HEMATITE VS. MAGNETITE AS THE SIGNATURE FOR PLANETARY MAGNETIC ANOMALIES?

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Abstract

Crustal magnetic anomalies are the result of adjacent geologic units having contrasting magnetization. This magnetization arises from induction and/or remanence. In a planetary context we now know that Mars has significant crustal magnetic anomalies due to remanent magnetization, while the Earth has some anomalies where remanence can be shown to be important. This picture, however, is less clear because of the nature and the magnitude of the geomagnetic field which is responsible for superimposed induced magnetization. Induced magnetization assumes a magnetite source, because of its much greater magnetic susceptibility when compared with other magnetic minerals.

We investigated the TRM (thermoremanent magnetization) acquisition of hematite, in weak magnetic fields up to 1 mT, to determine if the remanent and induced magnetization of hematite could compete with magnetite. TRM acquisition curves of magnetite and hematite show that multidomain hematite reaches TRM saturation (0.3-0.4 A m^2 / kg) in fields as low as 100 μT. However, multidomain magnetite reaches only a few percent of its TRM saturation in a field of 100 μT (0.02-0.06 A m^2 / kg). These results suggest that a mineral such as hematite and, perhaps, other minerals with significant remanence and minor induced magnetization may play an important role in providing requisite magnetization contrast. Perhaps, and especially for the Mars case, we should reevaluate where hematite and other minerals, with efficient remanence acquisition, exist in significant concentration, allowing a more comprehensive explanation of Martian anomalies and better insight into the role of remanent magnetization in terrestrial crustal magnetic anomalies.

Introduction

This report considers two assumptions central to the interpretation of large amplitude crustal magnetic anomalies. These are: 1) that the main magnetic mineral is magnetite, and 2) in the case of the Earth the mode of magnetization is entirely induction. Generally when someone considers how "magnetic" something is he or she may use a strong magnet to test for the attraction force between the magnet and the object. The strong magnet is a source of strong inducing field that is 3-5 orders of magnitude more intense than the intensity of the geomagnetic field. This procedure will raise the induced magnetization of the object (for example a rock with magnetite particles) 3-5 orders of magnitude, or in case of a very strong magnet towards the saturation point of the magnetic carriers. When attraction is observed it is most likely due to magnetite which has large induction because of its large magnetic susceptibility. The large values of induced magnetization exhibited by magnetite are responsible for the common belief that magnetite

is the likely source of terrestrial crustal magnetic anomalies (Shive and Fountain, 1988, Wasilewski and Mayhew, 1992)

Clark (1983) summarized the range of TRM expected for the principal iron oxide minerals found in terrestrial rocks. Insofar as we are aware (McSween, 1985) the same iron oxide mineralogies are found in the Martian rocks. Magnetic properties of iron oxide minerals change according to their grainsize. The critical single domain size for magnetite is 0.06 μm, for hematite the size is 15 μm, for titanomagnetite the size is 2.4 μm, and for pyrrhotite the size is 1.6 μm (Clark, 1983). Wasilewski and Warner (1994) used the SD-PSD-MD (Single Domain – Pseudo Single Domain – Multi Domain) categorization based on size dependent hysteresis properties (Day et al 1977) and presented magnetic hysteresis data for a wide range of samples including xenoliths, high grade metamorphic terrane, crustal sections etc. This SD-PSD-MD categorization suggests that most rocks contain PSD-small MD grains.

This paper reiterates the Clark (1983) emphasis on the importance of remanence in magnetic anomaly interpretation. Magnetite, titanomagnetite, and pyrrhotite, all of which are found in the SNC meteorites (McSween, 1985), and MD hematite (Christensen et al., 1999), should be considered as possible candidates for the large Martian remanent signature. Maghemite if present would be magnetically similar to magnetite (Dunlop and Özdemir, 1997).

Magnetization of hematite and magnetite

The most common terrestrial magnetic iron oxide is magnetite (Fe_3O_4). In the Earth's field ($5 \cdot 10^{-5}$ T) magnetite has the largest induced magnetization (60-220 A/m) among the common magnetic minerals (Maher, 1988). Induced magnetization, M_i, is function of magnetic susceptibility χ and the external magnetic field B ($M_i = \chi \cdot B/\mu$), where μ ($\mu = 4\pi \cdot 10^{-7}$ Ohm sec/meter) is the constant of vacuum magnetic permeability). Magnetite can also exist in a superparamagnetic state when the grainsize is smaller than 50

nm. Under this condition the susceptibility of a 30 nm size cube of magnetite, at room temperature, is about 650 (Dunlop and Özdemir, 1997) which produces an enormous induced magnetization of approximately 26,000 A/m.

A comparison of thermoremanent magnetization (TRM) of magnetite relative to induced (IM) is given in table 1. Schlinger (1985) suggested that the most common range of magnetite grain size is 20-200 μm for mid and deep crustal rocks.. This 20-200 μm grainsize range gives TRM values, in crustal conditions, of 25 - 250 A/m (Dunlop, 1990). Taking into account magnetite susceptibilities for these grainsizes (Maher, 1988) we have induced magnetization between 80 and 140 A/m (see Table 1). This indicates that in the geomagnetic field a magnetite-rich rock, with acquired thermoremanence, may have significantly larger remanent than induced magnetization. The relative significance of induced and remanent magnetization is expressed by their ratio known as Koenigsberger ratio (Q). Data in table 1 indicates that Q should be generally greater than one for both hematite and magnetite. This is not true in cases where the original thermoremanence was destroyed (chemically and/or physically) or when different types of remanence have been re-acquired (for review see table 3.1 in Merrill et al., 1996). For example, the introduction of superparamagnetic particles of magnetite, due to various types of chemical alteration of iron silicates, could be significant but is probably not common because the volume of coarse-grained magnetite in rock is usually much greater than the volume of superparamagnetic magnetite.

The second most abundant iron oxide found in crustal rocks is hematite (Fe_2O_3). Hematite as well as other common iron bearing minerals has susceptibility less than 0.01 SI. This would mean, that the total induced magnetization of a hematite-magnetite bearing rock is dominated almost entirely by magnetite (see table 1 and table 3). Given that the induced magnetization of hematite is not significant, would its remanent magnetization dominate the total magnetization of a rock where both minerals are present and hematite is significant volumetrically? To investigate this scenario hematite specimens were obtained

4

from all over the world (selected from the mineral collection in the National Museum of Natural History, Smithsonian Institution, Washington DC). The specimens from the Smithsonian collection could be divided into four groups (Figure 1). The first group consists of compact fine powder of reddish hematite with grainsize less that 1 μm (See Figure 1). The second group is made up of pencil-shaped rods, with the pencil-cross-sectional diameter between 0.2-3 μm. The third group contains equidimensional, shiny, coarse grains (>60μm). The forth group consits of thin plates where the plate thickness varies from 0.1 – 10 μm . These morphological groups of hematite show distinct magnetic hysteresis properties (Figure 2). The hysteresis loops were measured at room temperature in fields between –2T and +2T using a vibrating sample magnetometer (VSM, see appendix for more detailed description). Results show that coarse-grained hematite has relatively low coercivity (2-10 mT) and relatively large saturation remanence (0.25-0.35 Am^2kg^{-1}). Fine-grained hematite has correspondingly large saturation remanence, however, the coercivity of these samples is much larger (200-500 mT) than for the coarse-grained case. Both plate and pencil-like hematite grains have saturation remanence to saturation magnetization ratios close to unity. Plate-like hematite grains have a lower coercivity (7-20 mT) than the pencil-like ones (200-600 mT); this is probably because multiple domains prevail in large planar grains and single domains can prevail in the pencil-like grains.

The NRM and TRM values for the hematite samples used in this study are presented in histogram form in Figure 3. The SD powder samples and pencil shaped samples show negligible NRM's in the diagram and the TRM's are also small (<50 Am^{-1} for the fine powder and <150Am^{-1} for the pencil shaped samples). In contrast the plate like samples with NRM's up to 275 A m^{-1} can have TRM's up to 750 A m^{-1}. The coarse grained powder samples have NRM's >750 A m^{-1} and the TRM's are >1000 and up to 1550 A m^{-1} The coarse grained powders also retain the largest percentage of the remanence over time (using the comparison of TRM and NRM).

Of all the natural magnetic minerals studied thus far only the coarse grained hematite samples have a REM value (ratio between NRM and saturation remanence) much greater than 0.1 (Wasilewski and Kletetschka, 1999). Previously large REM values were considered to be associated with contamination or with lightning strikes. These data on MD hematite refine our understanding about remanence in rocks. Hereafter the large REM values must be confirmed not to be associated with MD hematite.

Remanence acquisition curves for hematite and magnetite

A fine grained sample (N114078) and a coarse grained one (N17174) were selected for detailed examination. Some of the other samples were likely to have anisotropic properties because of the plate-like and pencil-like morphologies. Consequently data for the coarse and fine grained hematite samples can be found in Figures 1, 2, 3, 4 and table 2.

Isothermal remanence acquisition curves are useful in that they reflect the coercivity of the material in question and in fact are related to the various high field characterization techniques that are presently in use (Denkers, 1981). The TRM acquisition curves are acquired in controlled weak fields for the purpose addressing the level of remanence that could be acquired over a range of weak fields realistic for planetary bodies with possible dynamo generated fields less than or greater than the geomagnetic field.

To create the isothermal remanence acquisition (RA) curve the sample was iteratively DC demagnetized to the remanent coercive force point when the return to zero field would result in zero remanence. The programmed excursions apply set magnetic field steps whereafter the remanence would be measured after each step after the applied field was reduced to zero. The field steps are programmed up to 2 Tesla. These RA curves for fine and coarse grained hematite are shown in Figure 4. The magnetic field required to achieve 50% saturation remanence is 0.005 Tesla for the coarse hematite and 0.2 Tesla for the fine hematite sample. These acquisition curves are consistent with the coercivities (see Figure 2).

The TRM acquisition curves were obtained by heating the samples in a shielded oven, up to 800°C, and by subsequent cooling to room temperature in a controlled external field. The magnetic field inside the oven was calibrated with a gaussmeter (Bell, model 620, for details see Appendix). The smallest field inside this shielded oven was 2-3 μT. Consequently we were not able to completely thermally demagnetize the coarse-grained hematite (NR17174) due to this residual magnetic field (2-3μT) inside the shielded oven. The maximum field inside this shielded oven was 1 mT. The fine-grained hematite did not saturate, 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. None of the thermally treated samples showed significant changes in their hysteresis properties.

Magnetic fields of tens of milli-Tesla would be required to saturate the fine-grained hematite but the coarse-grained hematite requires a surprisingly small hundreds of micro-Tesla field. Therefore, even when cooling in a field as small as the geomagnetic field we can obtain a remarkable 60-80% of the saturation of TRM (Figure 4). The surprising feature of this MD hematite acquisition is that we can have a TRM, equivalent to that of magnetite, by a mineral with only a fraction of the saturation magnetization of magnetite. This may be a very relevant consideration for magnetization models of the Martian crust (Connerney et al., 1999).

We measured TRM acquisition curves for mixtures of coarse-grained hematite and magnetite (see Figure 5). These samples were prepared by reducing the size of the pure minerals (hematite N115249, magnetite 90LP12) to 0.5 mm equidimensional grains, they were mixed and weighted (Table 3) to produce 25-30 mg samples. A 1 ml solution of adhesive ceramic was stirred into the oxide mixtures and this viscous substance was poured into a small cylindrical opening (0.1 cm^3) in the center of ceramic disc (2.54 x 1 cm) to solidify. The resulting TRM acquisition curves are shown in Figure 5. Magnetite TRM is much lower than TRM of hematite acquired in 50 μT external magnetic field. For magnetite

to match the remanence of coarse-grained hematite we would need 25 times more of this coarse-grained mineral.

Relevance to crustal magnetic anomalies

Table 3 illustrates the relation between induced and remanent magnetization of our artificial mixtures of hematite and magnetite. All of the hematite-magnetite mixtures have a greater thermoremanent magnetization than induced. Assuming only multidomain magnetite to be the magnetic carrier, modeling give us almost an order of magnitude lower magnetization than if the rocks contained the same amount of mutlidomain hematite. To illustrate this by example, using our experimental data (Table 3), rock with 1% of multidomain magnetite would have magnetization (40+190) A/m * 0.01 = 2 A/m . Rock with 1% of multidomain hematite generates magnetization (1165+7) A/m * 0.01 =12 A/m . Rocks with 1% of equal amounts of the two magnetic minerals have (590+109) A/m * 0.01 = 7 A/m. Magnetization of this magnitude (7A/m) is required by some of the magnetic anomaly models (Mayhew et al., 1985; Mayhew and LaBrecque, 1987; Shive et al., 1992).

If the oxygen fugacity and mineral composition allows hematite-magnetite assemblage to be formed, hematite minerals can provide dominant control over the distribution of magnetic anomalies by their thermally acquired magnetization. This was the case in Central Labrador, Canada, where Precambrian granulites are enriched with Ti-hematite and where the oxygen fugacity during the metamorphism was relatively high (Kletetschka and Stout, 1995). The magnetic anomaly in Central Labrador spans more than 5000 km^2 and is entirely due to concentration of hematite in the Wilson Lake allochthon (Kletetschka and Stout, 1998; Kletetschka, 1998).

Conclusions

Our analysis of remanent and induced magnetization of two major oxide minerals with very contrastive magnetic properties suggests that remanent magnetization may

dominate induced magnetization regardless of the level of induced magnetization.. Our results show that fine-grained hematite requires more than two orders of magnitude larger magnetizing field than coarse grained hematite to achieve both isothermal remanence acquisition and TRM saturation. By comparing TRM acquisitions of coarse-grained hematite and magnetite we demonstrate that hematite may control the remanent magnetization, even if the rock contains an order of magnitude greater amount of magnetite than hematite.

Acknowledgement:

Appendix

Some details of experimental procedures

Scanning Electron Microscopy

Scanning electron microscopy has been done on non-coated samples chipped off the USNM specimens. We used the SEM 500M, made by Philips Electron Optics operating at 25 KV accelerating voltage and spotsize of 320 Å.

Sample preparation and NRM measurements

Small pieces (about 50 mm^3) were chipped off the original USNM samples. Their mass was measured by Sartorius balance (type 2462). The mixture of 7.7 parts of ceramic adhesive (item #919, made by Cotronix) and 1 part of water was used to attach samples to the circular 1 inch glass slide. These sample slides were measured with the Superconducting Rock Magnetometer (SRM, Superconducting technology, model C102) The SRM was controlled by Macintosh-based software (MacSuperMag, version 2.0) written by Keith Hogie.

Measurements of hysteresis loops

Samples used in the NRM measurements were attached to the end of plastic rod by means of nonmagnetic scotch tape and measured with the vibrating sample magnetometer (VSM), model 7300, made by 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.

TRM measurements

Samples were removed from the glass slides and placed in a Thermal Specimen Demagnetizer (model TSD-1, made by Schonstedt Instrument Company). A maximum temperature of 800°C was used for all experiments. Oven is 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 made by Lambda Electronic Corp (model LR612FM). The magnetic field inside the cooling chamber was measured with a Gaussmeter made by 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, made by Schonstedt Instrument Company, model DM2220-S4 to ensured the calibration of magnetic field values. The field applied during the cooling of our samples was 50μT. Hysteresis loops were measured afterwards to see if any changes took place during heating and cooling.

None of our hematite samples changed its hysteresis behavior after the heating indicating no significant chemical or structural change.

IRM acquisition curves

IRM acquisition curves were determined with the VSM. After finishing magnetic hysteresis measurements the samples were demagnetized by application of an appropriate reversed field (coercivity of remanence). Then, increasing external fields were applied and turned off and magnetic remanence was measured (Figure 4). The minimum and maximum applied external fields were 20μT and 2 T respectively.

TRM acquisition curves

Samples were placed inside the TSD-1 oven and heated to 800°C. After cooling in a minimum magnetic field (5 μT) the magnitude and direction of magnetization were measured with the SRM. This procedure was repeated until we reached the maximum field

of 1 mT in the cooling chamber (Figure 4). Hysteresis loops were measured at completion of the experiments and none of our hematite samples indicated any change in hysteresis properties, indicating no significant chemical change.

Artificial mixtures

The mixtures of coarse-grained hematite and magnetite (see Figure 5) were prepared by reducing the size of the pure minerals (Hematite N115249, Magnetite 90LP12) down to about 0.5 mm equidimensional grains. Grains were picked from crushed samples. Each of the mixtures contained a total of 20 grains of oxide mineral. These grains were mixed and weighted (Table 3) and produced 25-30 mg of each oxide mixture. Separately, we mixed 7.7 parts of adhesive ceramic made by Cotronix (item #919) and 1 part of water. We stirred each of our oxide mixtures into 50 mm^3 of ceramic material and poured the viscous substance into a small cylindrical opening (0.1 cm^3) in the center of a ceramic disc and let it solidify.

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Magnetization of magnetite and hematite			
	Induced [A/m]	Thermoremanent [A/m]	Total [A/m]
Magnetite 20-200 μm	~140 Maher, 1988	60-25 Dunlop, 1990	200-165
2-20 μm	80-140 Maher, 1988	250-60 Dunlop, 1990	330-200
0.2-2 μm	60-80 Maher, 1988	1000-250 Dunlop, 1990	1060-330
0.02-0.2 μm	220-60 Maher, 1988	5000-1000 Dunlop, 1990	5220-1060
0-0.02 μm	26000 Dunlop, 1997	0	26000
Hematite 20-200 μm	~7 this study	600-1600 this study	600-1600
0-20 μm	0.02-2 Hunt et al., 1995	30-300 Clark, 1983	30-300

Table 1:
Isothermal and thermoremanent magnetization is acquired in a presence of 50 μT external magnetic field.

Samples of hematite and magnetite		
sample	origin	note
N115249	USNM, Brazil	Coarse-grained hematite
NR17174	USNM, Arizona	Coarse-grained hematite
N114078	USNM, Iran	Fine-grained hematite
B7379	USNM, Germany	Fine-grained hematite
No115380	USNM, Egypt	Fine-grained hematite
N66844	USNM, Germany	Pencil-like hematite
N13026	USNM, Germany	Pencil-like hematite
NR13597	USNM, England	Pencil-like hematite
B7371	USNM, Michigan	Plate-like hematite
N127244	USNM, Greenland	Plate-like hematite
N36085	USNM, England	Plate-like hematite
N46422	USNM, Africa	Plate-like hematite
L2	UofM, Labrador	Coarse-grained hematite
90LP12	UofW, Adirondacks	Coarse grained magnetite

Table 2
Most of the samples of hematite are from Smithsonian Institution, Department of Mineral Sciences (USNM). Sample L2 is a representative sample from an old iron mine near Fire Lake in Central Labrador, Canada, collected for the University of Minnesota (UofM) study (Kletetschka and Stout, 1998). Sample 90LP12 contains coarse crystals of non-titanium magnetite obtained from Prof. John Valley, University of Wisconsin (UofW).

Mixtures of hematite and magnetite						
Sample	Hematite [mg]	Magnetite [mg]	Total [mg]	TRM at 5 10^{-5}T [A/m]	Mass χ [m³/kg]	M_I at 5 10^{-5}T [A/m]
HM100	25.3	0	25.3	1165	0.18	7
HM75	15.5	8.3	23.8	750	1.87	74
HM50	14.8	14.9	29.7	590	2.74	109 ·
HM25	6.3	23.0	29.3	340	4.39	174
HM0	0	25.5	25.5	40	4.86	193

Table 3

Magnetic measurements on various mixtures of hematite and magnetite favor coarse-grained hematite as the main carrier of total magnetization. M_I and TRM indicate induced and thermoremanent magnetization respectively in the Earth magnetic fields. χ = susceptibility.
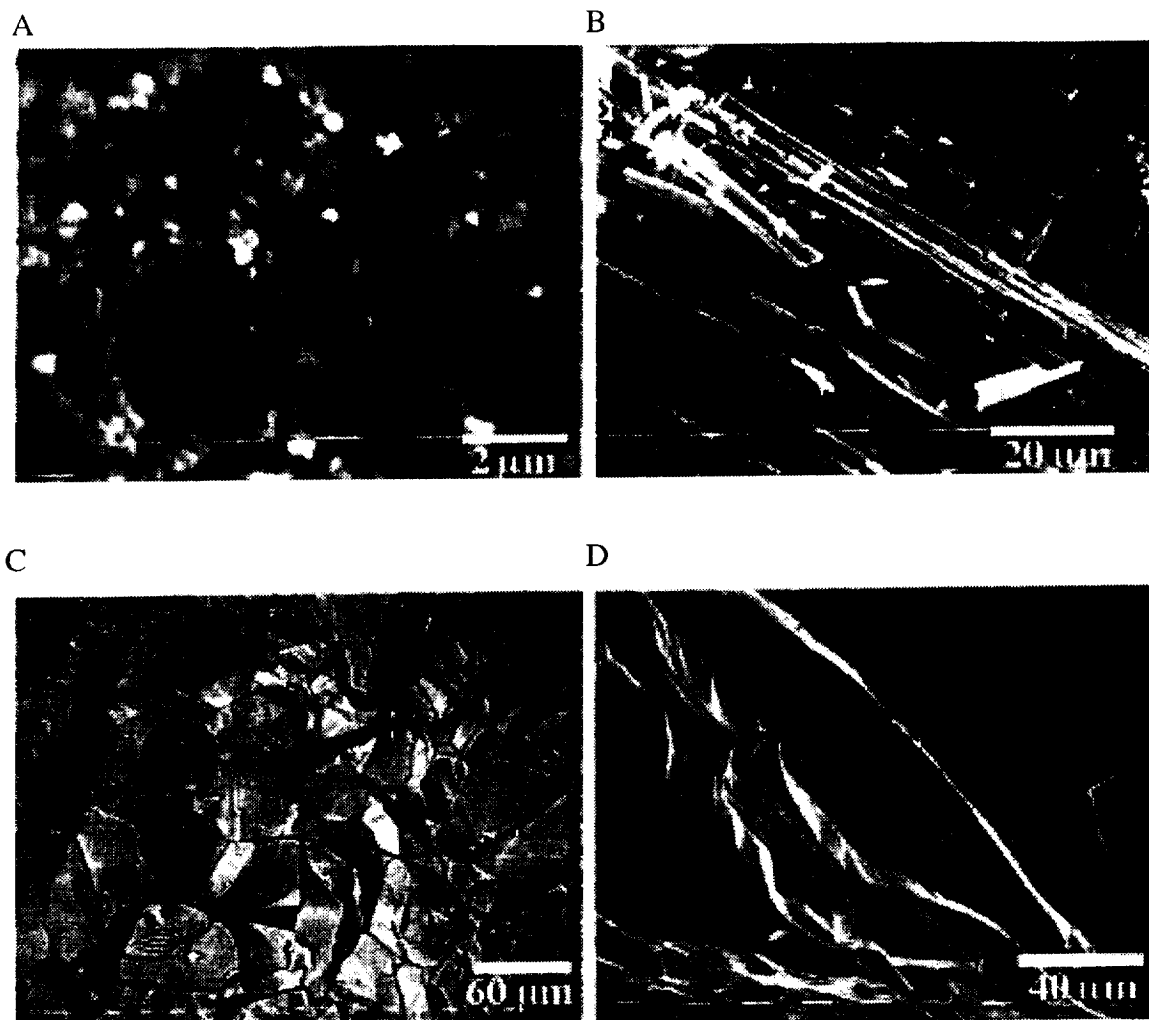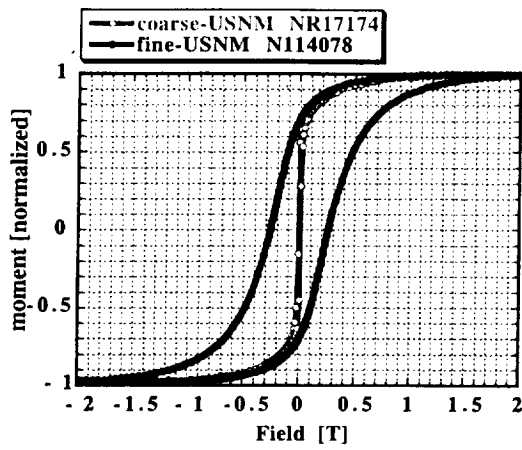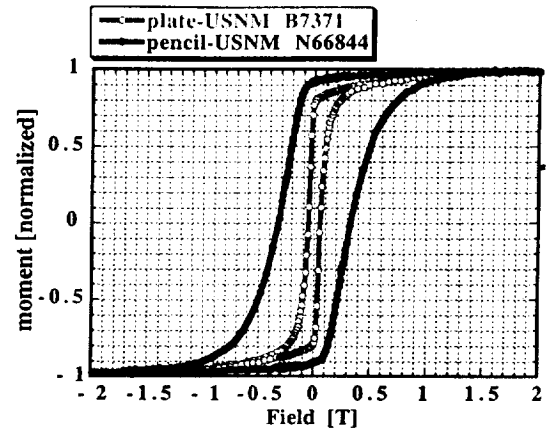
Figure 1
Four common forms of hematite: A. fine-grained reddish powder (N114078); B. pencil-like (N13026); C. equidimensional coarse-grained (NR17174); D. plate like (N36085).

A

B

Figure 2
Different morphology of hematite is reflected in the shape of the hysteresis loops. A. fine-grained and coarse-grained. B. plate-like and pencil-like.
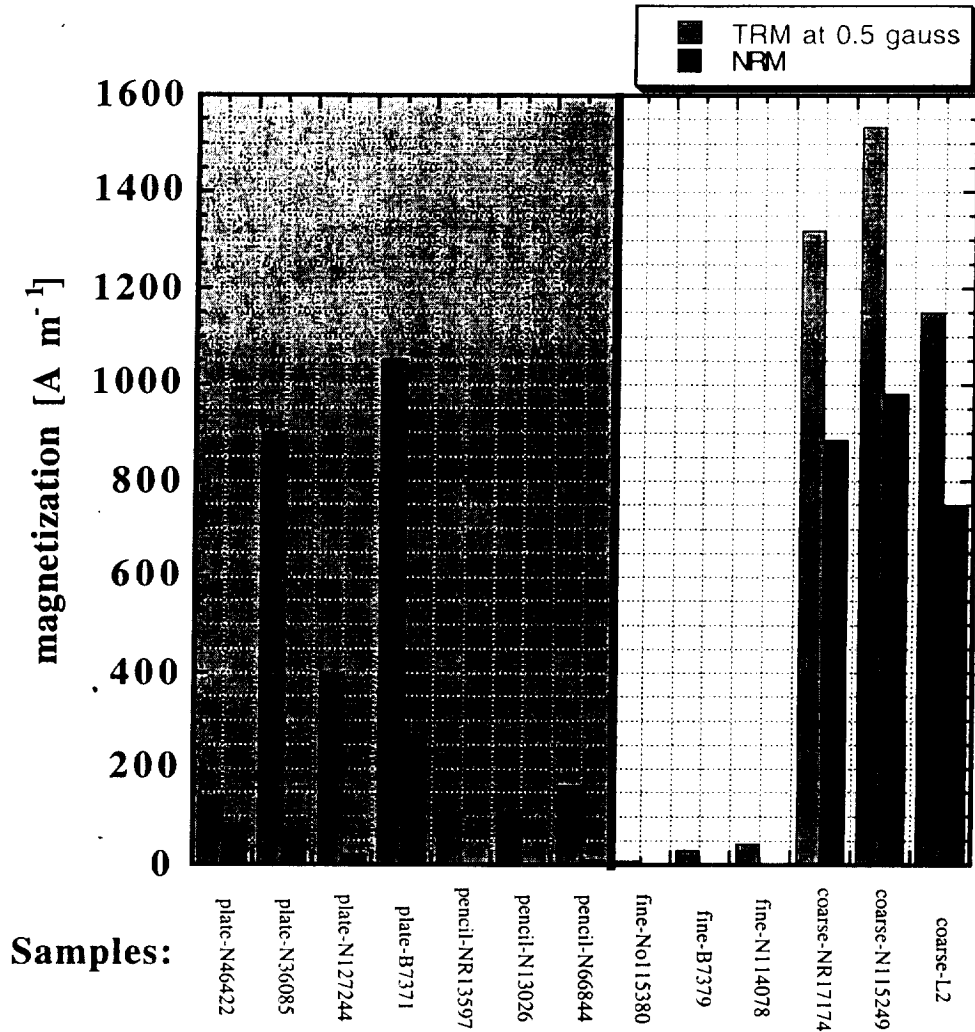
Figure 3
Magnetization of representative hematite samples characterizing the most common morphology. The anisotropic plate and pencil shaped samples are located in the shaded area. Sample numbers are those of the Department of Mineral Sciences, NMNH, Smithsonian Institution. Sample L2 is a coarse-grained hematite sample from Iron mine near Fire Lake in Central Labrador, Canada.
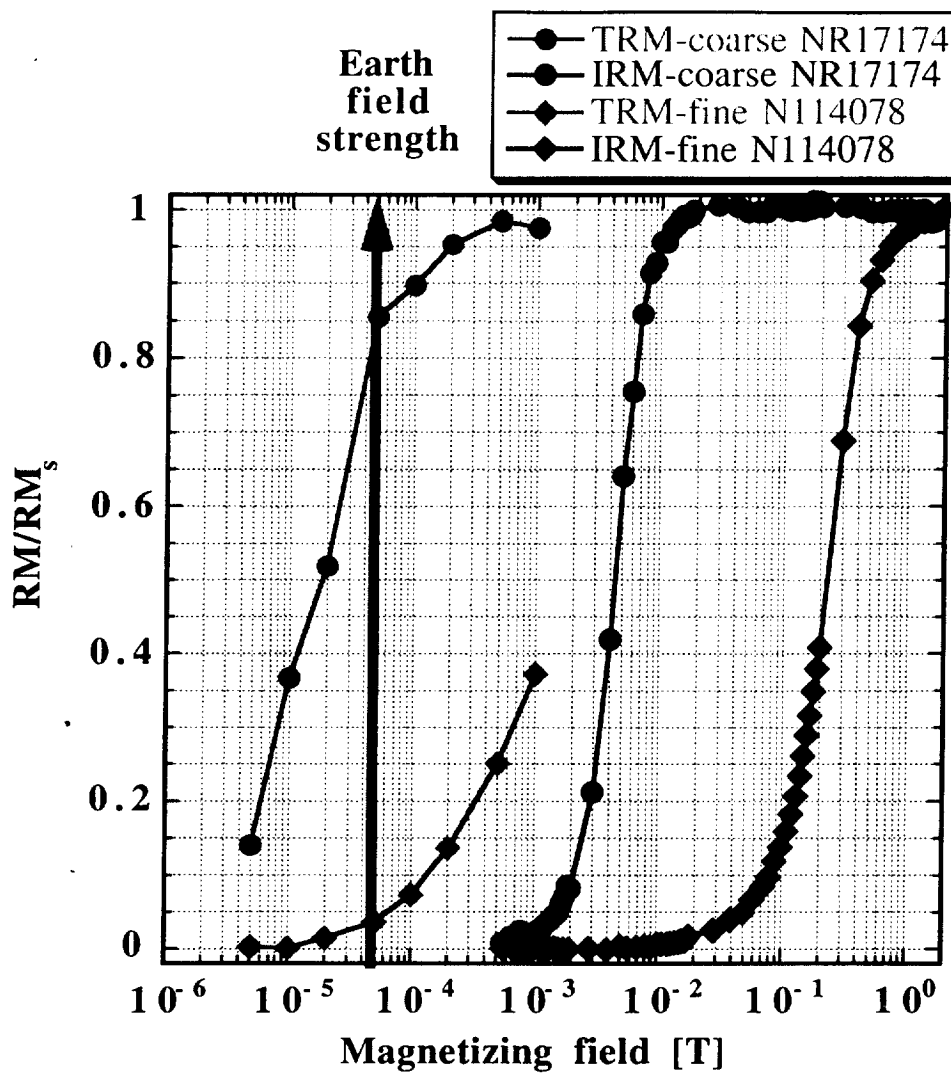
Figure 4
Thermal and isothermal remanence acquisition curves for coarse and fine-grained hematite. Note that multidomain hematite is nearly saturated by the Earth's field. TRM acquisition of fine-grained hematite did not achieve saturation due to limited magnetizing field of the cooling chamber.
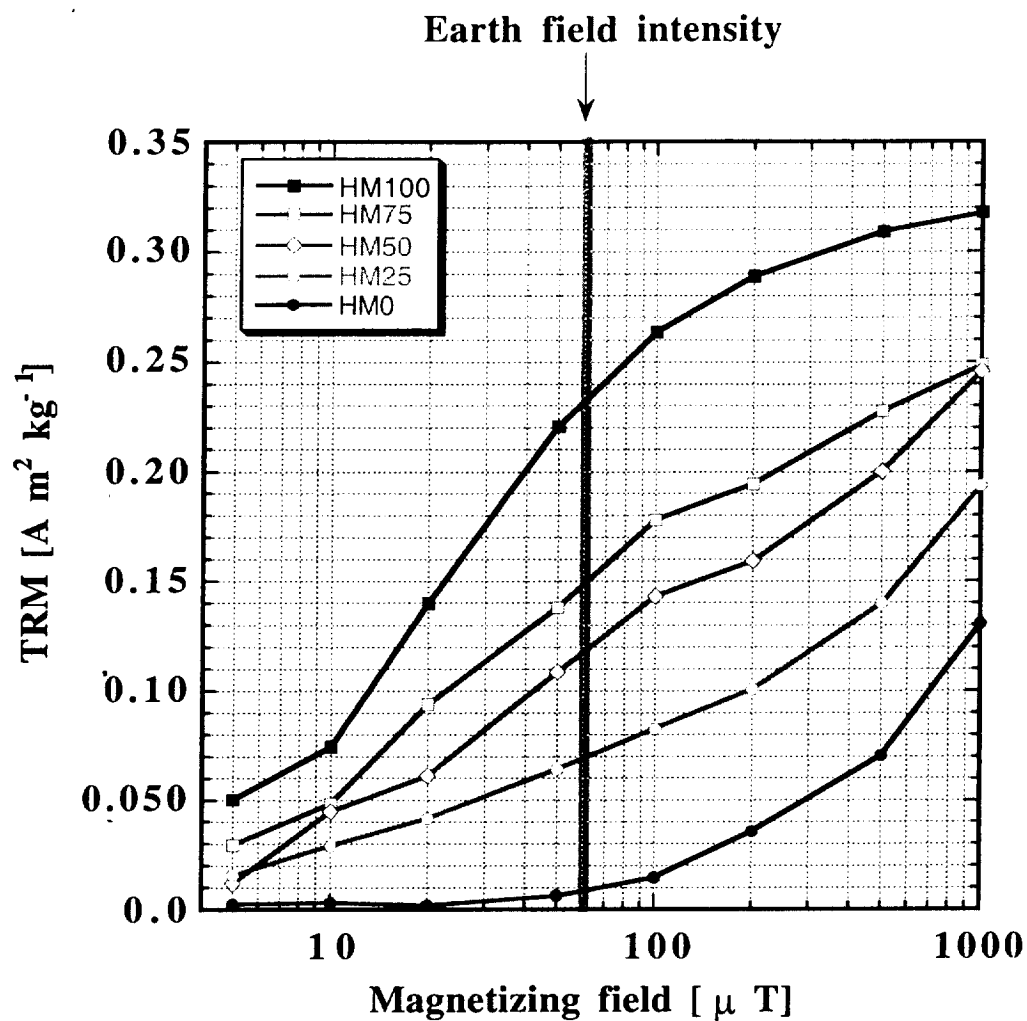
Earth field intensity

Figure 5
Thermoremanent acquisition curves for artificial mixtures of coarse-grained hematite (HM100=N115249) and magnetite (HM0=90LP12) randomly dispersed (grainsize >100μm) in ceramic adhesive. Note that the TRM of magnetite grains is only about 4% of the TRM of just hematite grains in the Earth field during cooling. The exact proportions of hematite and magnetite are given in Table 3.

Popular Summary of: Hematite vs. magnetite as the signature for planetary magnetic anomalies, G. Kletetschka, P. Taylor and P. Wasilewski.

When a region of the earth possess a greater or less magnetic field then we predict we call this magnetic feature a magnetic anomaly; that is, something that is unexpected. The reason for this anomaly is that this area of the earth has more magnetic material than the surrounding region. In some ways it is similar to having many small iron magnets buried in the ground, except that in the real world they are not small magnets but magnetic minerals. It is generally assumed that the magnetic material responsible for these magnetic anomalies is the mineral magnetite. The chemical formula for magnetite is Fe_3O_4. There is another mineral hematite, whose chemical formula is Fe_2O_3 , which is believed to be too weak to produce magnetic anomalies. Hematite is more oxidized or "rusted" than magnetite. We have measured the magnetic properties of both hematite and magnetite and determined that under the proper conditions hematite could produce these same magnetic field anomalies as magnetite. In addition, a great amount of hematite has been found on Mars and we suggest the hematite may be important in producing the magnetic anomalies observed on Mars.