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Unique thermoremanent magnetization of multidomain sized hematite: Implications for magnetic anomalies

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Abstract

Intense magnetic remanence (100–1000 A/m) associated with MD hematite and/or titanohematite and associated with high Koenigsberger ratios (40–1000) indicate that magnetic remanence may dominate the total magnetization if these minerals are volumetrically significant. Titanohematite behaves similarly to hematite and, thus, the grain size dependence of TRM acquisition in hematite is considered as a generalization. The transition between truly MD behavior and tendency towards SD behavior in hematite has been established to be between grain sizes of 0.1 and 0.05 mm. In contrast to magnetite and titanomagnetite, hematite exhibits inverse grain size dependence, with MD hematite acquiring a relatively intense TRM in the geomagnetic field, comparable to sub-micrometer sized magnetite and only an order of magnitude less than SD magnetite. Consequently MD hematite (and by analogy titanohematite) remanence may be of significance as a source of magnetic anomalies at all scales. MD hematite exhibits TRM weak field acquisition behavior that is different from all other magnetic minerals, being the only magnetic mineral having an REM (TRM/SIRM) value $\gg 0.1$ for TRM acquisition in the geomagnetic field. The very different TRM behavior of MD hematite in contrast to magnetite is due to two factors. The first is the lesser influence of demagnetizing energy with respect to wall pinning energy, at temperatures almost up to the Curie temperature for hematite. The second is the greater importance of the magnetostatic energy in the applied field, which for hematite dominates the total energy at high temperatures.

Keywords: hematite; multidomains; thermoremanent magnetization; magnetic anomalies; magnetic properties

1. Introduction

Thermoremanent magnetization (TRM) is one of the most efficient remanent magnetization mechanisms in nature (e.g. [1]) resulting in the largest specific magnetization intensity compared to other mechanisms. The only magnetization mechanism that provides more intense remanence is that associated with the magnetization in lodestones and other intensely magnetized rocks. This is a consequence of the magnetic field due to lightning [2]. However this magnetization is important locally and is relevant only to a thin layer of exposed rock. Among the magnetic minerals in the Earth's crust: magnetite, hematite, titanomagne-

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tite, titanohematite and pyrrhotite are the ones most frequently encountered. The grain size dependence of TRM acquisition in titanomagnetite and titanohematite with relatively small amounts of titanium, behaves almost identically to end member magnetite and hematite [3,4].

Most of the total magnetization of crustal rocks is usually considered to be associated with magnetite because of the large magnetic susceptibility in the presence of the inducing geomagnetic field [5,6]. Results from the German Continental Deep Drilling program (KTB) revealed amphibolite facies metamorphic rocks with the major magnetic carrier identified as monoclinic, ferrimagnetic pyrrhotite [7]. Balsey and Buddington [8] showed that remanent magnetization of reversed polarity carried by titanohematite was responsible for prominent negative magnetic anomalies associated with microcline granite gneisses from the Grenville terrane of the Adirondack Mountains, New York. Titanohematite is the main NRM carrier of large blocks (5000 km^2) of granulite facies metamorphic rocks in Central Labrador [9,10]. Titanohematite was also shown to be the main NRM carrier in high grade metamorphic rocks exposed in Lofoten-Versteralen, northern Norway [11]. These examples emphasize that pyrrhotite and titanohematite, with remanence dominant over induced magnetization, should also be considered when explaining magnetic anomalies over large crustal regions.

Single domain (SD) sized grains of magnetite, titanomagnetite and pyrrhotite acquire more intense TRM than the multidomain (MD) sized grains [3,4]. Hematite and titanohematite, however, acquire more intense TRM in its MD size than in SD size [3]. This identifies titanohematite and hematite as having an inverse grain size dependence when compared with other common magnetic minerals. Because single domain behavior is markedly different from that of MD we are interested in establishing the grain size at which hematite changes its behavior from a truly multidomain sized grain towards the SD sized behavior. Grain size dependent coercivity indicates that the truly SD grain size of hematite is between 0.025 and 15 μm [13,14].

2. Experimental procedures

Hematite samples L2 [10] and N114078 [12] were characterized by X-ray diffraction, Curie temperature and saturation magnetization. X-ray diffraction analysis of the powdered samples confirmed high purity of the hematite grains, where no other phase was detected. The absence of magnetite was also indicated by the measured values of saturation magnetization (Js) which ranged between 0.2–0.5 A m^2 kg^{-1}. No titanium component was detected during measurements of the Curie temperature, which coexisted with the temperature for pure hematite (670°C).

Iron-ore hematite sample L2, from Central Labrador [10], was crushed and sifted to obtain average grain sizes of 1, 0.5, 0.2, 0.1, and 0.05 mm by using USA standard testing sieves with openings 850, 250, 150, 75, 38 μm respectively. The fine red powdered hematite N114078 was used to represent the smallest grain size ($\sim$0.001 mm). The grain size of this fraction was based on SEM observation and the distribution ranged from 0.0005 to 0.003 mm (0.5–3 μm). Thirty mg of hematite grains were separated from each of the grain size fractions and added to 7.7 parts of adhesive ceramic (Cotronix, item #919) and one part of water. We mixed these oxide fractions with about 50 mm^3 of ceramic material. This viscous substance was poured into a small cylindrical opening (0.1 cm^3) in the center of a ceramic disc (2.54 cm $\times$ 1 cm). After solidification the grain size dependent TRM acquisition curves were measured.

Isothermal remanence acquisition (IRM) curves were determined with a Vibrating Sample Magnetometer (VSM), (model 7300, Lake Shore Cryotronics, Inc). The magnetic field was supplied by a large water cooled 12 inch Varian magnet, driven by a Tidewater Technological Inc. bipolar power supply. The maximum field used was 2 T.

TRM acquisition curves were acquired in a controlled weak field environment in order to investigate the grain size dependent intensity of TRM acquired over a range of weak fields. Samples were placed in a Thermal Specimen Demagnetizer (model TSD-1, Schonstedt Instrument Company). A maximum temperature of 750°C

was used for all experiments. The oven was equipped with a cooling chamber containing a conducting coil, which can be used to produce an axial magnetic field during the cooling process. We applied a current through this conducting coil using a high performance power supply. The magnetic field inside the cooling chamber was measured with a Bell model 620Z Gaussmeter. The fields applied during the cooling of our samples ranged from 0.005 to 1 mT. The smallest field inside this shielded oven was 0.002–0.003 mT. Hysteresis properties were measured before and after the thermal treatment to insure that the heating in air did not significantly change the characteristics of the mineralogy of our samples.

3. Results

Grain size dependence of TRM in magnetite and hematite (at 5×10^{-5} T) are shown in Fig. 1. The bend in the magnetite curve at $\sim$0.001 mm indicates a transition from SD to MD magnetic behavior [15]. The hematite data clearly show a distinction between MD (which reaches magnetization levels of SD sized magnetite) and the SD states. Our hematite TRM values between grain size of 0.1 and 1 mm are more or less constant suggesting an MD regime. TRM for 0.05 mm grain size is slightly lower, perhaps indicating a beginning of the transition from MD to SD behavior for hematite.

Dekkers and Linssen [16] and Harstra [17] observed similar grain size dependence in hematite (Fig. 1). Their TRM data were acquired in magnetic fields of 0.084 mT and 0.035 mT respectively. Our 0.1 mT data were compared with their [16,17] results by linearly recalculating the latter to 0.1 mT. The habit of each of the hematites used for Dekkers and Linssen [16] published data set, and including the present work, was different. Consequently we would expect systematic grain size trends as observed in Fig. 1, but not overlapping data. The inverse grain size trend is, however, established in Fig. 1, regardless of the data set.

To test if the 0.1 mm size of hematite is a boundary of the truly MD state we constructed

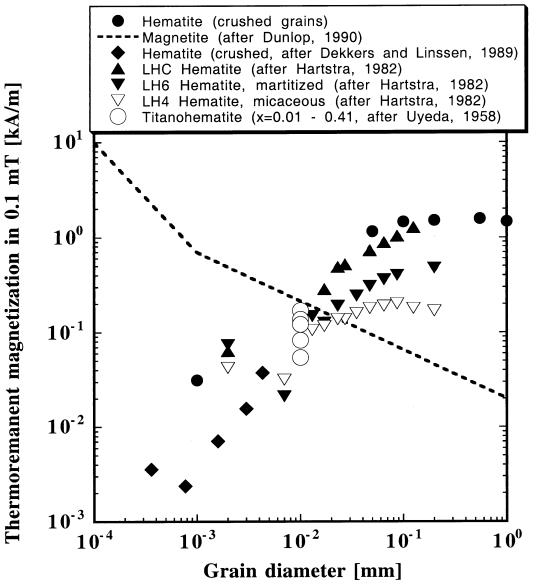

Fig. 1. Comparison of the grain size dependence of the intensity of weak field TRM in hematite and in magnetite (magnetite trend is from [15]). In order to approximate the 0.1 mT TRM field, hematite samples [16,17,28] were linearly recalculated.

TRM acquisition curves for each grain size fraction. Our result (left set of curves in Fig. 2) shows that all of the grain sizes above 0.1 mm cluster along one narrow acquisition path reaching 70% of the SIRM value of hematite in an Earth like field (5×10^{-5} T). This indicates that the REM value (see [2,18]) is unique and characteristic of this MD hematite. The sample with grain diameter of 0.05 mm clearly separated from the main trend and reached 50% of its SIRM for the field of 5×10^{-5} T. Thus a grain size of 0.05 mm shows a tendency towards SD behavior, which is illustrated by the acquisition curve for a grain size of 0.001 mm (Fig. 2). TRM acquisition curves in Fig. 2 clearly show that the larger MD grains of hematite acquire a substantially stronger remanence in weak magnetic fields compared to the SD hematite grains.

Previous TRM acquisition observations [19] for a 5 mm$\times$5 mm$\times$1 mm single crystal of hematite showed that 30% of the saturation remanence was achieved in geomagnetic field cooling. This consequently gives a large REM value. The sample had a saturation magnetization value of 2500 A/m

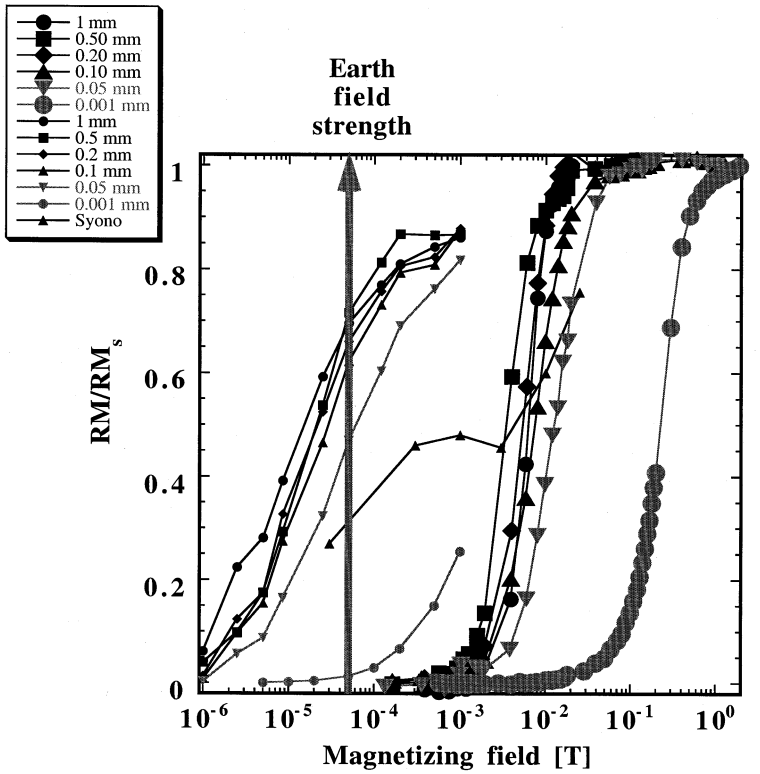

Fig. 2. TRM acquisition curves for different grain sizes of hematite are compared with the IRM acquisition curves done with the same samples. TRM and IRM are normalized to the saturation isothermal remanent magnetization (SIRM). All MD sized grains have REM values $\gg 0.6$. Syono TRM acquisition data [19] for single hematite crystal (5 mm$\times$5 mm$\times$1 mm) are also shown.

and likely had other magnetic phases. This is reflected in the TRM acquisition curve (Fig. 2) where TRM further increases after reaching apparent saturation at fields close to 10^{-3} T.

The right side of Fig. 2 illustrates isothermal remanent magnetization (IRM) acquisition curves acquired for the same grain sizes. IRM curves indicate that the behavior of the 0.05 mm grain size is again markedly distinct from all of the larger grain sizes which cluster along a narrow path. The IRM acquisition for SD hematite shows that a large magnetic field (>2 T) is required to saturate this sample.

In order to confirm if the larger MD hematite grains are magnetically softer than smaller grains we demagnetized the SIRM, imparted to our samples, with alternating magnetic fields up to 0.24 T. Again, the 0.05 mm grain size was clearly distinct from the larger grain sizes (Fig. 3). The smaller

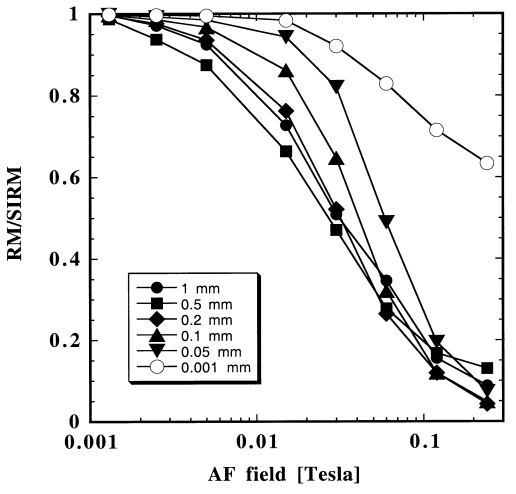

Fig. 3. Normalized SIRM alternating field (AF) demagnetization curves for different grain sizes of hematite.

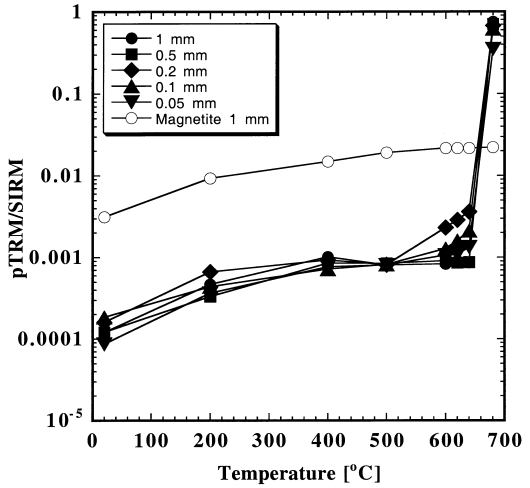

Fig. 4. SIRM normalized partial thermoremanent magnetization (pTRM) of multidomain hematite is compared with SIRM normalized pTRM of multidomain magnetite.

grain sizes of hematite resisted the demagnetizing field more effectively than larger grain sizes. The magnetization of the 0.001 mm fraction was more resistant against AF demagnetization and even after demagnetization in a 0.24 T peak alternating field 60% of its SIRM remained. This behavior confirms that even though MD hematite acquires more intense TRM, the remanent magnetization is less resistant to the AF demagnetization. The coercivity decreases with increasing hematite grain size verifying that MD hematite is magnetically softer than SD hematite [12].

The soft magnetic behavior of MD hematite, reflected by response to AF demagnetization, raises a question about whether MD hematite can acquire a significant partial thermoremanence (pTRM) on cooling below the Curie temperature, as is observed for pTRM acquisition in magnetite. The experiment shown in Fig. 4 illustrates that only if the temperature at pTRM acquisition reaches the Curie temperature, MD hematite will acquire significant partial thermoremanent magnetization (pTRM $>$ 0.1% of SIRM). At close proximity of the Curie temperature magnetization increases sharply to more than 50% of its SIRM. This sharp increase of pTRM is absent in MD magnetite where magnetization increases smoothly reaching only 2% of its SIRM value (Fig. 4). MD sized hematite pTRM data indicate that the major blocking temperatures for TRM acquisition cluster very closely to the Curie temperature with little pTRM acquired at lower temperatures. The studied grain size range of hematite shows no significant grain size dependence for acquisition temperatures below 670°C. When the temperature 670°C is reached, the acquired TRM increases with the grain size (Fig. 4).

4. Physics behind TRM of hematite

Hematite samples have been used to provide a 'magnified' view of pseudo single domain (PSD) processes [20]. Hematite possesses only a very limited number of domains, in spite of the fairly large grain size [21–23], implying that the PSD behavior of hematite may be relevant for understanding PSD behavior of other minerals, such as magnetite. We caution against making this generalization because, as the data in Fig. 1 illustrate, magnetite and hematite TRM grain size dependences for the transition between SD and PSD have slopes of opposite sign. The positive slope for the TRM grain size dependence of hematite seems to conflict with MD theory since MD sized hematite grains acquire a greater TRM than SD grains (Fig. 1).

According to theory, TRM should be lower for MD sized grains because of the domain interactions [1]. This would result in a negative grain size dependence for TRM. This paper presents results indicating positive grain size dependence for TRM of hematite. Similar results were obtained by [16,17] (see Fig. 1). In pyrrhotite a similar positive slope has been observed just within the PSD–MD transition [24]. However, SD pyrrhotite has TRM values an order of magnitude greater than MD pyrrhotite [3,4]. Another unique feature of MD sized hematite is the REM value exceeding 0.5. Fig. 2 indicates that the magnetization of MD sized hematite is a significant fraction of the saturation magnetization (REM $\gg$ 0.1). No other mineral can have REM ratio greater than 0.1 unless it was contaminated by a magnet and/or affected by lightning induced fields [2,18].

We propose that the seeming contradiction of

MD sized hematite behavior with the theoretical considerations can be explained by considering the difference between the magnitudes of the internal demagnetizing energy for MD sized magnetite and MD sized hematite.

In MD sized magnetite TRM cannot saturate in small magnetic fields because of the opposition of the internal demagnetizing field. The internal demagnetizing energy is proportional to $(Js)^2$, where Js denotes saturation magnetization. Js for magnetite ($\sim$90 A m^2 kg^{-1}) is almost 200 times larger than Js for hematite (0.4 A m^2 kg^{-1}). This suggests that during the TRM acquisition of MD sized hematite the internal demagnetizing energy is much less than in MD sized magnetite and allows MD sized hematite to approach saturation in weak magnetic fields.

A remaining question is why does the MD sized hematite persist until just below the Curie point where magnetization abruptly increases by almost three orders of magnitude (Fig. 4). Consequently, when cooling, a significant fraction of the saturation remanence is blocked, essentially leaving MD sized hematite in an SD state. We interpret this observation by maintaining domain walls up to the vicinity of the Curie point and failure to nucleate walls when cooling from the vicinity of the Curie point.

To explain this unusual behavior we assume that the pinning energy is the same for both hematite and magnetite. Fig. 5 schematically illustrates how in this case the different value of demagnetizing energy influences the magnetization of the MD sized grain. The demagnetizing energy for magnetite is large compared with domain wall pinning energy. This results in a lower magnetization because the domain wall can be stable only when the first possible local minimum is attained. This minimum is of very shallow character, causing relatively low thermal and magnetic stability. Apparently small perturbation of temperature and/or magnetic field can drive the domain wall out of the local minimum towards the global magnetic minimum representing the demagnetized state. When demagnetizing energy is low (hematite case) and approaches the value of pinning energy the defects essentially control the magnetization and allow the existence of local magnetic

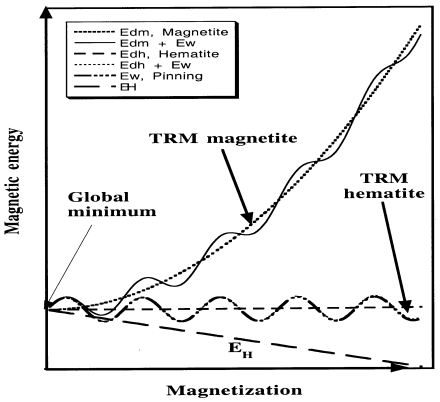

Fig. 5. Effect of the different values of demagnetizing energy for magnetite (Edm) and hematite (Edh) on magnetization of multidomain size grains with the pinning energies represented by sinusoidal variation Ew. The global minimum represents an MD grain that is completely demagnetized in zero field. Local minima correspond to MD grains with residual magnetization. The demagnetizing energy of hematite changes very little compared with the pinning energies causing almost identical representation of both pinning and total magnetic energies (Edh $\approx$ Edh+Ew). The contribution of E_H ensures that the equilibrium position of walls in hematite is highly displaced from the demagnetized state at high temperatures in fields comparable to the geomagnetic field. The slope of the line representing E_H is highly exaggerated for $H = 10^{-5}$ T at room temperature, but is realistic at high temperatures, where wall pinning energy and self-demagnetizing energy decrease faster than E_H.

minima close to saturation remanence, causing the MD sized hematite to stay in its SD like state. Because the demagnetizing energy is low the resulting local minimum is relatively deep and introduces large thermal magnetic stability of the MD sized hematite grain. These ideas require more rigorous theoretical treatment. We will follow the theoretical treatment in [1]. The theory of multidomain TRM [1,25] can provide a first order estimate of TRM intensity. During cooling below T_B (blocking temperature), the wall's displacement is frozen, so that magnetization $M_r(T < T_B)$ changes only by reversible increase in $M_s(T < T_B)$. Thus we have:

$$M_r(T) = \frac{M_s(T)}{M_s(T_B)} \frac{H_0}{N} \quad (1)$$

where H_0 is an external magnetic field and N is a

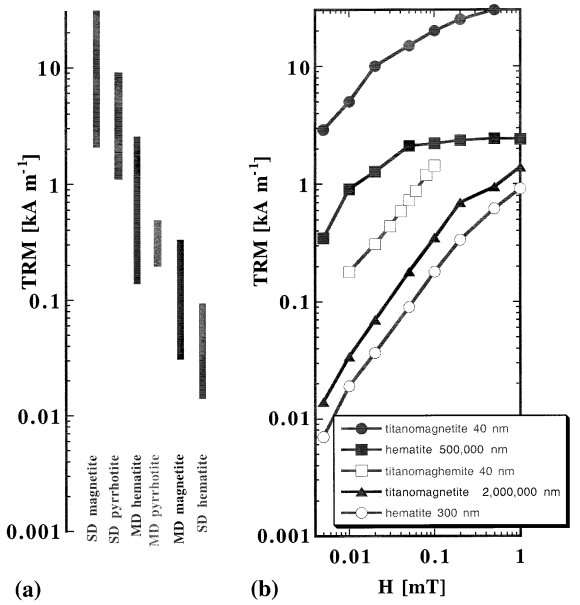

Fig. 6. Summary of TRM acquisitions in small magnetic fields: (a) Ranges of TRM intensities of different minerals acquired in the geomagnetic field (~0.05 mT). (b) TRM acquisition trends for variable magnetizing field intensity: Single domain hematite and multidomain hematite (N115249 and N114078 respectively) were obtained from the Department of Mineral Sciences, NMNH, Smithsonian Institution [12]. SD titanomaghemite data (40 nm) are from [35]. Ranges of TRM for magnetite, pyrrhotite, and hematite are from [3]. SD (40 nm) and MD (2 mm) titanomagnetite curves are from [35] and [36], respectively.

demagnetization factor. Eq. 1 represents linear dependence of TRM on applied field observed experimentally for weak fields (Fig. 6). Magnetization in Eq. 1 gives rise to an internal demagnetizing field H_d. This field generates soft induced magnetization M_{in} that partially opposes M_r:

$$M_{in} = \chi H_d = \chi[-N(M_r + M_{in})]$$

Thus by solving this for M_{in} and using Eq. 1 we have:

$$M_{in} = -N\frac{\chi}{1+N\chi}M_r = -\frac{\chi}{1+N\chi}\frac{M_s(T)}{M_s(T_B)}H_0$$

where χ is magnetic susceptibility and for the total magnetization M (TRM) we have:

$$M = M_r + M_{in} = \frac{M_s(T)}{M_s(T_B)}\frac{H_0}{N}\left(\frac{1}{1+N\chi}\right) \quad (2)$$

By using $T_B = 640°C$ (see Fig. 4), the block shape temperature curve of high field hematite magnetization (see fig. 3.20 in [1]) gives $M_s(T)/M_s(T_B) = 0.5$. Assuming $H_0 = 40$ A/m (0.05 mT), $N = 1/3$ (table 4.1 in [1]) and $\chi = 0.01$ SI, Eq. 2 gives $M = 240$ A/m. The corresponding Koenigsberger ratio ($= TRM/(\chi H_0)$) ranges from ~40 up to about 12 000 assuming induced magnetization of hematite ranging from 7 A/m to 0.02 A/m, respectively [12]. The typical Koenigsberger ratio for MD magnetite is 0.6 [26,27]. Koenigsberger ratio of our hematite samples ranged between 160–230. Uyeda [28] reported large Koenigsberger ratio (460) of 0.18 mm sized hematite with TRM = 950 A/m given in 0.2 mT field. He also found that synthetic titanohematites with $x < 0.5$ (grain size ~0.010 mm) have Koenigsberger ratios ranging from 179 ($x = 0.48$) to 705 ($x = 0.01$). The intensity of these 0.01 mm grains ranged between 100 A/m and 340 A/m (see Fig. 1). Another example was provided by Kobyashi and Smith [29] whose plots of titanohematite ($x = 0.05$) indicate TRM($H_0 = 0.2$ mT) = 740 A/m and a high Koenigsberger ratio of 340 for a large cylindrical (4.3 cm in length and 1 cm in diameter) specimen with coercive force 8 mT.

A more complete theory of MD TRM must incorporate the effects of the applied field on the high temperature domain structure and magnetization of hematite. The field blocking model [1] for the case of magnetite can be readily applied to MD hematite. Thus, for fields comparable to the geomagnetic field the TRM is blocked at somewhat lower temperature, either by:

1. rapid strengthening of wall pinning, trapping domain walls in positions that are highly displaced with respect to the zero magnetization state, as the grains cool in the applied field, or by
2. failure of wall nucleation, leaving the grain stranded in a metastable SD state; hematite retains such metastable saturated states much

more readily than magnetite, because the demagnetizing field is much lower in hematite.

For this second consideration we can assume that hematite is in SD state. Thus we can apply the original Néel's theory for SD particles. Néel [30] established a theoretical basis for understanding TRM which endures today. At time t in an ensemble of identical non-interacting SD grains, coherent reversals between states in which moments are either parallel or antiparallel to a weak field H_0, control the evolution of the net magnetization of the ensemble towards equilibrium:

$$M(t) = M(0)e^{-t/\tau} + M(\infty)(1-e^{-t/\tau})$$

where τ is the relaxation time (see [1], p. 202). $M(\infty)$ is the thermal equilibrium magnetization:

$$M(\infty) = M_s \tanh\left(\frac{\mu_0 VM_sH_0}{kT}\right) \quad (3)$$

M_s represents saturation magnetization, μ_0 is permeability of free space, V is volume of the SD grain, H_0 is applied magnetic field, k is the Boltzmann constant (1.38×10^{-23} J K^{-1}), and T is the temperature. Eq. 3 for SD grains predicts an increase in $M(\infty)$ as V increases: larger SD grains should align their moments more efficiently in the direction of H_0 than small grains and this is in agreement with our experimental data (Fig. 1) where TRM of hematite increases with grain size.

Domain wall pinning is temperature dependent through the dependences of magnetic anisotropy $K_1(T)$ and magnetostriction $\lambda(T)$. Both of these material properties vary as a power of $M_s(T)$ (see figs. 3.7b and 3.8b in [1]). At high temperatures, domain walls are less strongly pinned by defects. Based on these assumptions the wall pinning model [31] predicts the M_{tr} (TRM) in a form:

$$M_{tr} = \frac{n}{N}(n-1)^{(1-n)/n}H_0^{(n-1)/n}H_c^{1/n}(T_0) \quad (4)$$

Flanders and Shuele [32] found experimentally the proportionality factor $n=3$ for a large single crystal of hematite. Then Eq. 4 gives $M_{tr}=$ 977 A/m for $H_c(T_0)=3200$ A/m (4 mT), $H_0=$ 40 A/m (0.05 mT) and $T_B=665$°C. Thus TRM acquired in the geomagnetic field is a substantial proportion of the saturation remanence, as found experimentally (Fig. 2).

Immediately below the Curie temperature, both the internal demagnetization field and coercivity are much smaller than the external field causing even a small applied field to saturate magnetization of the mineral. Demagnetization field increases more rapidly than coercivity and, when it becomes larger than external field H_0, causes magnetization to decrease. While cooling the sample down, coercivity starts to dominate the demagnetization field and causes resistance to domain wall motion and thus field blocking ensues. When the external magnetic field is sufficiently weak the thermal activation field becomes the dominant blocking mechanism in magnetite. Compared to MD magnetite, thermally induced magnetic blocking is unlikely to be important for MD hematite in the geomagnetic field, because the volume of the Barkhausen moments in MD hematite grains is large compared to typical activation volumes in PSD magnetite. This relation is illustrated in [31] where thermal blocking replaces field blocking for field strengths below a threshold value $(H_0)_f$ according to:

$$(H_0)_f = \frac{n^n}{(n-1)^{n-1}}H_f(T_B) \quad (5)$$

Assuming that thermal energy is transferred to domain walls only by fluctuation in the amplitudes of the domain wall energy barriers to the domain wall, the fluctuation field $H_f(T)$ is given by:

$$H_f(T) = \frac{kT\log(f_0t)}{2VM_s(T_0)b(T)} \quad (6)$$

where V is the volume swept out by a domain wall in Barkhausen jump, f_0 is an atomic reorganization time, and $b(t)$ is normalized saturation magnetization. When taking $t=300$ s, $f_0=10^{-10}$ Hz, $k=1.38\ 10^{-23}$ J K^{-1}, $T=940$ K, $b(T)=0.1$, $M_s(T_0)=2000$ A/m, and typical Barkhausen volume V of 10^{-14} to 10^{-13} m^3 for 0.1 mm grain and

10^{-11} to 10^{-10} m^3 for 1 mm grains (see [33]) according to Eq. 6 we get $(H_0)_f = 10^{-4}$ mT for the smallest Barkhausen jump in 0.1 mm grains and 10^{-8} mT for the largest Barkhausen jumps in 1 mm grains. This indicates that the thermal fluctuation field is negligible within a few degrees of the Curie temperature. The corresponding threshold field from Eq. 5 below which TRM is thermally blocked is 6×10^{-4} mT, which is two orders of magnitude less than the geomagnetic field. Thus thermal fluctuation has negligible effect on initial magnetization causing the TRM of MD hematite to be extremely stable thermally even when heated to temperatures close to the Curie temperature.

Because the TRM of hematite is relatively close to the saturation remanence we want to estimate a high field limit for field blocked TRM [31]. This field limit occurs at a critical field $(H_0)_{crit}$ such that M_{tr} (TRM) reaches the saturation remanence $M_{rs}(T_0)$. This critical field depends on coercivity at room temperature ($H_c(T_0)$) and can be estimated as (see [31]):

$$(H_0)_{crit} = \frac{n-1}{n^{n/(n-1)}} H_c(T_0) \quad (7)$$

and given $n = 3$ and $H_c(300) = 2$–10 mT [12] we obtain from Eq. 7 fields of only 0.8–3.8 mT required to reach saturation remanence. Syono [19] found that a 5 mm $\times$ 5 mm $\times$ 1 mm single crystal of nearly pure hematite had a saturation magnetization of 2500 A/m and had TRM of 80% of the saturation magnetization acquired in a field of 30 mT. The main reason for the intense remanence is the much weaker influence of self-demagnetization in the case of hematite. More completely, the very different TRM behavior of MD hematite in contrast to magnetite is due to two factors.

The first is the lesser influence of demagnetizing energy with respect to wall pinning energy, at temperatures almost up to the Curie temperature for hematite.

The second is the greater importance of the magnetostatic energy in the applied field, which for hematite dominates the total energy at high temperatures. Thermal blocking only occurs just below the Curie temperature in MD hematite, because of the large volume associated with Barkhausen moments in such grains.

5. Relative significance of TRM

We have shown that MD hematite not only exhibits inverse grain size dependence (with respect to magnetite) for TRM acquisition, but also has magnetization intensity that would signal its importance if it were distributed significantly in crustal rocks. Fig. 6 is a review of the field dependence of TRM acquisition for the common magnetic minerals. Fig. 6a contains data for TRM acquired in the geomagnetic field and indicates the observed range for the appropriate SD or MD mineral species. These ranges came from numerous sources [3,4]. The curves (Fig. 6b), identified in the legend, are TRM field dependent acquisition curves.

Single domain magnetite will always acquire the most intense TRM at any field. SD hematite will acquire the least TRM at any field. Notable in Fig. 6 is the intensity of MD hematite which is actually greater than SD titanomagnetite. Consequently hematite (or titanohematite) can be a very effective source of remanence in the continental crust.

We therefore need to more accurately assess the mineralogy responsible for the remanent magnetization and the relative significance of remanent vs. induced magnetization. A hand magnet separation of a crustal rock for example will always overemphasize magnetite. As indicated in Section 1, and likely there are more examples, titanohematite (modeled by hematite in this paper) may be important as a remanent magnetism source in the crust.

6. Implication for magnetic anomalies

MD hematite can carry a significant remanent magnetization. Crustal rocks contain both coarse and fine grained magnetic minerals. Coarse MD magnetic grains can occur as single grains in between the silicate phases. A variable fraction of very small magnetic grains can be found within

the matrix of silicate minerals in the form of exsolution products. Most of the magnetic minerals are larger than SD [34]. SD magnetite, however, will acquire more than two orders of magnitude more TRM than MD magnetite. If there is only 1% of SD and 99% of MD grains of magnetite (see Fig. 6), SD magnetite can dominate the NRM signature of the magnetite bearing rock. This is why the remanent magnetization of the coarse MD grains in crustal rocks is commonly neglected and it is assumed that NRM is carried by small fraction of fine grained SD magnetite. But this is not true for MD sized hematite where SD like behavior allows these grains to reach TRM comparable with SD magnetite.

Our results suggest that if the conditions of metamorphism and crystallization allow MD hematite to be formed in the lower and middle crust then these hematite grains may contribute significantly to the magnetic remanence. This is consistent with the field observations in the Adirondacks Mountains, USA [8], Labrador, Canada [9,10] and Norway [11] where titanohematite in granulite facies rocks carry the majority of magnetic remanence. This also confirms the suggestion [34] that most of the crustal rocks contain grains close to transition between PSD/MD grains.

7. Conclusions

Multidomain hematite exhibits an inverse TRM grain size dependence across SD–PSD transition with respect to all other minerals found in the crust. This is proposed to be due to weaker influence of demagnetizing energy with respect to wall pinning energy in the case of hematite, at temperatures almost up to the Curie temperature. Another factor is the greater importance of the magnetostatic energy in the applied field, which for hematite dominates the total energy at high temperatures. Thermal blocking only occurs just below the Curie temperature in MD hematite, because of the large volume associated with Barkhausen moments in such grains.

Field dependent acquisition is very effective in MD hematite compared to any other crustal mineral. Consequently, the REM value is unique in MD hematite [2,18]. No other mineral has an REM value $\gg 0.1$ for TRM acquired in the geomagnetic field. The typical Koenigsberger ratio for MD hematite ranges between 40 and 1000. The TRM intensity of MD hematite is relatively large and comparable to TRM of submicron magnetite. Grain size between 0.1 and 0.05 mm is a size range where the magnetic properties of hematite start to grade towards the SD behavior. These unique properties of TRM in MD hematite require a re-evaluation of their role in the interpretation of magnetic anomalies.

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