturation isothermal remanent magnetization (SIRM); Paleointensity; Magnetite; Linear field dependence

1. Introduction

Intensity of ancient planetary magnetic fields provides clues to the early evolution of planets and asteroids in the solar system. Despite its importance, data constraining the past intensity of magnetic field of planetary bodies remain scarce. This scarcity mainly originates from the difficulty in finding suitable material because meteorites easily alter during repeated laboratory heating in Thellier-type (Thellier and Thellier, 1959) paleointensity determinations (e.g., Fuller, 1974; Cisowski, 1986). Thus, an alternative normalization technique using the ratio of natural remanent magnetization (NRM) to the saturation isothermal remanent magnetization (SIRM) with no heating would be an attractive alternative (e.g., Cisowski, 1986; Fuller et al., 1988) if it could be shown to give reasonable bounds on paleofield strength. Indeed, the ratio of NRM/SIRM has been applied to extraterrestrial material in order to constrain the ancient magnetic field intensity of planetary bodies (e.g., Wasilewski, 1981; Wasilewski and Kletetschka, 1999; Wasilewski and Dickinson, 2000; Wasilewski et al., 2002; Gattacceca et al., 2003; Kletetschka et al., 2003, 2004, 2006; Gattacceca and Rochette, 2004).

Using the NRM/SIRM ratio as a paleointensity proxy relies on the classical thermal fluctuation theory of single-domain (SD) grains (Néel, 1949). For an

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ensemble of randomly oriented non-interacting uniaxial SD grains, the ratio of thermoremanent magnetization (TRM) to SIRM is represented as follows:

$$\frac{M_{\mathrm{trm}}(\boldsymbol{B}_0)}{M_{\mathrm{rs}}} = \tanh\left[\frac{VM_{\mathrm{s}}(T_{\mathrm{B}})\boldsymbol{B}_0}{kT_{\mathrm{B}}}\right]$$

in which V is the grain volume, M_{s} the spontaneous magnetization (=480 kA/m for magnetite at room temperature), T_{B} the blocking temperature, $\boldsymbol{B}_0$ the applied field, and k is the Boltzmann's constant. Neel's SD theory predicts a linear field-dependence of TRM/SIRM only for a very limited grain-size range of magnetite (e.g., 40–80 nm; see Fig. 1 in Yu (2006)). Instead, a non-linear field dependence appears in >80 nm magnetite according to the calculation. In fact, a non-linear field dependence for non-uniformly magnetized magnetites is commonly observed for magnetite (Dunlop and Argyle, 1997). A complementary mathematical and experimental treatment on the non-linear field dependence for non-uniformly magnetized magnetites is beyond the scope of this study, but was provided by Dunlop and Argyle (1997).

In recent studies, Kletetschka et al. (2004, 2006) claimed an empirical relation between the efficiency of TRM/SIRM and the saturation magnetization. In particular, a simple linear field dependence of TRM/SIRM was observed for magnetites regardless of the grain size (see Fig. 1B in Kletetschka et al. (2006)). It is likely that such linearity disappears due to experimental uncertainty in low magnetic field ranges (<10 μT) in Fig. 1B of Kletetschka et al. (2006). In the present study, our goal is to provide high quality TRM acquisition in very low fields (<10 μT). The previous results were obtained in a Schoenstedt oven with poor temperature and field control. Our experiments have been carried out in an oven with excellent field and temperature control and we have failed to reproduce the non-linearity observed at low applied magnetic fields.

2. Samples

We selected seven magnetite-containing natural samples for which the magnetic and paleomagnetic properties of the samples are well documented (Yu, 1998; Yu and Dunlop, 2001, 2002). For a sample set here called SD, with remanence carrying minerals in the SD grain size range, we used three specimens from the Tudor Gabbro (Ontario, Canada) which yielded excellent paleointensity data (Yu and Dunlop, 2001). For typical pseudo-single-domain (PSD) and multidomain (MD) sample sets, we used two basalts (Yu, 1998) and two gabbros (Yu and Dunlop, 2002), respectively. These samples in the PSD and MD sets were rejected in previous paleointensity work because of their non-linear Arai plots. Importantly, during the initial paleointensity work, none of the samples from the SD, PSD, or MD sets showed any indication of alteration during repeated heatings; all the samples passed the partial TRM check within 5% at all temperature ranges.

We used magnetite-containing natural samples with insignificant anisotropy. These natural samples were chosen from a large collection of over 1000 specimens on the basis of their low magnetic anisotropy and their reproducible anhysteretic remanent magnetization (ARM) and TRM intensities (see Yu et al. (2002) for details). For instance, ARM and TRM were repeatedly produced six times over a period of 6 weeks. Intensities of ARM and TRM were reproducible within 3% to the initial ARM and TRM, respectively. In addition, principal components of the anisotropy of ARM (AARM) tensor are indistinguishable within 2%, suggesting a low degree of magnetic anisotropy.

We induced a TRM along the cylindrical axis of the specimen by cooling from 600 °C in a laboratory field of 50 μT. Stepwise alternating-field (AF) demagnetization was then carried out. After reproducing TRM, a stepwise thermal demagnetization was carried out to characterize the unblocking temperature spectrum. At each heating, samples were held for 30 min. Measurements were carried out in a magnetically shielded space with an ambient field less than 250 nT. The residual field in the furnace during nominally zero-field heatings was less than 5 nT. Throughout all heatings, temperatures were reproducible to better than 1 °C. All the measurements were carried out in a magnetically shielded room which houses a 2G enterprises cryogenic magnetometer whose resolution is better than 10^{-8} A/m. The current in the solenoid which produced the laboratory field was monitored throughout the experiment. Representative examples of the AF coercivity spectrum and unblocking temperature spectrum of TRM are shown in Fig. 1.

During AF demagnetization, the "SD" specimens have rather high (30 mT) median destructive fields (MDFs), a hallmark for the existence of fine-grained magnetite. MDF steadily decreases as the average grain-size increases (Fig. 1a). AF demagnetizations of undisplayed sister specimens yielded virtually identical behavior within the size of the symbol (Fig. 1a). During thermal demagnetization (Fig. 1b), the finer grained material (SD1–SD3) also has the characteristic of very narrow unblocking temperature spectrum (most of the remanence was unblocked between 500 °C and 580 °C). As the grain size increases, the unblocking temperature

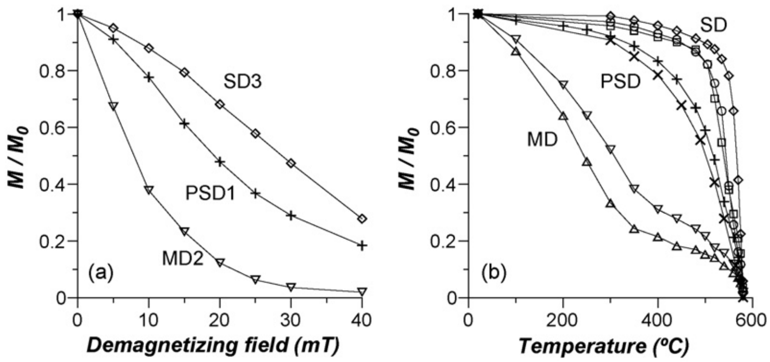

Fig. 1. (a) Alternating-field demagnetization and (b) thermal demagnetization curves. As the grain-size increases, we observed (a) a rapid demagnetization of TRM at low coercivity and (b) a wide unblocking temperature spectrum of TRM.

spectrum becomes more distributed (PSD and MD data in Fig. 1b).

3. Testing the linear field dependence of TRM in low magnetic fields

The reliability of TRM acquisition in low fields relies on whether we can induce a small but stable magnetic field. In order to maintain a stable field, we used a BK Precision DC power-supply (model 1730) that controls the current effectively. We attached this power supply to a home-built furnace which can control the temperature to better than 1 °C. As a preliminary test, we monitored the variation of $\boldsymbol{B}_0$ for 20 different TRM acquisitions. According to our preliminary test, maximum deviation or fluctuation of the uncertainty of the applied field was 0.04 μT. As a result, we set the minimum reliable inducing field intensity as 0.159 μT, four times larger than the maximum uncertainty.

We induced a TRM along the cylindrical axis of the specimen by cooling from 600 °C. In the present study, we used the following inducing fields: $\boldsymbol{B}_0 = 0.159$ μT, 0.278 μT, 0.610 μT, 1.041 μT, 2.185 μT, 5.150 μT, 10.04 μT, 20.04 μT, 50.00 μT, and 80.20 μT. These fields span three orders of magnitude with more or less the equal spacing in a log-scale. After all TRM experiments, we induced one additional TRM ($\boldsymbol{B}_0 = 50$ μT) as a reproducibility check to assess whether there was alteration during repeated heatings. We then compared four independent values of TRM ($\boldsymbol{B}_0 = 50$ μT): first for AF demagnetization (see Section 2), second for thermal demagnetization (see Section 2), third for TRM acquisition, and fourth as a final reproducibility check. These TRM values ($\boldsymbol{B}_0 = 50$ μT) are always within ±3% of the initial TRM acquisition without showing any growing or decaying trend (Fig. 2). For instance, values of TRM ($\boldsymbol{B}_0 = 50$ μT) for PSD1 were 42.985 mA m^2, 43.368 mA m^2, 42.384 mA m^2, and 43.221 mA m^2, respectively.

After all thermal experiments (thermal demagnetization, a suite of TRM acquisitions, and a TRM reproducibility check), an SIRM was produced by exposing specimens to field of 1 T using an ASC-10 impulse magnetizer. We normalized all the TRM acquisitions with respect to the SIRM.

4. Result and discussions

A linear field-dependence of TRM/SIRM was observed for all the samples used in the present study (Fig. 3). Most of all, a linear field dependence is observed even in low fields (<10 μT) (Fig. 3b). In particular, the results in Fig. 3 are quite different from the recent observations of Kletetschka et al. (2006) in two respects (Fig. 4), the non-linearity in low-field TRM and the TRM/SIRM ratio.

All specimens faithfully acquire TRMs for entire field ranges (0.159–80.2 μT) used in the present study

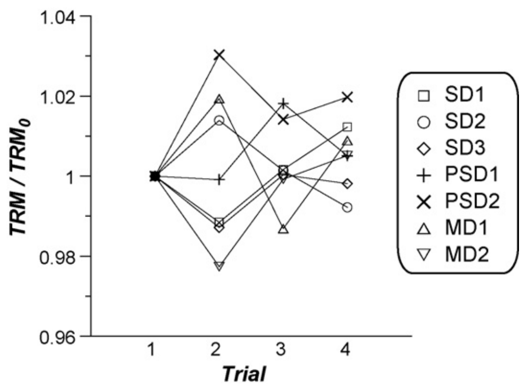

Fig. 2. Comparison of a suite of TRM intensity ($\boldsymbol{B}_0 = 50$ μT) produced for (1) AF demagnetization, (2) thermal demagnetization, (3) TRM acquisition, and (4) a TRM reproducibility check.

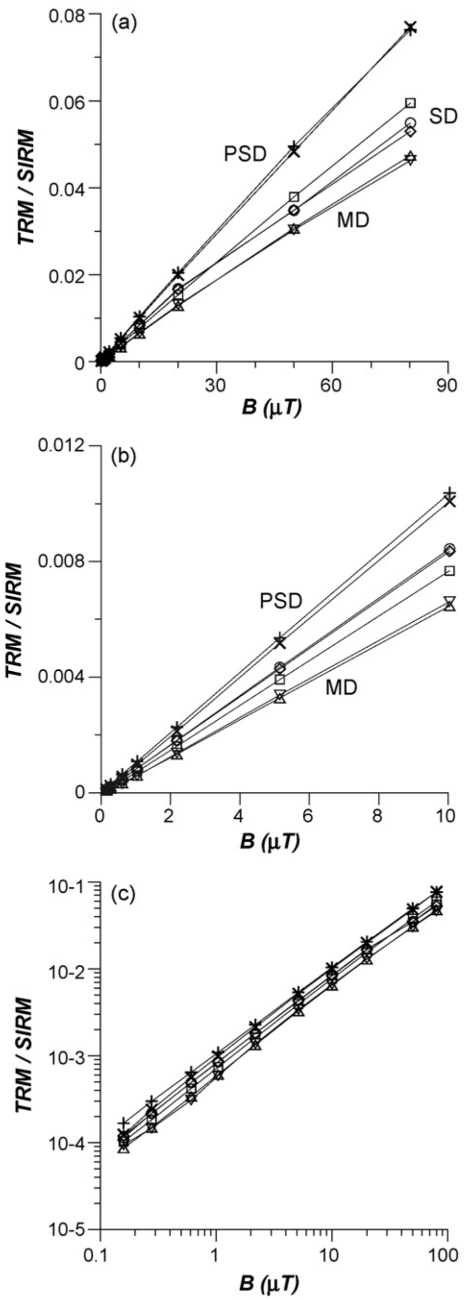

Fig. 3. The TRM/SIRM ratio as a function of applied field $\boldsymbol{B}_0$. In the present study, TRMs were produced by cooling from 600 °C in a steady field $\boldsymbol{B}_0$. The SIRM was produced by exposing samples in a field of 1 T. Note that the TRM/SIRM is proportional to $\boldsymbol{B}_0$.

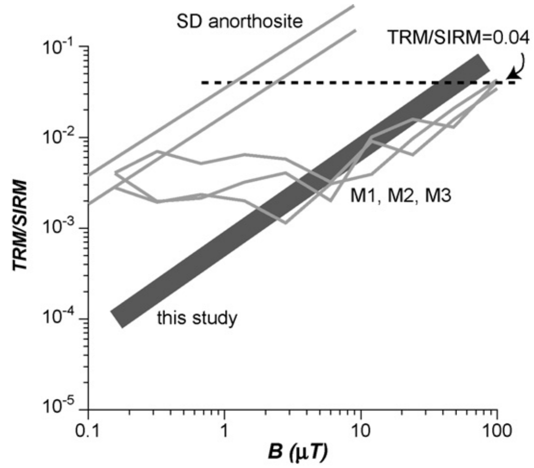

Fig. 4. Our TRM/SIRM trend line (grey lines) of magnetite shows a substantial improvement on the sensitivity of TRM acquisition in low fields. While the results M1–M3 (Kletetschka et al., 2006) show noisy results at <2 μT, our trend line linearly extends to 16 nT. The thin linear line is a SD anorthosite trend line of Kletetschka et al. (2006). Note that the TRM/SIRM of 0.04 is observed in fields ranging from 1 μT to 100 μT, suggesting that the TRM/SIRM provides very poor constraints on the ancient magnetic field.

(Fig. 3). This fundamental observation is at odds with a claim of limited sensitivity in acquiring TRMs in very low applied fields (e.g., Dunn and Fuller, 1972; Kletetschka et al., 2006). In Fig. 4, the documented results for M1–M3 (multidomain magnetite) of Kletetschka et al. (2006) shows an elbow ∼5 μT while the solid trend line of this study shows a linearity in all fields. The difference between the two results can be explained by poor field control in the oven in previous studies, particularly at very low fields. Note that the only data in Fig. 4 of Kletetschka et al. (2006) that did exhibit the low field insensitivity is the SD anorthosites which were measured in the Scripps Lab. On the contrary, all other non-SD data in Fig. 4 of Kletetschka et al. (2006) were acquired elsewhere using a different oven with less precise field control. It appears that a constant current supply in inducing $\boldsymbol{B}_0$ is the key factor in delicate TRM acquisition at low applied fields (<10 μT).

A second important discrepancy lies in the grain-size dependence of TRM/SIRM. For magnetite-containing samples, the TRM/SIRM is most efficient in PSD but similar between SD and MD (Fig. 3a). This observation agrees well with the compiled TRM/SIRM ratio of magnetites in the literature (e.g., Hartstra, 1982, 1983; Dunlop and Özdemir, 1997; Dunlop and Argyle, 1997; Muxworthy and McClelland, 2000; Yu, 2006). A distinctively different SD trend line (dashed lines in Fig. 4) in Kletetschka et al. (2006) results mainly from the unique morphology of magnetite samples. Kletetschka et al. (2006) used extremely elongated magnetite needles embedded within an anorthosite matrix (Selkin et al., 2000). In other words, the dashed SD trend line in Fig. 4 provided by Kletetschka et al. (2006) is an extreme measure of a shape anisotropy of magnetite. From this, it is clear that the TRM/SIRM ratio depends on the grain-size as well as the aspect ratio of magnetites and can only constrain the inferred ancient magnetic field to within two orders of magnitude. For instance, the same TRM/SIRM ratio 0.04 is observed for TRMs acquired in fields ranging from 1 μT to 100 μT (see the dashed line in Fig. 4). However, it would be fair to mention that the grain-size dependence can be somewhat reduced in practice by carefully adopting the refined technique of Gattacceca and Rochette (2004).

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