# Thermal sensitivity of MD hematite: Implication for magnetic anomalies

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## Abstract:

Magnetic remanence of crustal rocks can reside in three common rock-forming magnetic minerals: magnetite, pyrrhotite, and hematite. Thermoremanent magnetization (TRM) of magnetite and pyrrhotite is carried mostly by single domain (SD) grains. The TRM of hematite grains, however, is carried mostly by multidomain (MD) grains. This characteristic is illustrated by TRM acquisition curves for hematite of variable grainsizes. The transition between truly MD behavior and tendency towards SD behavior has been established between hematite grainsizes of 0.1 and 0.05 mm. Coarse grainsize of lower crustal rocks and the large sensitivity of MD hematite grains to acquire TRM indicates that hematite could be a significant contributor to long-wavelength magnetic anomalies.

## Introduction:

The most common magnetic minerals found in the Earth's crust are titanomagnetite, pyrrhotite and titanohematite (Clark, 1983). Induced and remanent magnetization of these minerals is responsible for producing magnetic anomalies (>500 km) detectable by satellite measurements. Permanent magnetization can significantly contribute to the observed magnetic anomalies as shown by Mars Global Surveyor magnetic field experiment (Acuña et al., 1998; Acuña et al., 1999, Connerney et al., 1999).

Natural remanent magnetization (NRM) of crustal rocks is usually thought to be carried by magnetite (e. g., Shive and Fountain, 1988; Wasilewski and Mayhew, 1992). Results from the German Continental Deep Drilling program (KTB), however, revealed amphibolite facies metamorphic rocks and found that the major magnetic carrier was monoclinic, ferrimagnetic pyrrhotite. The magnetic signature of this mineral disappears below about 8.6 km, corresponding to in-situ temperatures of 260 °C (Kontny et al., 1997). Kletetschka and Stout (1998) found that titanohematite is the main NRM carrier of large blocks (5000 $km^2$ ) of granulite facies metamorphic rocks in Central Labrador. Titanohematite was also shown to be the main NRM carrier in high grade metamorphic rocks exposed in Lofoten-Versteralen, northern Norway (Schlinger and Veblen, 1989). This means that all three minerals (titanomagnetite, pyrrhotite, and titanohematite) must be considered when explaining remanence signatures over large crustal regions. TRM is the most efficient mechanism of acquiring strong remanent magnetization (e. g. Dunlop and Ozdemir, 1997). TRM of titanomagnetite and titanohematite, with relatively small content of Ti, is very similar to their end-members, magnetite and hematite (Clark, 1983). Thus we will use thermoremanent properties of magnetite and hematite as a model for properties of titanomagnetite and titanohematite with low Ti content.

It is not well known that the thermal magnetic properties of hematite have a reversed grainsize dependence when compared with most common magnetic minerals, such as magnetite and pyrrhotite. Magnetite and pyrrhotite, when in single domain (SD) state, more easily acquire TRM than in multidomain (MD) state (e.g. Clark, 1983). Hematite, however, acquires TRM more easily in its MD state than in SD state (Kletetschka et al., 1999; Clark, 1983). Dunlop (1981) found the single domain size of hematite to be between 0.025 and 15 μm. Because single domain behavior is markedly different from that of MD we are interested in establishing the grainsize at which hematite behaves as a truly multidomain grain.

## Experimental Procedures

Different grainsizes were prepared from crushed hematite samples L2 and fine grained hematite from samples N114078 and B7379. These samples came from hematite ore in Central Labrador and from Smithsonian Institution, Department of Mineral Sciences (USNM, samples with larger numbers) (Kletetschka et al., 1999). Coarse iron-ore hematite sample L2, from Central Labrador, was crushed and sifted to obtain an average grainsizes of 1, 0.5, 0.2, 0.1, and 0.05 mm by using U.S.A. standard testing sieves with openings 850, 250, 150, 75, 38 μm respectively. The small red powdered hematite N114078, obtained from Smithsonian Institution and described in Kletetschka et. al., 1999) was used to represent the smallest grainsize (~0.001 mm). Thirty mg of hematite grains were separated from each of the grainsize fractions. 7.7 parts of adhesive ceramic (Cotronix, item #919) and 1 part of water. We mixed and combined with these oxide fractions 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 x 1 cm). After solidification the grainsize-dependent TRM acquisition curves were measured.

Isothermal remanence acquisition (IRM) curves were determined with the 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 (model 86130 DV). All of this equipment is controlled by software "Ideas TM VSM System" version 1.799, written by Lake Shore, Measurement and Control Technologies. The maximum field is 2 Tesla.

Samples were demagnetized by application of an appropriate reversed field (coercivity of remanence). Samples were iteratively DC demagnetized in a VSM until the remanence was zero at zero field. The programmed excursions applied magnetic field steps whereafter the remanence would be measured after the applied field was reduced to zero. The field steps were programmed up to 2 Tesla.

The TRM acquisition curves are acquired in controlled weak fields for the purpose of investigating the grainsize-dependent intensity of TRM that could be 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 700□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 Lambda Electronic Corp, model LR612FM. The magnetic field inside the cooling chamber was measured with a Gaussmeter, F. W. Bell model 620Z. The probe of this Gauss meter was bent to fit inside the cooling chamber. Because the probe was modified we tested this gaussmeter against a Digital Magnetometer, Schonstedt Instrument Company, model DM2220-S4, to ensure the calibration of magnetic field values. 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. The maximum acquisition field inside this shielded oven was 1 mT. The fine-grained hematite reached only about 40% of its SIRM, even when cooled in the maximum allowable 1 mT magnetic field. 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.

## Results

Grainsize dependence of TRM (at 5 $10^{-5}$ Tesla) is given in Figure 1with the comparison of the trend for magnetite (the trend is outlined from data set compiled by Dunlop, 1990). The bend in the magnetite curve at ~1µm indicates a transition from SD to MD magnetic behavior. Our hematite data clearly show a distinction between the hematite in MD state (which reaches magnetization values of single domain magnetite) and in the SD state (data from Dekkers and Linssen, 1989); which is comparable to TRM of MD magnetite. The TRM values between grainsize of 0.1 and 1 mm are more or less constant indicating a truly MD state. TRM for 0.05 mm is slightly lower, perhaps indicating a beginning of the transition from MD to SD behavior of hematite.

To test if the 0.1 mm size of hematite is a boundary of the truly MD state we ran the TRM acquisition curves for the same grainsizes. This result (left set of curves in Figure 2) shows that all of the grainsizes above 0.1 mm cluster along one narrow acquisition path (in blue) reaching 70% of the SIRM value of hematite in an Earth like field (5 $10^{-5}$ Tesla). The sample with grain diameter of 0.05 mm (light blue) clearly separated from the main trend and reached 50% of its SIRM for the field of 5 $10^{-5}$ Tesla. Thus grainsize of 0.05 mm shows a tendency towards SD behavior, which is illustrated by acquisition curve for grainsize of 0.001 mm (purple curve) in Figure 2. TRM acquisition curves in Figure 2 clearly show that the larger MD grains of hematite are more efficient in acquiring a significant magnetic remanence in weak magnetic fields than SD hematite grains.

The right side of Figure 2 illustrates isothermal remanent magnetization (IRM) acquisition curves acquired for the same grainsizes. IRM curves indicate that the behavior of the 0.05 mm grainsize is again markedly distinct from all of the larger grainsizes which cluster along a narrow path. The IRM acquisition for SD hematite is shown in brown (Figure 2) and indicates that a large magnetic field (>2 Tesla) is required to saturate this sample.

In order to confirm that larger MD hematite grains are magnetically softer than smaller once we demagnetized the SIRM imparted to our samples with an alternating magnetic field up to 0.24T. Grainsize 0.05 mm was clearly distinct from the larger grainsizes (Figure 3). The smaller grainsizes of hematite resisted the demagnetizing field more efficiently than larger grainsizes. The magnetization of 0.001 mm fraction was resistant against AF demagnetization even in 0.24 mT peak of the alternating field and kept 60% of its SIRM.

This behavior confirms that even if MD hematite can acquire its magnetization more effectively as a TRM the remanent magnetization is less stable when subjected to the AF demagnetization. The coercivity decreases with increasing hematite grainsize and, therefore, MD hematite is magnetically softer than SD hematite.

The soft magnetic behavior of MD hematite raises a question how easy it is for MD hematite to acquire magnetization in temperatures lower than the Curie temperature. We subjected MD grains of hematite to a partial Thermoremanence (pTRM) acquisition and compared it with pTRM of multidomain magnetite. Figure 4 illustrates that MD hematite does not acquire any significant partial thermoremanent magnetization (pTRM<0.1% of SIRM) until it reaches its Curie point, when magnetization increases sharply to more than 50% of its SIRM. MD magnetite on the other hand increases its magnetization smoothly but reaches only 2% of its SIRM value. These data indicate that the blocking temperatures of these hematite samples cluster very closely to the Curie point of hematite and there is virtually no pTRM acquired at lower temperatures. Therefore, eventhough MD hematite is magnetically rather soft thermally is substantially hard.

## Implication for magnetic anomalies

The large sensitivity of multidomain hematite to weak magnetizing fields introduces a potential for the coarse-grained mineral to 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. Fraction of very small grains of magnetic minerals can be within a matrix of silicate minerals in form of exsolution. Most of the magnetic mineral is coarse-grained (Wasilewski and Warner, 1994). SD-magnetite, however, has more than two orders of magnitude larger sensitivity to acquire TRM than MD-magnetite. If there is only 1% of SD- and 99% of MD-grains of magnetite (see Figure 5), SD magnetite can dominate the NRM signature. 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. Our results suggest that if the oxygen fugacity allows MD hematite to be formed in the lower and middle crust than these hematite grains can carry the bulk of the magnetic remanence, similar to the granulites in Labrador, Canada (Kletetschka and Stout, 1998; Kletetschka, 1998) and Norway (Schlinger and Veblen, 1989). This is consistent with observation by Wasilewski and Warner (1994) that most of the crustal rocks contain grains close to transition between PSD/MD grains.

The presence of abundant coarse-grained hematite and an effective Curie temperature exceeding 600 °C would give lower crustal rocks a large remanent magnetization. The Curie isotherm for pure hematite is 670°C for an atmospheric pressure. There is no experimental data for behavior of hematite remanence at variable pressure; but if the pressure dependence is similar to magnetite (Schult, 1970), the Curie isotherm would exceed 700°C.

## Conclusions:

Magnetic measurements on different grainsizes of hematite constrain a grainsize between 0.1 and 0.05 mm as a boundary where magnetic properties of hematite start to grade towards the SD behavior. Hematite is the only mineral who can acquire a stable TRM in its multidomain state. This has an important consequence. The crustal rock contains most of the bulk of the magnetic minerals in coarse grains. Remanence was generally thought to be due to SD grains that represented only small fraction of the total magnetic mineral content. Thus MD crustal grains of hematite are potentially able to carry the bulk of the magnetic remanence signature in crustal rocks. These unique properties of TRM of MD hematite require a re-evaluation of their role in the interpretation of magnetic anomalies.

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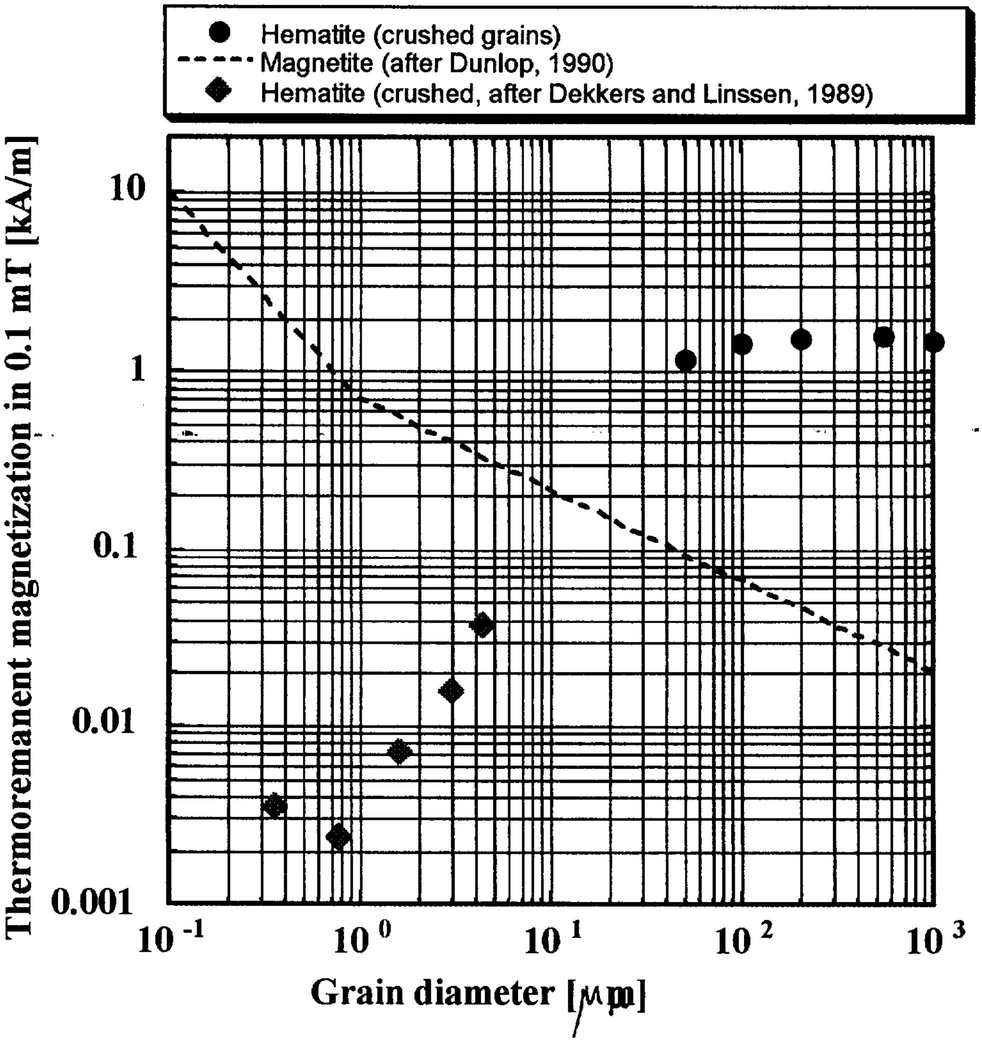

Figure 1:

Comparison of the grainsize dependence of the intensity of weak-field TRM in hematite with the trend of the intensity of weak field TRM in magnetite(magnetite trend is from Dunlop (1990). Fine-grained hematite samples are from Dekkers and Linssen (1989) linearly recalculated for 0.1 mT field from the original 0.084 mT.

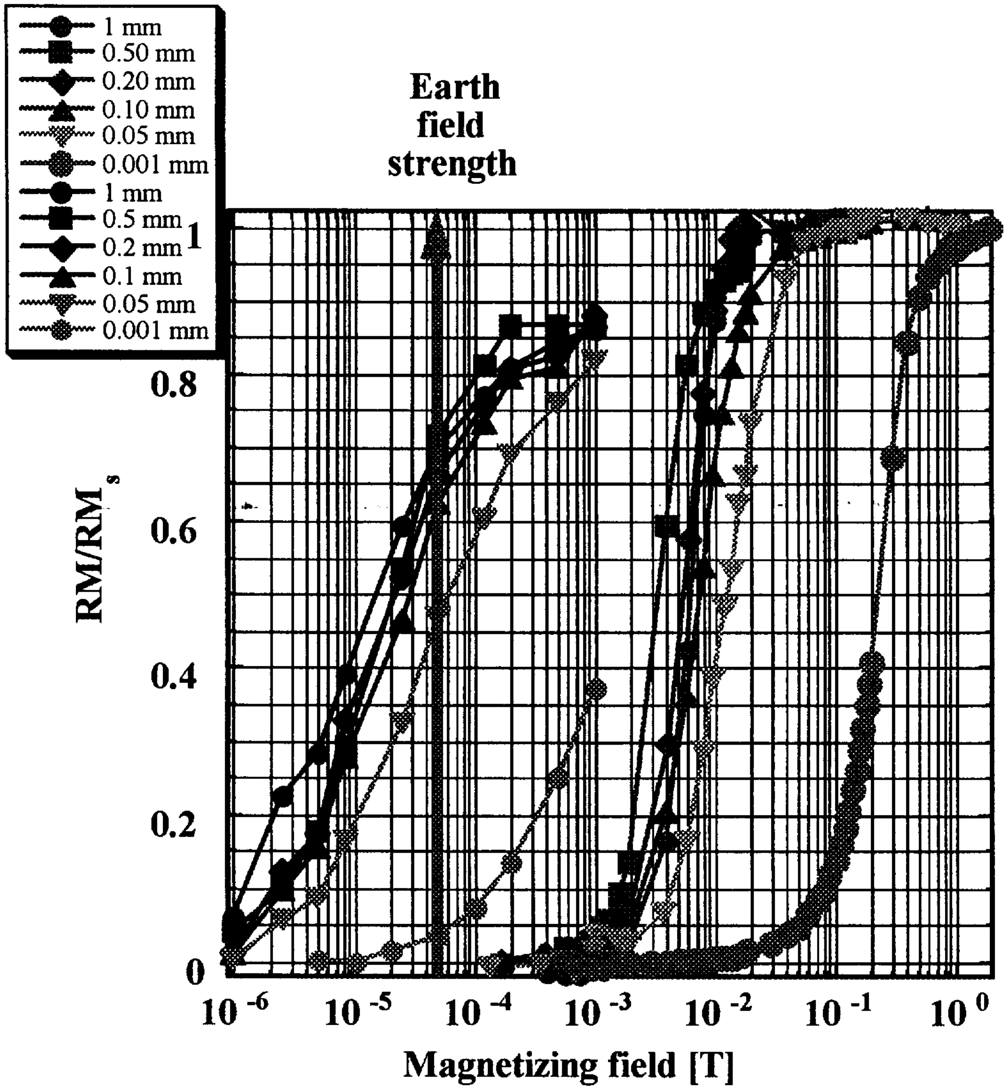

Figure 2:

TRM acquisition curves for different grainsizes of hematite are compared with the IRM acquisition curves done with the same samples. Remanent magnetization is normalized by saturation isothermal remanent magnetization (SIRM).

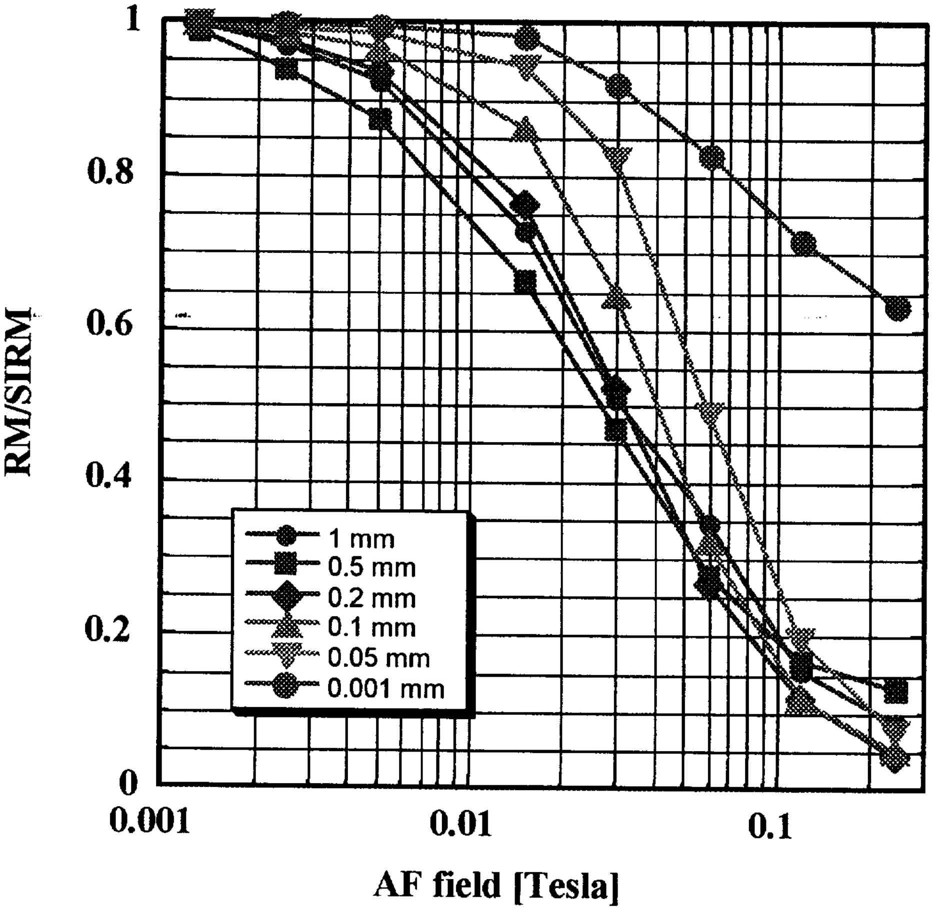

Figure 3:

AF demagnetization of SIRM for different grainsizes of hematite shows break from the general trend for the grainsize of 0.1 mm.

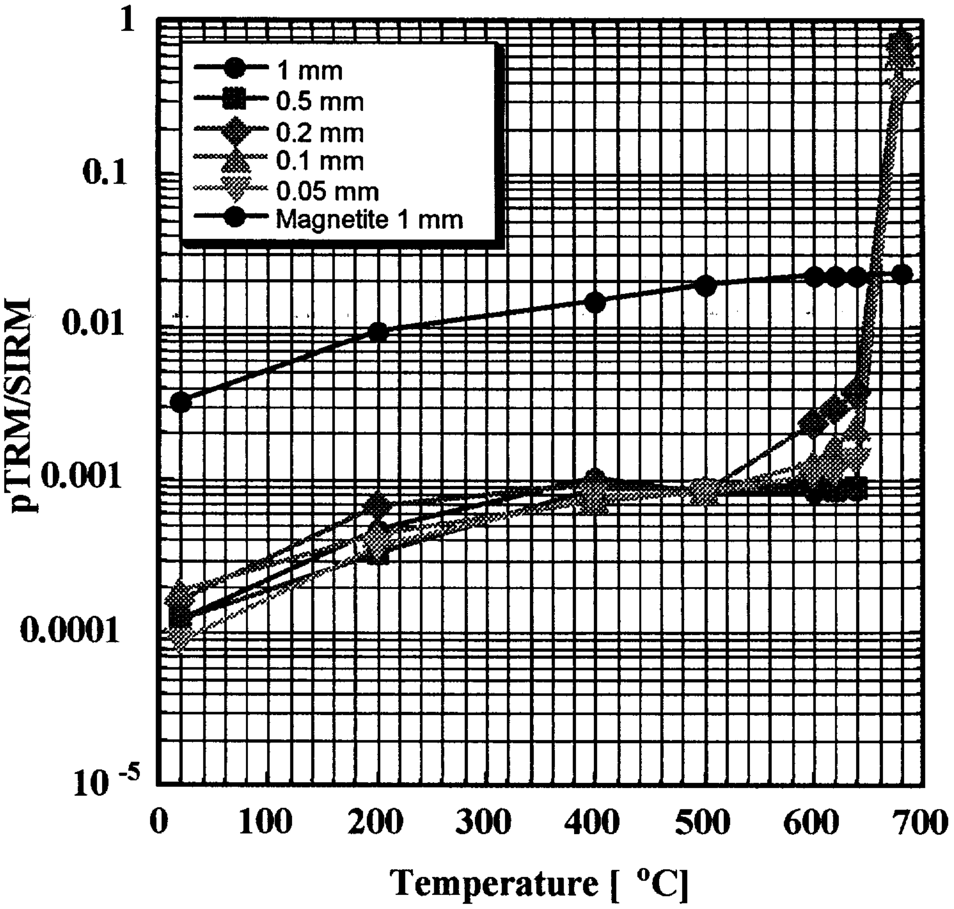

Figure 4:

Partial thermoremanent magnetization (pTRM) of multidomain hematite is compared with pTRM of multidomain magnetite.

- **Acquisition efficiency:**

**most efficient**

**SD magnetite**
**SD pyrrhotite**
**MD hematite**
**MD pyrrhotite**
**MD magnetite**
**SD hematite**

**least efficient**

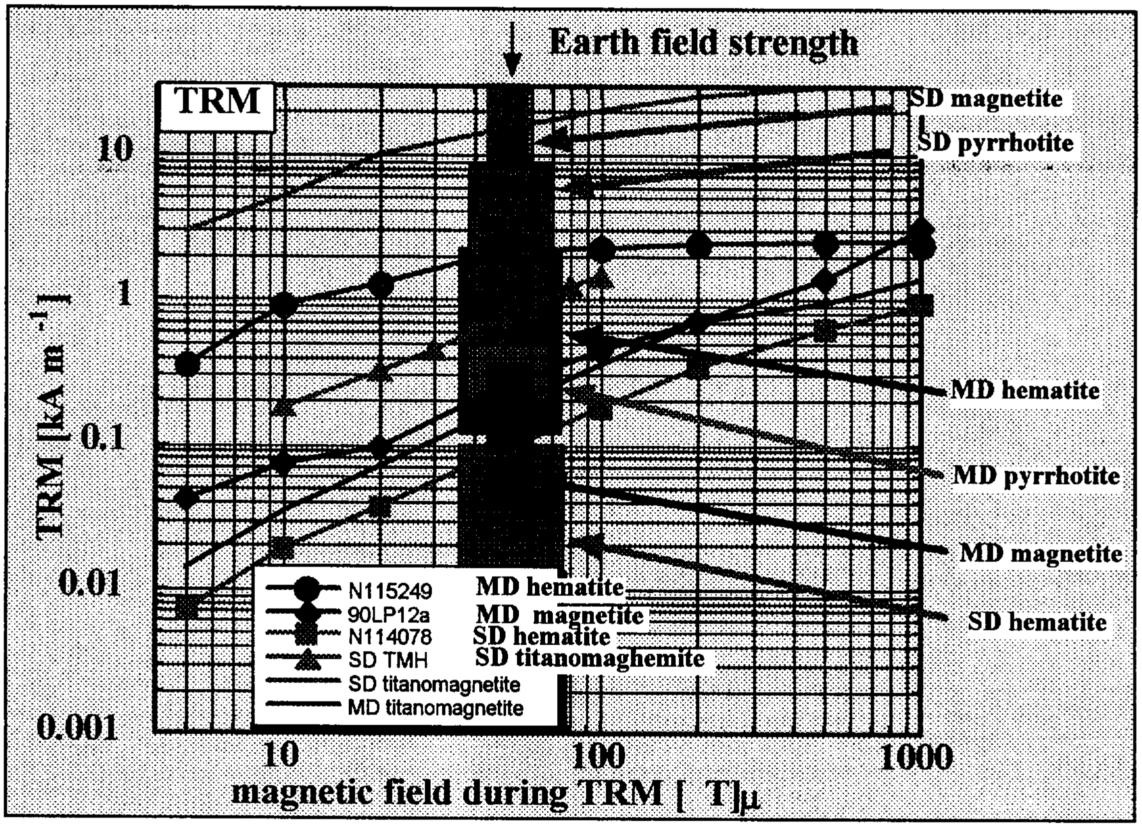

Figure 5:
Summary of TRM acquisitions in low magnetic fields. Single domain hematite, multidomain hematite, and magnetite sample numbers are those of the Department of Mineral Sciences, NMNH, Smithsonian Institution and described in Kletetschka et al., 1999. SD titanomaghemite data taken from Ozdemir and O'Reilly, 1982. Ranges of TRM for magnetite, pyrrhotite, and hematite are according to Clark, (1983). SD (0.04 mm) and MD (2 mm) titanomagnetite curves are trends taken from Ozdemir and Reilly (1982) and Tucker and O'Reilly (1982), respectively.