The IRM
Quarterly
Spring 2010, Vol. 20 No. 1

ISSN: 2152-1972

Inside...

Interpretation of Low-Temperature Data Part II: The Hematite Morin Transition

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In Part II of our ongoing series on interpretation of low-temperature data, we take a look at the nature of the hematite Morin transition. This is the first of several magnetic phase transitions that will be highlighted, including the magnetite Verwey transition and the spin glass transition in the hemo-ilmenite solid solution. Hematite (αFe_2O_3) is a common mineral in many natural samples, and its presence is often easy to recognize via its high coercivity and high unblocking temperatures (just below 675°C). However, in some cases a non-destructive method may be preferred, in which case identification of the Morin transition [Morin, 1950] at ~262K (-11°C) is diagnostic of hematite. Natural samples at high elevations or latitudes may cycle many times through the Morin transition, so an understanding of what happens to magnetic properties at this temperature is important for paleomagnetic interpretations.

The Morin Transition

The basic magnetic structure of hematite is antiferromagnetic; its two magnetic sublattices have equal moment. However at temperatures above the Morin transition temperature (T_M), the spins are not perfectly anti-parallel, and a slight canting leads to a weak, "parasitic" ferromagnetism in the basal plane, perpendicular to the hexagonal c-axis. At $T = T_M$, magnetocrystalline anisotropy changes sign, the easy axis of magnetization shifts, and the spins rotate from the basal plane into alignment with the c-axis at $T < T_M$. The sublattice spins are now also perfectly anti-parallel, and the parasitic moment disappears. The only remaining remanence arises from defects in the crystal structure (a "defect ferromagnetism").

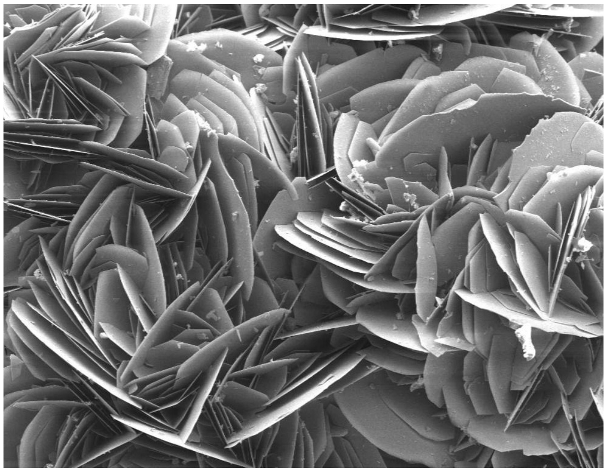

Figure 1*. Scanning electron microscope image of hematite. Image is ~800 microns across. (Image from Wikipedia Commons)*

The exact temperature of the Morin transition is dependent on a number of variables: grain size, cation substitution, lattice defects (which lead to strain), pressure, and applied field. For pure, stoichiometric hematite at 1 atm, $T_M \approx 262K$ [Morrish, 1994]. A weak grain size dependence from 10,000 µm to ~0.1 µm results in a suppression of T_M by only ~10 K (to 250 K) at the small end of this range [Özdemir et al., 2008; and references therein]. For grains smaller than ~0.1 µm, T_M is strongly dependent on grain size and decreases dramatically, from

cont'd. on pg. 8...

IRM phases in usage fees

Since its inception in the fall of 1990, the *IRM* has provided the Earth Science research community with cost-free access to state-of-the-art facilities and technical expertise for magnetic material characterization and experiments. Rising costs now threaten to outstrip available funding, and the *IRM* must ask users to make a contribution towards facility operations. Substantial discounts or subsidies will be provided for Visiting Fellows, other academic researchers, and especially for students. We have strived to develop a system that is fair, flexible, and most of all will not fundamentally limit access to the facility for any potential users. We anticipate that the *IRM* will continue to provide the community with the resources for developing new research directions and techniques and for advancing into fresh and potentially transformative areas of study.

Please read the entire article on page 2.

IRM to Phase in Usage Fees

Mike Jackson, Bruce Moskowitz, and Joshua Feinberg, IRM

Since its inception in the fall of 1990, the *IRM* has provided the Earth Science research community with cost-free access to state-of-the-art facilities and technical expertise for magnetic material characterization and experiments. The cost-free mode of community-based, facility-located research has been made possible by strong continuing support from the NSF Geoscience Instruments & Facilities (IF) program and the University of Minnesota (UM), and by two initial instrumentation grants from the W.M. Keck Foundation. No-cost access reflects the founding philosophy that the *IRM* is a shared resource belonging to the entire GP community. It has also given the community considerable freedom to use the *IRM* instrumental facilities for incubation of new research directions and techniques, using innovative but unproven methods, and advancing into fresh and potentially transformative areas of study.

During the next several years of facility operations (with continuation funding anticipated for 11/2010 – 10/2013), some changes will be necessary in the way that visiting scientists use the *IRM* – in particular, usage fees will now be charged in some cases.

Why?

The need for usage fees is imposed by a simple inescapable fact: the costs of operating our facility have risen faster than IF and UM support can sustain. The largest part of this increase is the ballooning cost of liquid helium [*National Research Council*, 2010; see also *IRM Quarterly* 17(3), 2007]. In contrast to a typical paleomagnetic lab, where less than 100 liters of liquid He per year is required to keep a SQUID magnetometer operating, the IRM has four major high-field low-temperature instruments that collectively require more than 10,000 liters annually for running superconducting magnets and for establishing controlled low-temperature sample environments. The per-liter price of this nonrenewable resource has roughly tripled in the past decade, and our total annual He cost now significantly exceeds that of a full-time professional staff position, even though we have reduced consumption significantly by limiting usage to the highest-priority projects.

Changes are also occurring on the funding side of the equation, both at IF and at UM. Over the past twenty years an increasing proportion of the IF program budget has gone into facility support, at the expense of instrument grants for individual investigators [*Jeanloz et al.*, 2008]. More recently IF has attempted to redress the balance, making an effort to limit facility growth and renewing its emphasis on research infrastructure (rather than research activity, for which funding is available through other programs at NSF and through other funding agencies). Of the 15 EAR/IF-supported national multi-user facilities, *IRM* is currently the only one that does not charge usage fees for supplies and other direct support of visiting scientists' research.

Over the past 20 years, nearly 20% of the *IRM*'s direct-cost support has come from UM cost sharing. Now, like many states, Minnesota has enormous budget problems, and UM is taking heavy reductions in state funding. Despite this, the pending three-year operations grant includes an 18% direct-cost match, a remarkable show of support in difficult times. Nevertheless, the prospects for continued institutional support in the future are uncertain. After consultation with present and former members of our Review and Advisory Committee, we decided to be proactive with the imposition of usage fees to maintain the quality of the facility.

How?

The model that we are proposing will, we hope, allow us to continue operating with relatively flat or diminished NSF and UM support and rising costs for liquid helium, while still keeping access as open as possible. There are three keys to our approach. First, fees will primarily be charged for expensive instrument usage (especially those requiring a lot of liquid helium; e.g., the low-T VSM uses ~30 liters per day). We have calculated a fee structure based on actual costs of facility operation (staff support, supplies, instrument upkeep), and by applying the calculation retroactively to recent visitors, have determined that an average Visiting Fellowship represents $4000 to $5000 of facility operation costs. We have therefore proposed that Visiting Fellows in the new grant period (starting Nov. 1, 2010) be given a $4000 credit toward usage and travel costs (up to $750 for travel), and will be charged only for costs beyond that. However it is important to emphasize that ranking of VF proposals will continue as before and will not depend on whether applicants can afford the fees. Second, for informal visitors (outside the Fellows program), we plan to charge full costs only to corporate researchers, with substantial discounts for academic users and especially for students. Finally, for the next year or two at least, fees will not be strictly mandatory: like AGU page charges, we will request payment but not deny access to those unable to cover costs. With this initial flexibility we hope that researchers will have ample time to budget IRM visits into their future research grants.

How Much?

A major purpose of our present announcement of future fees is to enable researchers in the community to begin preparing for the change by including IRM research costs into new proposals. Standard daily rates for each instrument will be posted on the IRM website, and will range from about $50 for relatively low-maintenance instruments (e.g., Kappabridge and 2G RF-SQUID magnetometer) up to around $300 for those with large helium appetites (e.g., low-temperature VSM).

Bottom Line

The last decade has seen a great surge of interest in the low-temperature magnetic behavior of remanence-carrying minerals, nanophase materials, biomagnets and other natural and synthetic substances. Together with strong magnetic fields, low-temperature measurements allow for nondestructive characterization and give us effective experimental tools for probing the physical origins of magnetic stability. Maintaining these capabilities and providing news ones in the future (e.g., the LT-Probe for 3-axis magnetic measurements) is important for the geomagnetism/ paleomagnetism/rock-magnetism community, and we are doing everything we can to ensure continued access to these resources. Acquiring the ability to recover and reuse the helium boil-off from our instruments is a high priority for stabilizing and containing future operational costs, and we are continuing to pursue possibilities in this direction. Nearly 300 Visiting Fellows and several hundred Guest Researchers from more than 100 institutions have benefited from the instrumentation and professional experience available at the *IRM*. We are dedicated to continuing this type of open access and high level of support to the world-wide GP community with a usage fee policy that is both fair and flexible to all researchers.

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Visiting Fellow's Reports

Magnetic properties of desert varnish samples

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(Note: Table 1 and additional Supplementary Figures can be found online at: http://www.irm.umn.edu/quarterly/supp/Guth.pdf)

Desert varnish is a thin (≤200µm), microlaminated, rock coating that may record a paleoclimatic signal [1]. Previous work by [2] and [3] suggested that the magnetic materials present in varnish were magnetite (Fe_3O_4), maghemite (γ- Fe_2O_3) and goethite (α-FeO(OH)). Birnessite (a Mn, Na, Ca, K oxide) and hematite (Fe_2O_3) have also been identified in varnish [4].

One goal of this research was to examine a number of samples from the Kenya Rift, a previously unstudied area in terms of desert varnish, and compare with varnish from Nevada, which can be considered a 'type locality' for varnish. Overall I hoped to assess the possibility of using magnetic properties to pin varnish layering to a timeline. Because so little has been done with the magnetic properties of varnish, most of the work at the IRM was exploratory in nature. To better understand the magnetic properties of these samples, the susceptibility and remanence temperature dependence below 300K, magnetic hysteresis and natural remanent magnetization (NRM) were measured. Magnetic force microscopy (MFM) was also conducted.

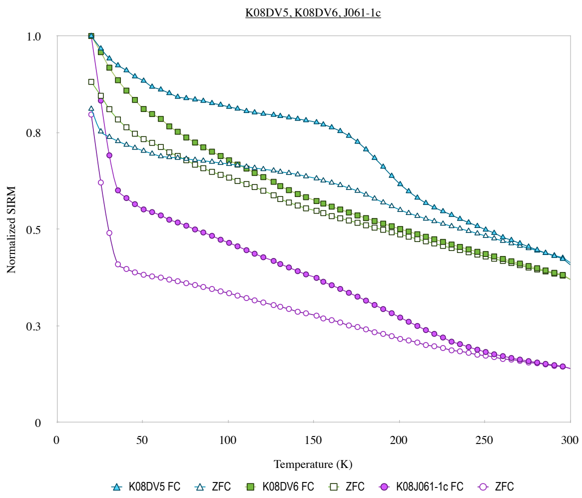

Figure 1. Selected FC (solid symbols) and ZFC (open symbols) remanence curves for varnish, normalized to 20K FC

Varnish was scraped off of the host rock using a small ceramic screwdriver to minimize the possibility of metal contamination. Low temperature thermal demagnetization measurements were conducted with the Quantum Design Magnetic Properties Measurement System (MPMS). Measurements were taken every 5 K during warming and cooling cycles under different field conditions described below:

1. Samples were cooled from 300K to 20K in a field of 2.5 T followed by thermal demagnetization of the field cooled (FC) saturation isothermal remanence (SIRM) by warming from 20K to 300K in zero field (ZF). All subsequent temperature cycling was also done in ZF.

2. Samples were cooled to 20K where a 2.5T saturating field was applied to impart a zero field cooled (ZFC) SIRM, followed by thermal demagnetization warming from 20K to 300K.

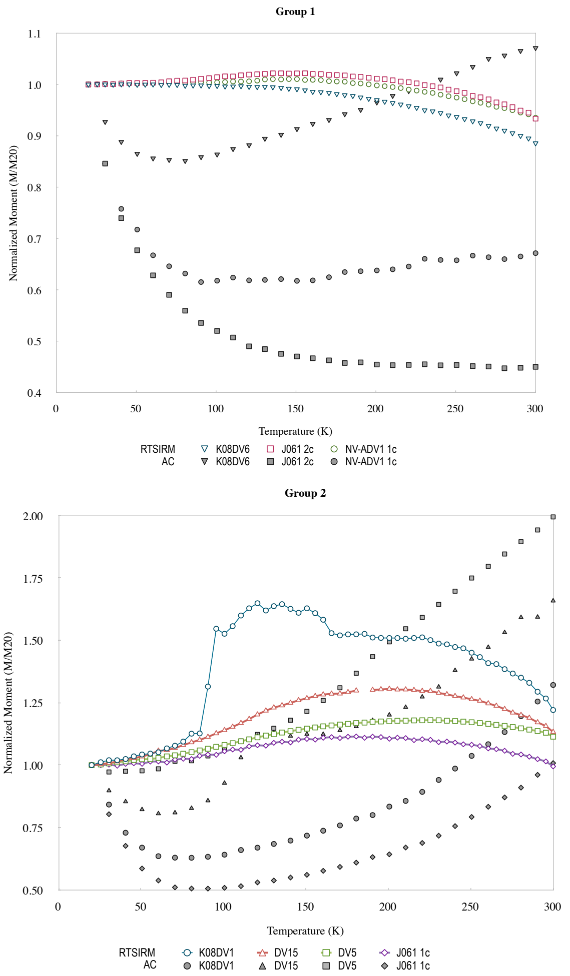

Figure 2. *Varnish groupings based on similar RTSIRM warming (open symbols) and AC Susceptibility (filled symbols) behavior. All plots have been normalized to the 20K values.*

3. Samples were finally subjected to a 2.5T saturating field at 300 K, to apply a room temperature SIRM (RTSIRM). Thermal demagnetization of this remanence was measured during a 300K-20K-300K cycle.

Figure 1 shows representative FC and ZFC remanence curves. In two samples (K08DV1 and K08DV15) the relative dominance of the FC and ZFC curves switch, which may indicate the presence of multi-domain (MD) titanomagnetites [5]. Low temperature transitions of unknown origin are observed in the RTSIRM cooling curves (online supplement, Table 1). For most samples these transitions are only seen during cooling of the RTSIRM, while the re-warming curves are gently humped (contrast K08DV1 with other samples in Fig 2). Why this transition would be visible during cooling of the RTSIRM but suppressed on re-warming is unknown. Özdemir and Dunlop [6] suggest the humped form seen at temperatures above the Verwey transition is a behavior of oxidized magnetite, however transitions in their samples were seen during both cooling and re-warming, and were more pronounced in the re-warming cycle.

The varnish samples can be partitioned into two groups based on RTSIRM warming and alternating current (AC) magnetic susceptibility behavior (Fig. 2). The overall decline seen in Group 1 RTSIRM remanences on re-warming is similar to that observed by [6] for oxidized magnetite.

Magnetic hysteresis parameters (online supplement, Table 1) were measured at room temperature using a vibrating sample magnetometer. Low coercive force (B_c) and coercivity of remanence (B_{cr}) values, suggest dominance of magnetically soft minerals (e.g. magnetite, maghemite, pyrrhotite). This is in contrast to the varnish examined by [3] which showed a dominantly hard component (goethite). Samples K08DV5 and K08DV15 exhibited "wasp wasted" hysteresis loops (Fig. 3) which may be the result of mixed grain size within the sample [7].

To assess the potential of varnish as recorder of NRM, 8 specimens representing three oriented Kenyan samples were measured with the 2G Superconducting Rock Magnetometer. Measurements were taken of the the varnished rock, and again after removal of the varnish. The bare rock signal was subtracted from the bulk to obtain the magnetization direction of the varnish. Figure 4 shows the plotted inclinations and declinations obtained for the varnish and bulk samples. There is obviously some recorded magnetic signal in the varnish that is different than the host rock, but the origin and significance of this signal is not clear.

MFM imaging was conducted on a subsample from the Nevada specimen (NV-ADV1) which was mounted in epoxy and polished such that the examined face provided a cross sectional view of the varnish. Achieving the flat surface required for imaging was accomplished with polishing films impregnated with 30, 3 and 0.1 µm diamond. It was originally hoped that MFM imaging would reveal magnetic layering similar to the compositional banding often seen in varnish. No obvious layering was seen, but discrete magnetic grains were imaged using this method which demonstrates that varnish can be successfully prepared for the MFM. Figure 5 shows the response of these grains following and during the application of different fields. The sample had been pulsed with a 1T field and later a 30-35 mT magnetic field was applied both into and out of the field of view with images captured while the field was active.

Conclusions

The NRM experiment indicates that there is some sort of signal recorded in the varnish which may indicate the presence of a magnetic stratigraphy despite the lack of ob-

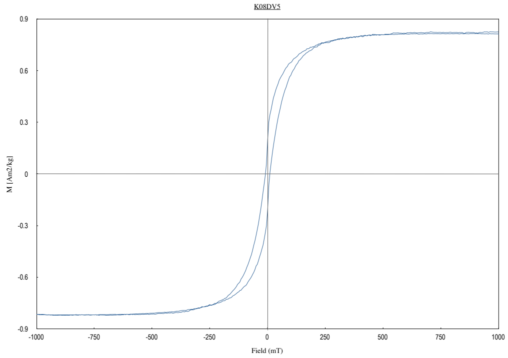

Figure 3. *Example of a "wasp-waisted" hysteresis loop. Two of the examined samples showed this behavior. Hmax = 1T.*

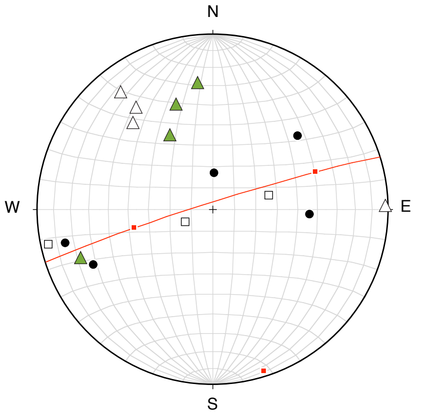

Figure 4. *An equal-area net showing virtual poles acquired for Kenyan Varnish. Line is the cylindrical best fit great circle, and the pole to that best-fit plane is at 162.5° with a 3.3° dip. Triangles are data for bulk measurements, filled symbols have positive inclinations, vectors with negative inclinations are plotted in the lower hemisphere and have open symbols.*

servable layering in the MFM images. Magnetic changes may have been too subtle, or the surface topography too great, to resolve magnetic banding using the MFM. Enhanced sample preparations using ion milling may allow for cleaner MFM imaging, or perhaps another technique entirely would be better suited to such a study.

Overall, the low temperature magnetic behavior is relatively consistent despite the samples spanning two continents. The behavior however, is not simple and likely represents a complicated mineralogy. Magnetic experiments indicate a soft magnetic component likely dominated by (titano)magnetite, however the magnetic expression is distinctive from examples typically presented in the literature. Scanning electron microscopy and energy dispersive x-ray spectroscopy indicate the presence of magnetite and titanomagnetite grains with a range of sizes (<0.3 to ~10 μm), varying Ti compositions ($0 \leq x \leq 0.3$), and varying presence of lesser impurities (Mn, Al, Mg, Cr, each < 2 wt%). The varnish matrix is also rich in iron, and may contain a finer grained magnetic component. Due to the perplexing behavior of the low temperature magnetic experiments, any suggestions for interpreting the magnetic mineralogy of these samples would be welcomed.

Acknowledgments

I would like to thank the IRM for hosting my visit, Mike Jackson and Joshua Feinberg for their generous help and enthusiasm, and Aleksey Smirnov for suggesting this project and providing editorial support. Funding for my stay in Minneapolis was provided by the Michigan Space Grant Consortium.

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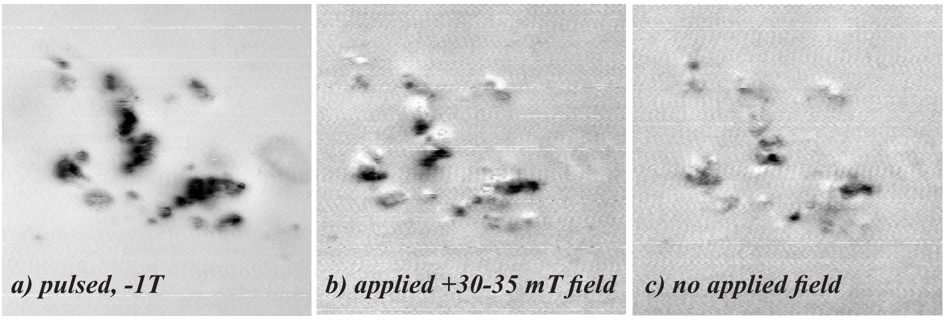

a) pulsed, -1T

b) applied +30-35 mT field

c) no applied field

Figure 5. *MFM phase images for magnetic particles within varnish. Images are all 7.84 μm square. Lift start height = 150 nm, Lift Scan height = 50 nm, 0.751 Hz, 0° scan angle, tip velocity 11.8 μm/s. Images have been manually adjusted for brightness and contrast.*

Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Press (© American Geophysical Union), and The Earth and Planetary Express (© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the IRM Quarterly are always welcome.

Anisotropy/Magnetic Fabrics

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Morin transition (continued from pg. 1)

~250 K at 0.1 µm, to 190 K at 30 nm, and to < 5 K at 16 nm [Özdemir et al., 2008]. The suppression of the Morin transition temperature in nano-hematite arises in part from high internal strain [e.g. Schroeer and Nininger, 1967; Muench et al., 1985] and from a small surface to volume ratio, which allows surface effects to dominate spins [e.g. Kündig et al., 1966].

Cation substitution will also suppress T_M; 1 mol% Ti substitution will suppress T_M to < 10K [e.g. Morin, 1950; Curry et al., 1965; Ericsson et al., 1986]. Other cations (with the exception of rhodium, ruthenium and iridium), as well as lattice defects, produce similar effects [Morrish, 1994]. The presence of a magnetic field will also decrease T_M [e.g. Besser and Morrish, 1964; Özdemir et al., 2008; Morrish et al., 1994 and references therin]; the effect is roughly linear in fields < ~3 T, lowering T_M by ~6 K/T.

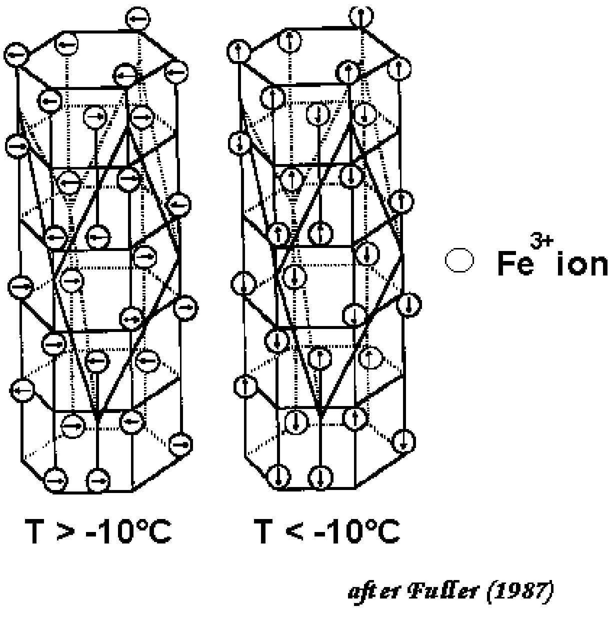
Significant *increases* in T_M can be induced via hydrostatic pressure, with estimates of the variation ranging from ~10 K/GPa to ~37 K/GPa [e.g. Bruzzone and Ingalls, 1983; Umebayashi et al., 1966; Worlton et al., 1967]. Thus, at room temperature the “spin-flop” transition may be brought about by application of pressures in the range of ~2 GPa [Morrish, 1994], although with increasing pressure, the transition may be less abrupt. Conversely, the application of uniaxial stress results in decrease in T_M [Allen, 1973]. In contrast, to static, *in-situ* pressure experiments, samples that have undergone shock treatments have reduced Morin transition temperatures, likely as a result of reduced grain size and increased crystal defects [Williamson et al., 1986].

Finally, we note only in passing that annealing of samples frequently results in both an increase of T_M and a sharper transition, resulting from reduction in defects, crystal growth, or both [e.g. Dekkers and Linssen, 1989].

Remanence Data

On cooling through the Morin transition, the parasitic ferromagnetic remanence will rapidly decrease (Fig. 3), leaving only the (typically) much smaller defect moment. On warming back through T_M, remanence is partially recovered. Özdemir and Dunlop [2005; 2006] proposed that this remanence "memory" arises from small zones of canted spins (pinned via crystal defects) that do not fully rotate into the alignment with the c-axis below T_M. These zones serve as nuclei for the re-establishment of remanence on warming back through T_M, even in a zero-field environment. The percent recovery on warming is not strongly correlated with grain size, but instead scales with the magnitude of the defect moment at $T < T_M$ [Özdemir and Dunlop, 2006]. However, Kletetschka and Wasilewski [2002] find a minimum in remanence recovery associated with a grain size near the SD-MD transition, at ~100 µm.

Thermal hysteresis in the Morin transition is frequently observed in the low-temperature cycling of an IRM; the transition occurs at lower temperatures on cooling than on warming. This is not due to temperature lag in the sample, but is expected in a first order phase transition such as the Morin transition. While hysteresis is seen in almost all samples, Özdemir et al. [2008] note that a larger temperature difference between cooling and warming (ΔT_M) is typically seen in samples with a smaller grain size and/or higher defect density. The effect is not strong in the relatively coarse-grained natural hematite shown in Fig. 3a. By contrast, a decreased T_M and increased ΔT_M are clear in a relatively fine-grained (~ 1µm) synthetic hematite powder sample (Fig. 3b).



after Fuller (1987)

Figure 2. *Crystal structure of hematite. Above the Morin transition (left), spins are in the basal plane perpendicular to the rhombohedral c-axis, and a weak ferromagnetism arises from spin canting. Below the Morin transition (right), spins rotate parallel to the c-axis and are perfectly antiferromagnetic. Image after Fuller [1987] and from the Hitchhikers Guide to Magnetism [Moskowitz, 1991].*

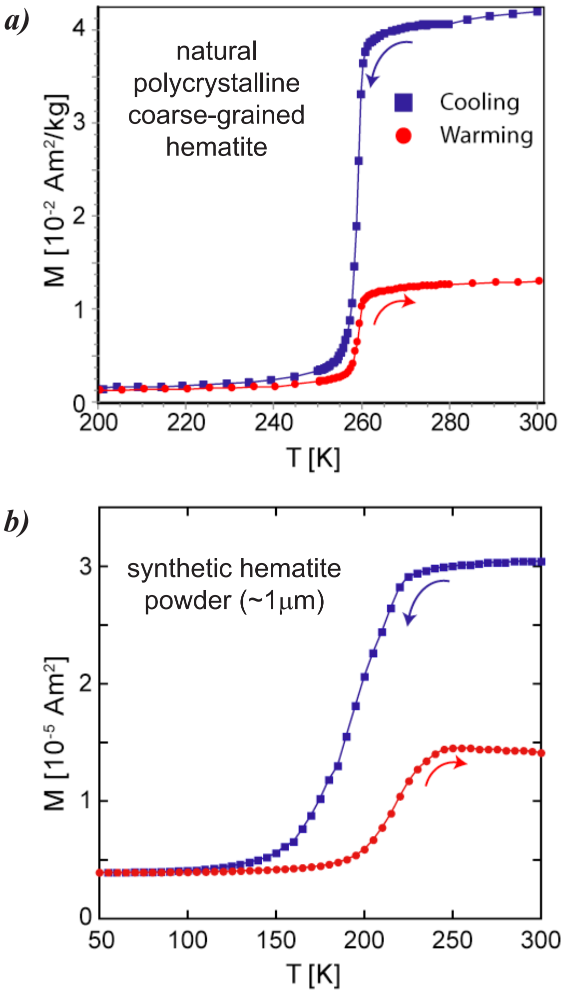


Figure 3. *Low-temperature cycling of a room-temperature IRM. On cooling through T_M, magnetization decreases to near zero as the spins become perfectly antiferromagnetic. Small regions of canted spins likely remain at low temperature, explaining the recovery of remanence on warming in zero field [Özdemir and Dunlop, 2006; see text].* ***(a)*** *A natural, coarse-grained hematite with $T_M \approx 260$ K and very little thermal hysteresis.* ***(b)*** *A synthetic, relatively fine-grained hematite powder has a suppressed T_M and significant thermal hysteresis.* ***Note temperature scales in (a) and (b) are different.***

(Low-Field) Susceptibility Data

Above T_M, low-field susceptibility is strongly dependent on crystallographic orientation; there is a weak, 3-fold anisotropy in the basal plane, and susceptibility is much lower parallel to the c-axis [e.g. Hrouda, 1982]. Below T_M, antiferromagnetic susceptibility in the basal plane is ~2 orders of magnitude lower than above T_M and decreases with decreasing temperature. Susceptibility parallel to the c-axis, however, remains nearly constant from T = 0 K to the Néel temperature of 948 K, with a small increase at T_M [Stacey and Banerjee, 1974]. In a sample with randomly-oriented hematite grains, susceptibility decreases on cooling to a small fraction of its room-temperature value at $T < T_M$. (This neglects susceptibility from the defect moment, which may be considerable.) In practice, samples display a wide range of susceptibility decreases across T_M [e.g. de Boer et al., 2001], dropping to ~5% of the room-temperature susceptibility for coarse-grained samples (Fig. 4a) to >90% for synthetic powders with micron-sized particles (Fig. 4b).

Morin Transition Imposters

Just as we discussed superparamagnetic imposters in Part I of this series, we briefly note a common Morin transition imposter. When measuring wet sediments, grain reorientation can take place as the water freezes (at ≤ 273 K), resulting in a drop in remanence. This is occasionally misinterpreted as the Morin transition.

It is also possible for hematite to masquerade as magnetite. Because the Morin transition temperature can be significantly suppressed in nano-hematite or cation-substituted hematite, a transition around 120 K in a room-temperature remanence may be mistaken for the magnetite Verwey transition. The two can be distinguished by the fact that magnetite should acquire a significant magnetization at low temperatures, while hematite will not.

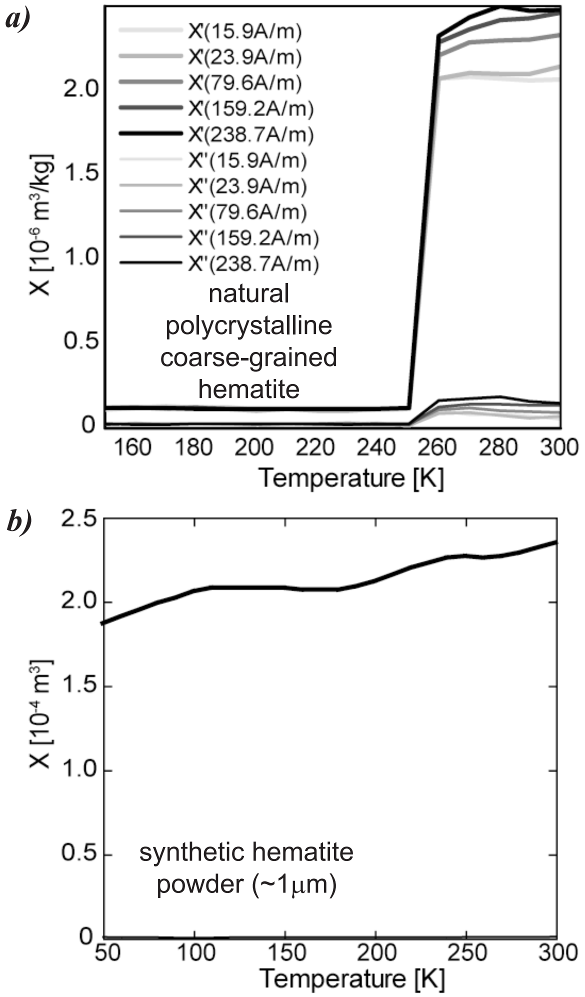


Figure 4. *In phase (X') and out-of-phase (X") susceptibility.* ***(a)*** *Susceptibility decreases dramatically at $T < T_M$ in a natural, coarse-grained hematite. Above T_M, the field-dependence of susceptibility is characteristic of many multi-domain minerals.* ***(b)*** *In a relatively fine-grained hematite, T_M is suppressed to ~200 K. Susceptibility also changes very little across T_M, in contrast to remanence data (Fig. 3b).* ***Note temperature scales in (a) and (b) are different.***

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The Story Behind the Story:

Prequel to the IRM's New Low-Temp Probe for 3-Axis Measurements

Mike Jackson, IRM

In our article describing a newly-developed low-T magnetometer insert (*IRMQ v.19*, n.4), our main goals were to explain how it works and to show a sampling of preliminary results, and we neglected to give background information on previous related work. Lest the omission leave any mistaken impressions about the origins of the fundamental idea, we note here that there is a long history of distinguished precedents for variable-temperature measurements of remanence vectors, using a wide variety of magnetometers and differing approaches to controlling temperature. Nor is the following brief summary free of omissions (e.g., pioneering work with astatic magnetometers), but we freely and gratefully acknowledge our indebtedness to all those who have paved the way.

Vibrating-sample magnetometers most commonly measure just one component of the magnetization vector (parallel to the applied field), and for decades they have been used for variable-temperature single-axis measurements of remanent or in-field magnetizations [e.g., Nagata et al., 1964]. More recently vector VSMs have been developed, capable of measuring two [e.g., Benito et al., 2006] or three [e.g., Le Goff & Gallet, 2004] components over a range of temperatures. Spinner magnetometers typically measure two orthogonal components, but innovative new designs now allow determination of all three vector components at elevated temperatures [Wack & Matzka, 2007]. SQUID magnetometers, developed in the 1970's [Goree & Fuller, 1976], were almost immediately modified with internal or external furnaces for measurement of samples at high temperature [Day et al., 1977; Dunn & Fuller, 1984; see also Fuller, 1987]. Low-temperature single-axis SQUID measurements have become standard in rock magnetism with the availability of commercial instruments such as the MPMS, but the development of a low-T insert for three-axis measurements on a 2G has proven more difficult [Smirnov et al., 2004]. The IRM's design builds on these previous works, exploiting the recent affordability of liquid-helium-free cryocooling combined with a long, single-crystal sapphire rod for efficient, solid-state heat transfer.

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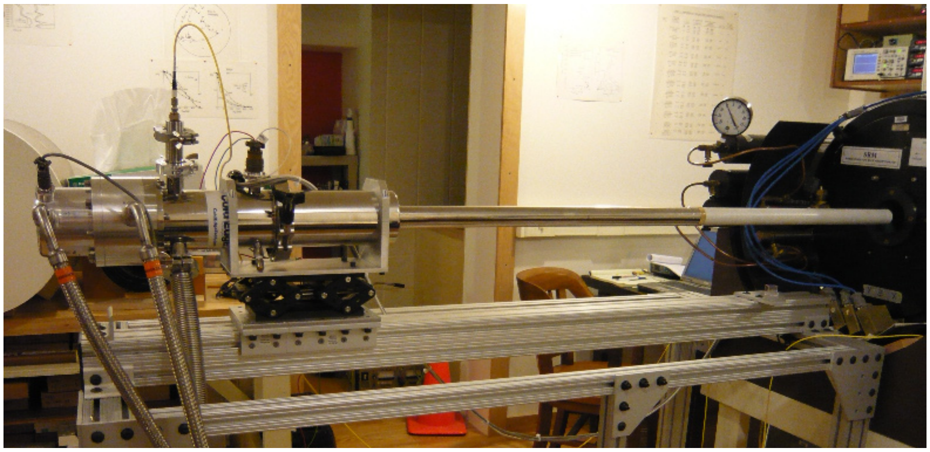

Low-temperature insert installed on the IRM's RF SQUID magnetometer. On the left are the cryocooler and compressor lines. The fiberoptic temperature sensor extends vertically up from the cryocooler. On the right is the vacuum shroud extension.

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Funding for the *IRM* is provided by the **National Science Foundation**, the **W. M. Keck Foundation**, and the **University of Minnesota**.

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