The IRM
Quarterly
Summer 2006, Vol. 16 No. 2

Santa Fe VII

Subir Banerjee
Bruce Moskowitz
IRM

The following describes some of the presentations and discussion from IRM's seventh biennial conference on rock magnetism at Santa Fe. Space limitations required the omission of several excellent presentations. For example, Reid Cooper's talk on "Kinetic Paths, Metastable States & Ferrite Nucleation: The Impact of the 'Semiconductor Condition'" is not mentioned; however, the slides from his talk may be found on IRM's web site.

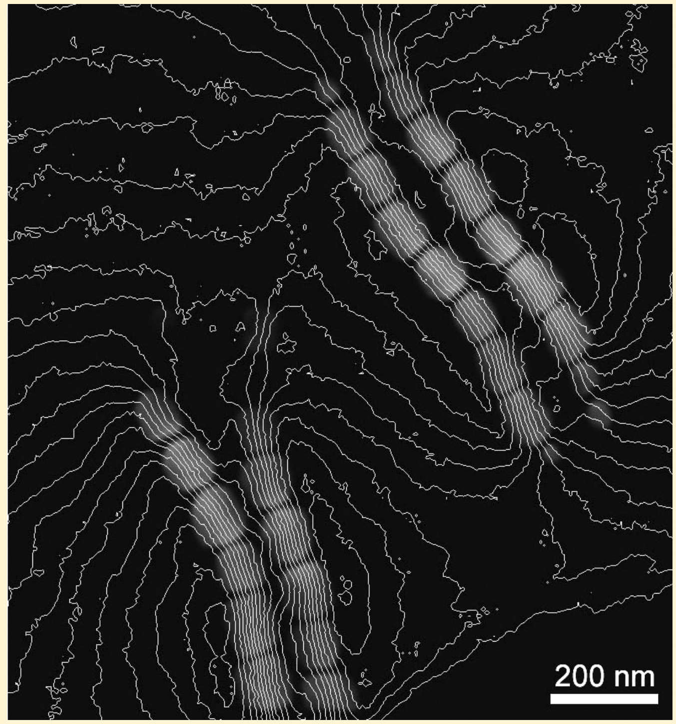


Figure 1--Magnetic induction map recorded using off-axis electron holography from two pairs of magnetite chains from a bacterial cell collected in Séd stream, Veszprém, Hungary. The contours show the strength and direction of the in-plane component of the magnetic induction in the specimen integrated in the electron beam direction. The contour spacing is 0.25 radians. Acknowledgments: Ed Simpson, Takeshi Kasama, Mihaly Posfai, Peter Buseck, Richard Harrison, Rafal Dunin-Borkowski

Crustal Magnetic Fields of the Moon, Mars and Earth

In the case of the Moon, the biggest mystery after visiting and sampling Moon rocks was that while the rocks were often magnetized strongly, the present lunar field is too weak to be the source for their (presumed) thermo-remanent magnetization (TRM). The mystery deepened when polarized electron reflectance data from low orbit mini-satellites found that the largest magnetic anomalies (300 nT at 20 km altitude) were located mainly above ancient (3.8-3.9 Ga) highlands while the topographically low and flat mare basins of younger age (less than 3.8 Ga) were much more weakly magnetized. Following Santa Fe conference conveners' request, instead of an exhaustive review of lunar magnetic anomalies and their possible sources, Lon Hood (Lunar and Planetary Lab, University of Arizona) focused on the odd correlations of large anomalies with regions of high albedo (curvilinear, unknown origin). It has been postulated that the lunar surface darkens (low albedo) due to nanophase (~1-10 nm) iron formation from cumulative solar wind ion bombardment. Thus strongly magnetized regions retain their light color by electromagnetically deflecting the charged particles and preventing the formation of nanophase iron, the agent for darkening. Superparamagnetic nanophase iron spheres, known to have very high magnetic susceptibility, cannot cause large anomalies, since the present day field is weak. With our current strong interest in terrestrial nanophase iron oxides, generation of superparamagnetic (pure) iron spheres by energetic ions is certainly an item of curiosity.

Hood also discussed another oddity: the large coherently magnetized rocks antipodal to major impact sites on the moon. It has been suggested that the charged dust plasma from an impact shock may travel swiftly and converge and compress at the antipodes to provide a large enough field for imparting TRM to the hot ejecta, also traveling to the impact antipodes. It may thus appear that an internal magnetic field from a short-acting lunar dynamo (itself a subject of contention) may not be necessary to produce strongly magnetized breccia located antipodally to major impact sites. Hood's point was that it is not necessarily so. Impact/transport models show that since the plasma will arrive first, enhancement

Santa Fe, continued on page 4

Visiting Fellows' Reports

France Lagroix,

Institut de Physique du Globe de Paris

lagroix@ipgp.jussieu.fr

Investigating the Magnetic Phase Diagram of Ferrian Ilmenites [yFeTiO3·(1-y)αFe2O3 (y = 0.7, 0.8, 0.9, 1.0)]

THE MAIN OBJECTIVE of this trip to the IRM was to investigate the magnetic phase changes within the hematite-ilmenite solid solution proposed by *Ishikawa et al.* [1985] for *y* values greater than 0.65. Two sets of synthetic single phase ferrian ilmenites were available for this study.

The first set was synthesized by C.A. Lawson and contains *y* = 0.7 single phase ferrian ilmenites quenched from various temperatures above the cation ordering transition (1300°C, 1200°C, 1100°C, 1050°C) and below (900°C). All samples were synthesized from sintered pellets of a mixture of Fe_2O_3 and TiO_2 held at 1300°C for a minimum of 36 hours in a furnace outfitted with a flowing CO_2/H_2 gas mixture maintaining an oxygen fugacity of -5.68 [*Lawson*, 1981]. These samples have been extensively studied with respect to their microstructure [*Lawson*, 1981, *Lawson et al.*, 1981] and their ability to acquire a stable reversed thermoremanent magnetization (rTRM) [*Nord and Lawson,* 1989, 1992; *Lagroix et al.,* 2004].

The second set, composed of three samples with *y* = 0.8, 0.9 and 1.0 and all quenched from 1300°C, was obtained from R. Harrison. These samples were synthesized from sintered pellets of a mixture of Fe_2O_3 and TiO_2 held at 1300°C for 24 hours in a furnace outfitted with a flowing CO_2/CO gas mixture maintaining an oxygen fugacity of -6.50, -7.50, and -9.40 respectively for *y* = 0.8, 0.9, and 1.0. These samples have been investigated with respect to the cation ordering phase transition using time-of-flight neutron powder diffraction [*Harrison et al.* 2000a, b] and are currently being investigated, with the same technique, at low-temperatures.

As currently drawn in Figure 1, the magnetic phase diagram predicts a transition from paramagnetism to: 1) ferrimagnetism to spin glass for *y* = 0.7; 2) superparamagnetism to ferrimagnetism to spin glass for *y* = 0.8; 3) superparamagnetism to spin glass for *y* = 0.9; and 4) antiferromagnetism for *y* = 1.0.

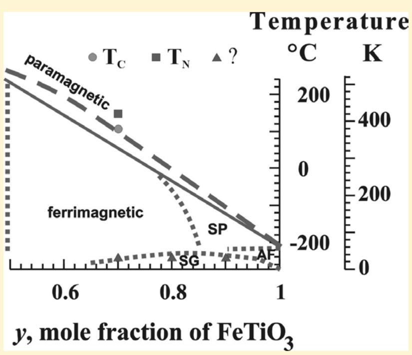


Figure 1 A focused view of the hematite-ilmenite solid solution series magnetic phase diagram for y greater than 0.5 and temperatures less than 240°C. The magnetic ordering temperatures across the solid solution series (solid line), to a first approximation, linearly decrease as y increases such that TC or TN in °C = 675-885y [Nagata and Akimoto, 1956]. However, slightly elevated ordering temperatures (dashed line) with respect to the linear trend, are predicted by thermodynamic calculations [Ghiorso, 1997]. The magnetic phase boundaries shown as dotted lines are based solely on observations made by Ishikawa et al. [1985] (SP: superparamagnetic, SG: spin glass, AF: antiferromagnetic).

Concerning the *y* = 0.7 samples, results in *Lagroix et al.* [2004] demonstrated that the Curie temperature (T_C) of the *y* = 0.7 samples (T_C = 380 K) is independent of the thermal history (circle in Figure 1). However, an 'imperfect' antiferromagnetic state is first initiated below the paramagnetic state prior to the onset of ferrimagnetism, and T_N is dependant on the thermal history (rectangle in Figure 1 extends the temperature range of observed T_N). Unpublished frequency and amplitude dependence of AC susceptibility data (Figure 2), measured prior to the IRM visit, clearly show magnetic relaxation phenomena below 50 K (in all samples except the pure ilmenite sample). The magnetic relaxation is expressed as a dependence of frequency in both in-phase (not shown) and quadrature components (Figure 2) of the AC susceptibility and is not associated with any amplitude dependence. The temperature at which the magnetic relaxation phenomena occurs (triangles in Figure 1) hints at a possible relationship with the magnetic phase transition to a spin glass state.

In order to fully characterize the magnetic behavior of the ferrian ilmenite samples with the objective of investigating the magnetic phase transitions, the following measurements were subsequently conducted while at the IRM:

1) Hysteresis loops from ~10 K to just above T_C or T_N at close temperature intervals especially over temperature ranges showing anomalies in AC susceptibility measurements.

2) $M_{ZFC} - M_{FC}$ experiments in 1 mT and 5 mT DC fields

3) Low field (0.1 mT) induced magnetization relaxation experiments targeting the detection of (cluster) spin glass (random system of competing interactions of variable signs) behavior.

The experiments completed were successful. Hysteresis data and $M_{ZFC} - M_{FC}$ data integrated with AC susceptibility data provide key evidence towards mapping the various magnetic phase changes. Furthermore, results from Experiment (3) provide evidence for a spin glass state in certain samples, for which superparamagnetism cannot be the cause.

Finally, I thank the entire IRM family for the scientific expertise provided, the stimulating discussions and the hospitality.

References

Ghiorso, M.S., Thermodynamic analysis of the effect of magnetic ordering on miscibility gaps in the FeTi cubic and rhombohedral oxide minerals and the FeTi oxide geothermometer, *Physics and Chemistry of Minerals*, *25*, 28-38, 1997.

Harrison, R.J., U. Becker, and S.A.T. Redfern, Thermodynamics of the R-3 to R-3c phase transition in the ilmenite-hematite solid solution, *American Mineralogist*, *85*, 1694-1705, 2000b.

Harrison, R.J., S.A.T. Redfern, and R.I. Smith, In-situ study of the R-3 to R-3c phase transition in the il-

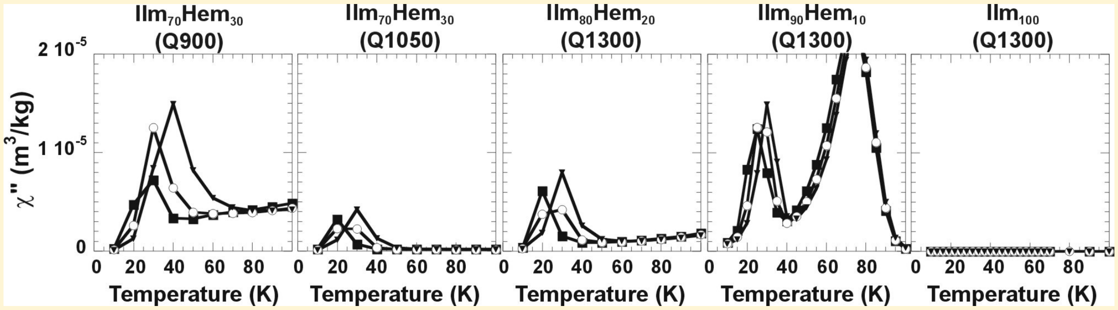


Figure 2 Plotted is quadrature AC susceptibility measured in a field amplitude of 239 A/m and frequencies of 1 Hz (filled squares), 10 Hz (open circles), 100 Hz (filled triangles) for the four studied compositions. The temperature at which each composition was quenched (Q) from is indicated in parentheses. Ilm70Hem30 (Q1050) and Ilm80Hem20 were quenched from above the cation order/disorder transition (TOD), the other three were quenched from below TOD.

menite-hematite solid solution using time-of-flight neutron powder diffraction, *American Mineralogist*, *85*, 194-205, 2000a.

Ishikawa, Y., N. Saito, M. Arai, Y. Watanabe, and H. Takei, A New Oxide Spin Glass System of (1-x)$FeTiO_3$-xFe_2O_3. I. Magnetic Properties, *Journal of the Physical Society of Japan*, *54* (1), 312-325, 1985.

Lagroix, F., S.K. Banerjee, and B.M. Moskowitz, Revisiting the mechanism of reversed thermoremanent magnetization (rTRM) based on observations from synthetic ferrian ilmenite (y = 0.7), *Journal of Geophysical Research*, *109* (B12108), doi:10.1029/2004JB003076, 2004.

Lawson, C.A., Magnetic and microstructural properties of minerals of the ilmenite-hematite solid solution series with special reference to the phenomenon of reverse thermoremanent magnetism, Ph.D. thesis, Princeton University, Princeton, New Jersey, 1981.

Lawson, C.A., G.L. Nord, E. Dowty, and R.B. Hargraves, Antiphase Domains and Reverse Thermoremanent Magnetism in Ilmenite-Hematite Minerals, *Science*, *213*, 1372-1374, 1981.

Nagata, T., and S. Akimoto, Magnetic properties of ferromagnetic ilmenites, *Geofisica Pura E Applicata*, *34*, 36-50, 1956.

Nord, G.L., and C.A. Lawson, Order-disorder transition-induced twin boundaries and magnetic properties in ilmenite-hematite, *American Mineralogist*, *74*, 160-176, 1989.

Nord, G.L., and C.A. Lawson, Magnetic Properties of $Ilmenite_{70}$-$Hematite_{30}$: Effects of Transformation-Induced Twin Boundaries, *Journal of Geophysical Research*, *97* (B7), 10,897-10,910, 1992.

Double-maxima FORC distributions in monoclinic PSD magnetite

Alexei V. Smirnov.

Yale University

aleksey.smirnov@yale.edu

I APPLIED THE FIRST-ORDER REVERSAL CURVE (FORC) method to study low-temperature magnetic hysteresis properties of five polycrystalline magnetite samples. The samples varied in grain size and shape, representing nearly single-domain (SD), pseudo-single domain (PSD), and multidomain (MD) magnetic hysteresis behavior. Before measurement, the samples were reduced in a controlled atmosphere to create nearly stoichiometric magnetite.

I measured FORC distributions at 20 K after zero field cooling (ZFC) and after cooling in a strong magnetic field of 1.5 T (field cooling, FC). The most striking result of this study is the discovery of unusual hysteresis behavior of two PSD magnetite samples (mean grain sizes of 0.75 and 1.5 μm). Namely, their ZFC FORC distributions manifest two distinct maxima located almost symmetrically with respect to the zero interaction field axis (Hu=0) on a FORC diagram (Figure 1a, b). The height of the upper and lower peaks is equal. In contrast, the FC FORC distributions measured from the same samples have a "regular" shape with a single maximum on the Hu axis (Figure 1c).

The effect of peak splitting is isotropic (i.e. does not depend on the direction of FORC measurement). Importantly, the effect is observed only below the Verwey transition temperature. When heated from 20 K to room temperature, the two maxima merge into a single one at about 100 K. The peak splitting is much less pronounced in non-reduced counterparts of the PSD magnetite samples.

In contrast to the PSD magnetites, the reduced SD and MD samples manifest "normal" low-temperature FORC distributions (with a single maximum located on the Hu axis) after both ZFC and FC.

Because the peak splitting is best pronounced in reduced magnetite samples, I suggest that processes related to the Verwey transition (namely, monoclinic twinning) must play a causal role. Indeed, the stressed twin boundaries and junctions may act as highly effective pinning sites for magnetic domain walls. I hypothesize that in terms of the effect on hysteresis behavior, the twin-related pinning is analogous (with some reservations) to the stabilization of domain structure due to the ionic/electron diffusion process, observed in some ferrites and other materials after magnetic annealing.

The diffusion-driven stabilization of magnetic domains results in the constant permeability and the absence of hysteresis in the Rayleigh region (the perminvar effect). The perminvar effect also manifests itself in constricted

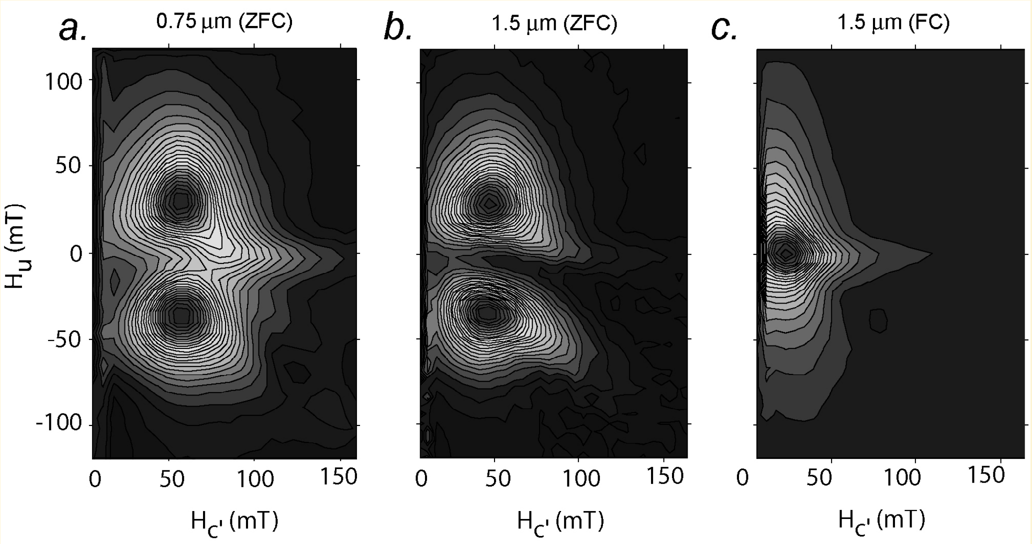


Figure 1. FORC diagrams measured from two PSD magnetite samples (mean grain sizes of 0.75 and 1.5 µm) at 20 K after zero-field cooling (a, b) and after field cooling (c)

(wasp-waisted) hysteresis loops. I hypothesize that the appearance of two maxima on ZFC FORC distributions observed from my PSD samples is a manifestation of a perminvar-like behavior due to the twinning-related stabilization of the magnetic domain structure in monoclinic magnetite.

My experimental data further suggest that the effect of monoclinic twinning on remagnetization is only pronounced within a certain grain size range. The double-maxima ZFC FORC distribution appears to be a distinctive property of PSD hysteresis behavior, which cannot be reproduced by mixing SD and MD magnetites.

The striking results of this study emphasize the importance of developing a theoretical model of magnetic hysteresis in monoclinic magnetite, which would incorporate the effects of crystallographic twinning.

Santa Fe, continued from page 1

of field at the antipodes due to compressed plasma-associated ions will have decayed during the nearly 4.8 hours estimated for the impact breccia to arrive at the antipode and become magnetized. His suggestion was that a strong lunar field of 2 x 10^{-2} mT (0.2 G) or more was necessary during the impact to slow down the dusty plasma enough, by electromagnetic 'braking', allowing the plasma to survive until the hot breccia arrived at the antipode. In other words, steady magnetic fields of the order of geomagnetic field are still a preferred model to explain the strongly magnetized lunar rocks. The "take home" message for rock magnetists is that future advances in our knowledge of lunar origin and evolution requires major advances in modeling the composition of lunar magnetic carriers and the source(s) of strong magnetic field mainly during the first few hundred million years.

When discussion turned to Mars and its magnetic anomalies, there was lively participation from the floor. Hood emphasized the hemispheric dichotomy, i.e., the strongest anomalies are located above the older (Noachian age) southern highlands while the northern hemisphere (as well as the large impact basins in the south) has weaker magnetic anomalies. Regarding the impact basins, IRM Quarterly readers may recall a piece by Laurent Carpazen where he proposed that impacts help scatter ("disorient") a previously homogenous magnetic vector. But Pierre Rochette, Lon Hood and their colleagues have ascribed the lower magnetization to shock demagnetization of pyrrhotite, which causes a ferromagnetic to paramagnetic phase transition at about 7 GPa pressure.

There has been considerable interest among rock magnetists and anomaly modelers about the source minerals for the Martian mega-magnetic anomalies. A recent review by D.J. Dunlop and J. Arkani-Hamed (JGR – Planets, 2006) provides a thorough discussion of the many potential mineral sources and magnetizing processes, while S. Brachfeld at this meeting gave a highly acclaimed presentation on the same topic.

Lon Hood focused on another peculiarity of the Martian anomalies, the claim that a best-fit dipole-magnetized crust can explain a large portion of the observed crustal-magnetization distribution. If this dipole model is correct and since there is now no ambient field on Mars, the 'frozen' magnetization distribution could be evidence for a functioning Martian core dynamo before 4.15 Ga. To make matters more interesting, Hood pointed out that such a dipole axis (assuming a time-averaged dipole orientation) would not be coincident with the current rotation axis of Mars suggesting true polar wander in ancient Mars. The event that caused the true polar wander, according to Hood, could be the formation of Tharsis originally at mid-northern latitude (at one pole of the magnetic dipole), followed by its relocation towards the Martian equator.

The suggestion generated a lively exchange among (terrestrial) rock magnetists. L. Tauxe noted the well-known lack of precision in the pole locations from anomaly modeling, as shown by R.L. Parker when he dealt with the seamounts of the Pacific. As we describe later, even without true polar wander, Martian mega-anomalies may require magnetized crusts with homogenous areal magnetization of 25 A/m. On Earth, such high values are approached only occasionally at plate tectonic ridge crests and in ancient deep crustal terrains studied by S. McEnroe and colleagues. Whatever the future judgment may be about the Martian polar wander hypothesis, one of the rock magnetists' research goals is already cut out: identify the magnetic mineralogy of various large magnetization deep crusts on Earth and the mechanisms behind their thermo-remanent (or thermo-chemical remanent) magnetization.

Paleointensity and the Paleoenvironment

Characterizing the geomagnetic field's past intensity, or paleointensity, presents a grand challenge in methodology, whether one uses igneous rocks for absolute intensity or lake and marine sediments for relative intensity. In the first of three overview talks, Rob Coe (University of California, Santa Cruz) focused on three goals of paleointensity research. First was the average intensity during the last 2 My, the period for which we have the most likelihood of success. Extrusive rocks and sediments of this age are the least altered; but as to whether we can trust that the recent field has been two to three times stronger than the average calculated for the last 300 My see below. Second, Coe recommended a search for convincing proof that the time-averaged field during the last normal polarity superchron (83 – 110 Ma) was much higher or lower than the 300 Ma average. Third, he recommended developing highly reliable thermal paleointensity technique for application to rocks from 'deep time', 2.5 to 4.0 Ga. All three goals, if achieved, would impact geomagnetic and geodynamic research, far beyond the borders of rock magnetism.

"Whatever the future judgment may be about the Martian polar wander hypothesis, one of the rock magnetists' research goals is already cut out: identify the magnetic mineralogy of various large-magnetization deep crusts on Earth and the mechanisms behind their thermo-remanent (or thermo-chemical remanent) magnetization."

Coe emphasized the need to deliver truly time-averaged values, i.e. without secular variation. This theme was picked up by the next speaker, John Tarduno (Rochester), who suggested that thermal (or Thellier-type) methods provide one hard datum: the field has not varied by more than a factor of two or three during the last 300 Ma. He was not as persuaded that the more recent field (averaged from zero to 10 My) has been higher by a factor of two when compared to older rocks varying in age from 10 – 300 Ma. Tarduno repeated the claim he has made elsewhere that, based on his experience with thermal methods applied to whole rock lava flow samples, older rocks yield unusually low, and incorrect paleointensities and should be avoided or experimentally corrected. He attributes this to low temperature oxidation and loss of natural magnetization in titanomagnetites from continental basalts of any age. His opinion was not shared by a few in the audience who, presumably, have experience with obtaining very accurate paleointensities from deuterically oxidized basalts with exsolved, pure magnetite.

Tarduno strongly recommends the use of single crystals of feldspar extracted from basaltic lava flows. These carry single domain magnetite phenocrysts that have been protected from chemical alteration by their silicate 'jackets'; he recently reviewed this problem in Reviews of Geophysics (2006). Tarduno concludes that magnetite from feldspars older than 10 Ma yield dipole moments much like that of the younger rocks, 8 x 10^{22} Am^2. Slightly smaller values are obtained from coeval submarine basaltic glass samples, whose use was pioneered by Lisa Tauxe. Staying with the theme of reliable intensity (or dipole moment) values, Tarduno expects the Archaean rocks to have an additional artifact: loss of natural magnetization by Néel-Arrhenius thermal relaxation, due to their very old age.

Regarding the effects on paleointensity of cooling rate differences (natural vs. laboratory), Julie Bowles (Scripps) has carried out controlled laboratory experiments to show that even though cooling rate differences can lead to errors in paleointensity as large as 10 – 30%, it is possible to reproduce in the laboratory the natural cooling rates of lavas.

It would be fair to say that most people at the meeting who were interested in more accurate thermal methods of paleointensity had in mind the question of geodynamo behavior, early in its life (3.0 Ga or earlier). In addition to Tarduno's recommendation to remove, or at least recognize, the possible role of long-term ambient temperature oxidation of basalts, there was a demonstration by Nobutatsu Mochizuki (Geological Survey of Japan) that a non-Thellier method popularized in the 1970's by John Shaw (Liverpool) can yield reliable thermal paleointensity from relatively young basalts, if additional corrections are incorporated. It was hard not to conclude that rock magnetists need to search intensively for more accurate thermal methods if we want to add to the current meager 10 or 12 reliable paleointensity values covering the one billion years spanning 3 to 4 Ga time-windows.

Relative paleointensity methods for soft sediments were also a topic for discussion. Lisa Tauxe (Scripps) treated us to her current (and continuing) work on modeling realistically the acquisition of depositional remanent magnetization (DRM) in soft sediments. Tauxe theorizes that sub-micron magnetite particles attached electrostatically to much larger (say, 1 – 50 micrometer) 'flocs' of clay minerals are the magnetic carriers. Her theoretical modeling shows an unexpected result: if the magnetite particle is smaller than 20 micrometer, the modeled DRM is non-linearly dependent on ambient magnetic field even though linearity is present for larger particles. Non-linearity would certainly complicate the interpretation of relative peleointensity in soft sediments. Here too rock magnetists can make important contributions to relative, or even absolute, paleointensity acquisition from both young (lake) and older (marine) sediment cores.

Relative paleointensities of sediments from a classic site, Mono Lake, were used by Susan Zimmerman (Lamont-Doherty) to determine the age of the "Mono Lake Excursion." She accomplished this with Dennis Kent's (Rutgers) help by comparing Mono Lakes's characteristic 'wiggles' with the features in global paleointensity time series from Sediments (GloPIS) assembled by Carlo Laj, Catherine Kissel and colleagues at LSCE-Gif in Paris. If Zimmerman is correct, the Mono Lake excursion is close to or the same age as the global Laschamp excursion at ~40 ka. Another contribution to the sediment paleointensity discussion was made by Toshitsugu Yamazaki (Geological Survey of Japan) who reviewed the amount of errors introduced when ARM normalization is carried out ignoring magnetostatic inter-particle interactions. Yamazaki finds that first order reversal curve (FORC) diagrams suggest that his model of inter-particle interactions is correct for ocean sediments studied by him.

Paleoenvironment and Paleoclimate Reconstruction from Environmental Magnetism

There were three invited presentations on this topic by Andrew Roberts (Southampton), Ken Kodama (Lehigh) and Ramon Egli (IRM). Roberts' talk explored Milankovitch's orbital theory of climates as evidenced in marine sediments collected from the western Mediterranean and the western Pacific oceans. In the Mediterranean, saturation isothermal remanent magnetization (SIRM) of bulk sediments, followed by AF demagnetization to remove the magnetite contribution, tracks hematite input from the Sahara. The resulting time series shows both orbital and sub-Milankovitch periodicities. In the western Pacific, as a contrast, hematite shows only non-orbital periodicities.

Kodama took us on a whirlwind tour of rock magnetic studies that have deciphered past environmental changes. They included studies of eolian dust in Holocene Tibetan lake sediments; Cretaceous carbonates in Mexico; magnetite inputs into Lake Ely (PA) over the last 100 years as well as in a carbonate lake (White Lake, NJ). Finally, he talked about a study of Miocene growth strata in the Pyrenees where 1000 m of sediments were densely sampled at 15 to 75 cm intervals. For Lake Ely the focus was on rock magnetic parameters that can best distinguish strongly magnetic iron oxides from sulfides, representing oxic versus anoxic lake history. It was interesting to note that Kodama observed ~1500 yr periodicities in White Lake, which agree with the Bond cycles (sub-Milankovitch abrupt climate change events) seen in N. Atlantic sediments. However, in Mexico and the Pyrenees, rock magnetic parameters showed Milankovitch periodicities. Kodama clearly showed that careful selection of rock magnetic parameters is rewarded with information about Milankovitch and sub-Milankovitch climate change records.

> *"[C]areful selection of rock magnetic parameters is rewarded with information about Milankovitch and sub-Milankovitch climate change records."*

Ramon Egli demonstrated new uses for his component analysis technique by distinguishing pedogenic iron oxides from those associated with parent-material. He included examples from Minnesota and Argentina. High-resolution anhysterertic remanent magnetization (ARM) curves are a pre-requisite for applying Egli's component analysis method. Christoph Geiss (Trinity) used another version of this technique where data gathering is less onerous while yielding reliable analysis.

Brian Carter-Stiglitz (IRM) and Joe Stoner (Oregon State) presented applications of newly developed rock magnetic parameters to southern hemisphere loess deposits and high-latitude lake sediments, respectively. Carter-Stiglitz has developed a measurement protocol that allows quantification of weakly magnetic hematite in the presence of overwhelmingly magnetic magnetite. He showed that rock magnetic, Mössbauer spectra and Sm – Nd geochemical data can lead to reliable multi-proxy climate records from loess sediments even though they may not necessarily show the typical magnetic enhancement seen in many soils and paleosols. Stoner used AF-demagnetized NRM and ARM to discover 100–150 year periodicities and abrupt declination changes in recent geomagnetic field. The declination changes were correlated in time with "archaeomagnetic jerks" in the geomagnetic field observed by Yves Gallet.

New Techniques and Measurements

Small was the big word in the "Techniques of measurement and modeling" session, where small refers to our ever increasing ability to measure minute magnetic moments. Recent advances in instrumentation and methodology are providing rock magnetists with new tools. With electron holography (Rafal E. Dunin-Borkowski, Cambridge) we can measure the magnetization of individual, submicron-sized particles; with scanning SQUID microscopy (Ben Weiss, MIT) we can measure paleomagnetic vectors at the thin-section scale; and with ferromagnetic resonance spectroscopy (Bob Kopp, Caltech) we can measure the relative contributions of different coercivity fractions in bulk samples and identify magnetofossils.

The first talk of the session was given by Ben Weiss (MIT) on his work on scanning SQUID microscopy (SSM). SSM has the potential to impact paleomagnetism much the same way as cryogenic SQUID magnetometers did by increasing measurement sensitivity and allowing more types of weakly magnetized materials to be routinely studied. SSMs were originally developed by F. Baudenbacher and J. Wiskow at Vanderbilt University to investigate the weak magnetic fields produced by the heart, but in collaboration with J. Kirshvink (CalTech) and B. Weiss (MIT) SSMs have been designed to investigate geological materials. The latest versions of SSMs have field sensitivities of $1.5x10^{-12}$ $T/Hz^{1/2}$ and moment sensitivities of 5.4 x 10^{-18} $Am^2/Hz^{1/2}$ for frequencies above 1 Hz. The increase in moment sensitivity is about a factor of 1000 over the newest versions of DC SQUID magnetometers. To achieve such high sensitivity, the SQUID senor is miniaturized to a diameter of 80 µm so it can be brought very close to the sample surface (~ 100 µm), which is at room temperature while the sensor is maintained at liquid He temperature. Then, the sample is rastered under the sensor producing a map of the spatial variations of the normal component of the magnetic field above the sample's surface with submillimeter resolution.

"[B]eautiful images of magnetic flux lines in chains of magnetosome particles (see cover) [show] that the particles are indeed SD and magnetized parallel to each other along the chain axis. Interestingly, within a magnetosome at the end of the chain, the magnetic field contours 'fan out' suggesting a flower state."

Like more familiar areomagnetic or marine surveys, a magnetic anomaly map is produced but with a sensor "flying" over the sample topography (the thin section) at an elevation of 100 µm. And, just like with aeromagnetic data, there is the classic problem of mathematical non-uniqueness associated with converting a distribution of magnetic fields into a reasonable model of subsurface magnetization. However, as Weiss pointed out, there are inversion techniques amenable to this type of problem, e.g. seamount magnetization inversions. Also by using vector measurements (possible with 3 SQUID sensors), and even gradiometer measurements, the inversion process can be furthered constrained. Results so far have concentrated on the thermal stability of magnetization in Martian meteorite ALH84001; and investigating the processes of impact demagnetization. Weiss and his group at MIT are also developing measurements schemes to determine paleointensities.

In the second talk of the session, Dr. Rafal Dunin-Borkowski described electron holography, a transmission electron microscopy technique that is capable of measuring the magnetization of individual nanophase particles. This technique also visualizes magnetic structure and its correlation with physical structure. In off-axis electron holography, the sample is positioned in the transmission electron microscope so that it covers approximately half the field of view. A charged electrostatic biprism then causes the electron wave that has passed through the specimen to overlap with a reference wave that has only passed through vacuum. The resulting hologram is an interference pattern which contains amplitude information in the relative amplitude of the cosine-like fringes; and contains electron-wave phase-shift information in the fringe positions. The holographic phase data can be decomposed into electrostatic and magnetic contributions and displayed as thickness contours and magnetic field lines, respectively. According to Dunin-Borkowski, the spatial resolution is around 1 nm for 2D scans, but by varying the tilt angle between sample and electron beam, 3D field distributions with 5 nm resolutions are possible.

An important advantage of electron holography over the high-resolution imaging afforded by magnetic force microscopy is that electron holography provides information about the internal magnetic configuration and not just the surface stray fields. However, samples must be thin enough (< 1 µm) to be electron transparent. Nonetheless, electron holography is well suited for studying nanostructured materials. For instance, it can provide invaluable information on the micromagnetic structure of submicron SD and small PSD particles of magnetite (e.g. vortex spin configurations, remanent magnetization, Hc). Variable field and temperature imaging can also be done yielding single-particle hysteresis loops, blocking temperatures, and direct measurement of critical magnetic transition sizes, e.g., superparamagnetic to stable SD and SD to non-SD states. Importantly, it can image within the size range where we have the best high-resolution 3-D micromagnetic models available for direct comparisons with micromagnetic structures from individual particles obtained by electron holography. Coupled with other TEM techniques that can provide complimentary information such as 3D shapes of particles, compositional variations, and crystalline defect structures, one can study the influence of the specific types of physical microstructures on the micromagnetic structure.

Dunin-Borkowski and his colleagues have produced beautiful images of magnetic flux lines in chains of magnetosome particles (see cover) showing that the particles are indeed SD and magnetized parallel to each other along the chain axis. Interestingly, within a magnetosome at the end of the chain, the magnetic field contours 'fan out' suggesting a flower state.

Bob Kopp (Caltech) summarized the latest work on the identification of biogenic magnetite particles using ferromagnetic resonance (FMR) spectroscopy. FMR is a microwave spectroscopy method, similar to electron paramagnetic resonance (EPR) spectroscopy, but for probing the magnetization of ferro- or ferri- magnetic materials because the resonance effects in this instance are associated with the internal anisotropy field resulting from shape, magnetocrystalline, stress, or interparticle interactions. The phenomenon is produced when a system of magnetic spins absorbs energy at a specific (resonant) frequency when subjected to a magnetic field sweep. In a typical set-up, the sample is exposed to a microwave field at a fixed frequency (in the GHz range) while a dc magnetic field is swept over a range of values. The resulting absorption intensity is a function of the sum of the external field and the (internal) anisotropy field. The method has been around for almost a century since its discovery in 1911, but its application in rock magnetism has been limited to a few studies.

Renewed interest in FMR is due to its sensitivity to the anisotropy field, and the demagnetizing field related to the shape of a magnetic particle. Differential spectra have different shapes for positive anisotropy (e.g., elongated particles) and for negative anisotropy (e.g., oblate particles). The Caltech group has demonstrated that chains of magnetosomes produced by magnetotactic bacteria produce distinctive FMR spectral characteristics that can be used as a marker for their presence in bulk samples of soils, sediments and ancient sedimentary rocks, and possibly even in extraterrestrial materials. For chains of magnetosome particles, the intrinsic magnetocrystalline anisotropy is not the main source of the coercivity but instead a combination of grain elongation (giving rise to shape anisotropy) and their linear arrangements in chains (producing positive magnetostatic interaction between grains) controls the remagnetization process. They estimate that the sensitivity of their method is ~1 nAm^2 in sample sizes up to 200 mg. However, FMR measurements, like other types of magnetic measurements on bulk materials, still suffers from the usual problems of unmixing associated with natural heterogeneous materials.

On the theoretical side, Dr. Andrew Newell (N. Carolina State University) presented a micromagnetic model of a SD particle of magnetite with a single dislocation. The basic experimental observation that favors some type of dislocation control of coercivity is that for pure magnetite, magnetocrystalline anisotropy should yield a Hc ~ 8 mT. Yet in "near" spherical particles or in octhaedra, Hc is significantly higher than the magnetocrystalline contribution, at least to find grain sizes up to about 1 μm. In addition, it is usually difficult for small particles to be free of defects. Newell's preliminary numerical results show that in a SD grain with one dislocation, the stress effect is zero when the dislocation is located in the center of the grain (average stress over the grain is ~ 0). However, a maximum effect occurs when the dislocation is along one edge of the grain. In this instance, the stress anisotropy is about a factor of 10 greater than the magnetocrystalline anisotropy, and even larger than shape anisotropy. One can imagine that with the technique of electron holography, it may be possible to test these models directly.

To summarize, the sixth Santa Fe conference showed much vitality among rock magnetists who are making advances in both basic and applied rock magnetism. However, they appear to be much more keen than a decade ago to use magnetic proxies to develop baseline data for testing various models: from early geomagnetic field to the validity of Milankovitch theory of climate change in sediment archives of all types: eolian, lake sediments and marine sediments. And rock magnetists are as keen as ever to adopt new technologies to answer outstanding questions in rock magnetism and earth science.

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.

Please Note: Due to copyright issues the University's general counsel directed the *Quarterly* to stop printing abstracts, in paper or electronically. In this issue, we print only an author list, title and journal information for each article. We have highlighted a few articles by including our own abstract. At this point, we question the utility of an article list without access to the abstract text, online or otherwise. We would appreciate our readers' input. Do you find the article list sans abstract text useful or should we devote the space to something else? Please send comments to:
Brian Carter-Stiglitz, cart0196@umn.edu.

Alteration and Remagnetization

Cederquist, D.P., R. Van der Voo, and B.A. van der Pluijm, **Syn-folding remagnetization of Cambro-Ordovician carbonates from the Pennsylvania Salient post-dates oroclinal rotation**, *Tectonophysics*, *422* (1-4), 41-54, 2006.

Elliott, W.C., A. Basu, J.M. Wampler, R.D. Elmore, and G.H. Grathoff, **Comparison of K-Ar ages of diagenetic illite-smectite to the age of a chemical remanent magnetization (CRM): An example from the Isle of Skye, Scotland**, *Clays and Clay Minerals*, *54* (3), 314-323, 2006.

Elmore, R.D., J.L.E. Foucher, M. Evans, M. Lewchuk, and E. Cox, **Remagnetization of the Tonoloway Formation and the Helderberg Group in the Central Appalachians: testing the origin of syntilting magnetizations**, *Geophysical Journal International*, *166* (3), 1062-1076, 2006.

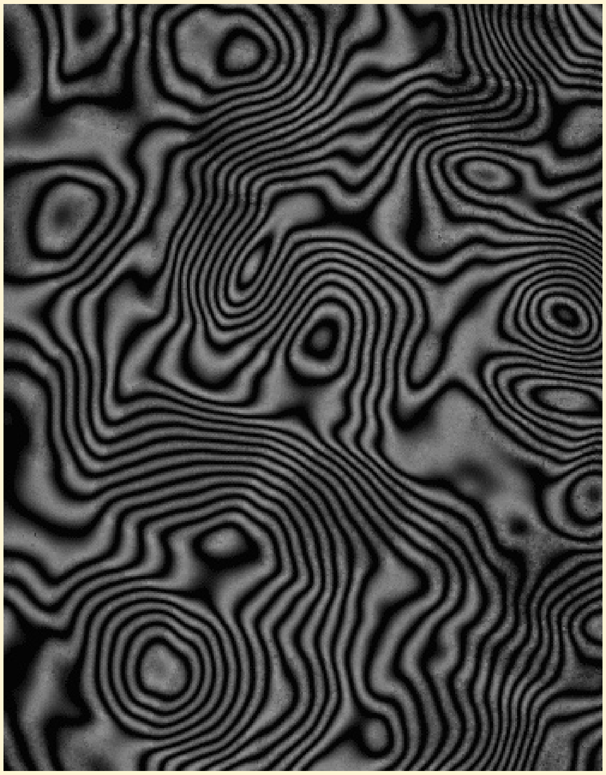
Font, E., R.I.F. Trindade, and A. Nedelec, **Remagnetization in bituminous limestones of the Neoproterozoic Araras Group (Amazon craton): Hydrocarbon maturation, burial diagenesis, or both?,** *Journal of Geophysical Research-Solid Earth*, *111* (B6), 2006.

Biogeomagnetism

Frankel, R.B., and D.A. Bazylinski, **How magnetotactic bacteria make magnetosomes queue up**, *Trends in Microbiology*, *14* (8), 329-331, 2006.

Han, C.S., H.Y. Lee, and Y. Roh, **On biologically produced nanomaterials**, *International Journal of Nanotechnology*, *3* (2-3), 236-252, 2006.

Kasama, T., M. Posfai, R.K.K. Chong, A.P. Finlayson, P.R. Buseck, R.B. Frankel, and R.E. Dunin-Borkowski, **Magnetic properties, microstructure, composition, and morphology of greigite**



Electron holography image showing remanence state in a natural titanomagnetite specimen with magnetite rich blocks separated by paramagnetic ulvospinel. The field of view in the horizontal direction is approximately 1 micron. Acknowledgments: Richard Harrison, Andrew Putnis, Rafal Dunin-Borkowski

nanocrystals in magnetotactic bacteria from electron holography and tomography, *American Mineralogist*, *91* (8-9), 1216-1229, 2006.

Kobayashi, A., J.L. Kirschvink, C.Z. Nash, R.E. Kopp, D.A. Sauer, L.E. Bertani, W.F. Voorhout, and T. Taguchi, **Experimental observation of magnetosome chain collapse in magnetotactic bacteria: Sedimentological, paleomagnetic, and evolutionary implications**, *Earth and Planetary Science Letters*, *245* (3-4), 538-550, 2006.

Kopp, R.E., B.P. Weiss, A.C. Maloof, H. Vali, C.Z. Nash, and J.L. Kirschvink, **Chains, clumps, and strings: Magnetofossil taphonomy with ferromagnetic resonance spectroscopy**, *Earth and Planetary Science Letters*, *247* (1-2), 10-25, 2006.

Kukkadapu, R.K., J.M. Zachara, J.K. Fredrickson, J.P. McKinley, D.W. Kennedy, S.C. Smith, and H.L. Dong, **Reductive biotransformation of Fe in shale-limestone saprolite containing Fe(III) oxides and Fe(II)/Fe(III) phyllosilicates**, *Geochimica Et Cosmochimica Acta*, *70* (14), 3662-3676, 2006.

Lins, U., M.R. McCartney, M. Farina, R.B. Frankel, and P.R. Buseck, **Crystal habits and magnetic microstructures of magnetosomes in coccoid magnetotactic bacteria**, *Anais Da Academia Brasileira De Ciencias*, *78* (3), 463-474, 2006.

Schubbe, S., C. Wurdemann, J. Peplies, U. Heyen, C. Wawer, F.O. Glockner, and D. Schuler, **Transcriptional organization and regulation of magnetosome operons in Magnetospirillum gryphiswaldense**, *Applied and Environmental Microbiology*, *72* (9), 5757-5765, 2006.

Smith, M.J., P.E. Sheehan, L.L. Perry, K. O'Connor, L.N. Csonka, B.M. Applegate, and L.J. Whitman, **Quantifying the magnetic advantage in magnetotaxis**, *Biophysical Journal*, *91* (3), 1098-1107, 2006.

Taoka, A., R. Asada, H. Sasaki, K. Anzawa, L.F. Wu, and Y. Fukumori, **Spatial localizations of Mam22 and Mam12 in the magnetosomes of Magnetospirillum magnetotacticum**, *Journal of Bacteriology*, *188* (11), 3805-3812, 2006.

Environmantal Magnetism

Brachfeld, S.A., **High-field magnetic susceptibility (chi HF) as a proxy of biogenic sedimentation along the Antarctic Peninsula**, *Physics of the Earth and Planetary Interiors*, *156* (3-4), 274-282, 2006.

Carter-Stiglitz, B., S.K. Banerjee, A. Gourlan, and E. Oches, **A multi-proxy study of Argentina loess: Marine oxygen isotope stage 4 and 5 environmental record from pedogenic hematite**, *Palaeogeography Palaeoclimatology Palaeoecology*, *239* (1-2), 45-62, 2006.

Ellwood, B.B., W.L. Balsam, and H.H. Roberts, **Gulf of Mexico sediment sources and sediment transport trends from magnetic susceptibility measurements of surface samples**, *Marine Geology*, *230* (3-4), 237-248, 2006.

Gendler, T.S., F. Heller, A. Tsatskin, S. Spassov, J. Du Pasquier, and S.S. Faustov, **Roxolany and Novaya Etuliya- key sections in the western Black Sea loess area: Magneto stratigraphy, rock magnetism, and paleopedology**, *Quaternary International*, *152*, 78-93, 2006.

Gyllencreutz, R., and C. Kissel, **Lateglacial and Holocene sediment sources and transport patterns in the Skagerrak interpreted from high-resolution magnetic properties and grain size data**, *Quaternary Science Reviews*, *25* (11-12), 1247-1263, 2006.

Hanesch, M., H. Stanjek, and N. Petersen, **Thermomagnetic measurements of soil iron minerals: the role of organic carbon**, *Geophysical Journal International*, *165* (1), 53-61, 2006.

Larrasoana, J.C., A.P. Roberts, A. Hayes, R. Wehausen, and E.J. Rohling, **Detecting missing beats in the Mediterranean climate rhythm from magnetic identification of oxidized sapropels (Ocean Drilling Program Leg 160)**, *Physics of the Earth and Planetary Interiors*, *156* (3-4), 283-293, 2006.

Li, Y.X., Z.C. Yu, K.P. Kodama, and R.E. Moeller, **A 14,000-year environmental change history revealed by mineral magnetic data from White Lake, New Jersey, USA**, *Earth and Planetary Science Letters*, *246* (1-2), 27-40, 2006.

Michaud, F., H.U. Ramirez-Sanchez, C. Parron, P.F. Zarate-del Valle, F. Fernex, and G. Barci-Funel, **Strong magnetic levels in Lake Chapala sediments (western Mexico): Their mineralogy and stratigraphic significance**, *Journal of Paleolimnology*, *35* (4), 819-836, 2006.

Prajapati, S.K., S.K. Pandey, and B.D. Tripathi, **Monitoring of vehicles derived particulates using magnetic properties of leaves**, *Environmental Monitoring and Assessment*, *120* (1-3), 169-175, 2006.

Reynolds, R.L., M.C. Reheis, J.C. Neff, H. Goldstein, and J. Yount, **Late Quaternary eolian dust in surficial deposits of a Colorado Plateau grassland: Controls on distribution and ecologic effects**, *Catena*, *66* (3), 251-266, 2006.

Roberts, A.P., **High-resolution magnetic analysis of sediment cores: Strengths, limitations and strategies for maximizing the value of long-core magnetic data**, *Physics of the Earth and Planetary Interiors*, *156* (3-4), 162-178, 2006.

Umbanhowar, C.E., P. Camill, C.E. Geiss, and R. Teed, **Asymmetric vegetation responses to mid-Holocene aridity at the prairie-forest ecotone in south-central Minnesota**, *Quaternary Research*, *66* (1), 53-66, 2006.

Zhao, Y.C., J.Y. Zhang, J.M. Sun, X.F. Bai, and C.G. Zheng, **Mineralogy, chemical composition, and microstructure of ferrospheres in fly ashes from coal combustio**n, *Energy & Fuels*, *20* (4), 1490-1497, 2006.

Extraterrestrial Magnetism

Chevrier, V., P.E. Mathe, P. Rochette, O. Grauby, G. Bourrie, and F. Trolard, **Iron weathering products in a CO_2+(H_2O or H_2O_2) atmosphere: Implications for weathering processes**

on the surface of Mars, *Geochimica Et Cosmochimica Acta*, *70* (16), 4295-4317, 2006.

Lanci, L., and D.V. Kent, **Meteoric smoke fallout revealed by superparamagnetism in Greenland ice**, *Geophysical Research Letters*, *33* (13), 2006.

Rochette, P., J. Gattacceca, V. Chevrier, P.E. Mathe, and M. Menvielle, **Magnetism, iron minerals, and life on Mars**, *Astrobiology*, *6* (3), 423-436, 2006.

Souza-Egipsy, V., J. Ormo, B.B. Bowen, M.A. Chan, and G. Komatsu, **Ultrastructural study of iron oxide precipitates: Implications for the search for biosignatures in the Meridiani hematite concretions**, Mars, *Astrobiology*, *6* (4), 527-545, 2006.

Magnetic Field Records and Paleointensity Methods

Bowles, J., J.S. Gee, D.V. Kent, M.R. Perfit, S.A. Soule, and D.J. Fornari, **Paleointensity applications to timing and extent of eruptive activity, 9 degrees-10 degrees N East Pacific Rise**, *Geochemistry Geophysics Geosystems*, *7*, 2006.

Constable, C., and M. Korte, **Is Earth's magnetic field reversing?**, *Earth and Planetary Science Letters*, *246* (1-2), 1-16, 2006.

Fuller, M., **Geomagnetic field intensity, excursions, reversals and the 41,000-yr obliquity signal**, *Earth and Planetary Science Letters*, *245* (3-4), 605-615, 2006.

Hill, M.J., J. Shaw, and E. Herrero-Bervera, **Determining paleointensity from the Gilbert Gauss reversal recorded in the Pu'u Heleakala lava section, Wai'anae Volcano, Oahu, Hawaii**, *Earth and Planetary Science Letters*, *245* (1-2), 29-38, 2006.

Mazaud, A., A **first-order correction to minimize environmental influence in sedimentary records of relative paleointensity of the geomagnetic field**, *Geochemistry Geophysics Geosystems*, *7*, 2006.

Tarduno, J., R. Cottrell, and A. Smirnov, **The paleomagnetism of single silicate crystals: Recording geomagnetic field strength during mixed polarity intervals, superchrons, and inner core growth**, *Reviews of Geophysics, 44 (1)*, 2006.

A great review article with a self-explanatory title.

Tauxe, L., **Long-term trends in paleointensity: The contribution of DSDP/ODP submarine basaltic glass collections**, *Physics of the Earth and Planetary Interiors*, *156* (3-4), 223-241, 2006.

Tauxe compiles nearly 1000 paleointensity experiments conducted on submarine basaltic glass. All of the data are available on the MagIC database. Tauxe concludes, inter alia, a positive relationship between polarity-interval length and paleointensity.

Magnetic Microscopy and Spectroscopy

Bandyopadhyay, D., **Study of kinetics of iron minerals in coal by Fe-57 Mossbauer and FT-IR spectroscopy during natural burning,** *Hyperfine Interactions*, *163* (1-4), 167-176, 2005.

Cave, L., T. Al, D. Loomer, S. Cogswell, and L. Weaver, **A STEM/EELS method for mapping iron valence ratios in oxide minerals**, *Micron*, *37* (4), 301-309, 2006.

Chou, L.J., M.T. Chang, Y.L. Chueh, J.J. Kim, H.S. Park, and D. Shindo, **Electron holography for improved measurement of microfields in nanoelectrode assemblies**, *Applied Physics Letters*, *89* (2), 2006.

Ferrow, E.A., and B.A. Sjoberg, **Oxidation of pyrite grains: A Mossbauer spectroscopy and mineral magnetism study**, *Hyperfine Interactions*, *163* (1-4), 95-108, 2005.

Golla-Schindler, U., R. Hinrichs, O. Bomati-Miguel, and A. Putnis, **Determination of the oxidation state for iron oxide minerals by energy-filtering TEM**, *Micron*, *37* (5), 473-477, 2006.

Jordan, K., A. Cazacu, G. Manai, S.F. Ceballos, S. Murphy, and I.V. Shvets, **Scanning tunneling spectroscopy study of the electronic structure of Fe3O4 surfaces**, *Physical Review B*, *74* (8), 2006.

Keimpema, K., H. De Raedt, and J.T.M. De Hosson**, Electron holography image simulation of nanoparticles**, *Journal of Computational and Theoretical Nanoscience*, *3* (3), 362-374, 2006.

Lovely, G.R., A.P. Brown, R. Brydson, A.I. Kirkland, R.R. Meyer, L.Y. Chang, D.A. Jefferson, M. Falke, and A. Bleloch, **HREM of the {111} surfaces of iron oxide nanoparticles**, *Micron*, *37* (5), 389-395, 2006.

Nasir, S., and A.D. Al-Rawas, Mossbauer characterization of upper mantle ferrikaersutite, *American Mineralogist*, *91* (7), 1163-1169, 2006.

West, G.D., and R.L. Higginson, **Characterisation of high temperature oxidation using electron backscatter diffraction**, *Materials at High Temperatures*, *22* (3-4), 201-205, 2005.

Rock and Mineral Magnetism

Biggin, A.J., **First-order symmetry of weak-field partial thermoremanence in multi-domain (MD) ferromagnetic grains: 2. Implications for Thellier-type palaeointensity determination**, *Earth and Planetary Science Letters*, *245* (1-2), 454-470, 2006.

Biggin, A.J., and T. Poidras, **First-order symmetry of weak-field partial thermoremanence in multi-domain ferromagnetic grains. 1. Experimental evidence and physical implications**, *Earth and Planetary Science Letters*, *245* (1-2), 438-453, 2006.

Carter-Stiglitz, B., J.P. Valet, and M. LeGoff, **Constraints on the acquisition of remanent magnetization in fine-grained sediments imposed by redeposition experiments**, *Earth and Planetary Science Letters*, *245* (1-2), 427-437, 2006.

Carvallo, C., and A. Muxworthy, **Low-temperature first-order reversal curve (FORC) diagrams for synthetic and natural samples**, *Geochemistry Geophysics Geosystems*, *7*, 2006.

Doubrovine, P.V., and J.A. Tarduno, **N-type magnetism at cryogenic temperatures in oceanic basalt**, *Physics of the Earth and Planetary Interiors*, *157* (1-2), 46-54, 2006.

Draeger, U., M. Prevot, T. Poidras, and J. Riisager, **Single-domain chemical, thermochemical and thermal remanences in a basaltic rock**, *Geophysical Journal International*, *166* (1), 12-32, 2006.

Harrison, R.J., **Microstructure and magnetism in the ilmenite-hematite solid solution: A Monte Carlo simulation study**, *American Mineralogist*, *91* (7), 1006-1023, 2006.

Heslop, D., A. Witt, T. Kleiner, and K. Fabian, **The role of magnetostatic interactions in sediment suspensions**, *Geophysical Journal International*, *165* (3), 775-785, 2006.

Maki, D., J.A. Homburg, and S.D. Brosowske, **Thermally activated mineralogical transformations in archaeological hearths: Inversion from maghemite gamma Fe2O4 phase to haematite alpha Fe2O4 form**, *Archaeological Prospection*, *13* (3), 207-227, 2006.

Muxworthy, A.R., J.G. King, and N. Odling, **Magnetic hysteresis properties of interacting and noninteracting micron-sized magnetite produced by electron beam lithography**, *Geochemistry Geophysics Geosystems*, *7*, 2006.

Muxworthy, A.R., and W. Williams, **Low-temperature cooling behavior of single-domain magnetite: Forcing of the crystallographic axes and interactions**, *Journal of Geophysical Research-Solid Earth*, *111* (B7), 2006.

Ozdemir, O., and D.J. Dunlop, **Magnetic domain observations on magnetite crystals in biotite and hornblende grains**, *Journal of Geophysical Research-Solid Earth*, *111*

Dennis Gabor

b. June 5, 1900
d. February 8, 1979

Born in Budapest, Hungary, Gabor's love of physics began when he was a teenager. He and his brother set up a laboratory in their parents' garage allowing them to repeat modern physics experiments, including experiments with X-rays. He was trained as an electrical engineer in Germany; but eventually fled a Nazi Germany to England, where he did the holography work for which he won the Nobel prize in 1971.

(B6), 2006.

Robinson, P., F. Heidelbach, A.M. Hirt, S.A. McEnroe, and L.L. Brown, **Crystallographic-magnetic correlations in single-crystal haemo-ilmenite: new evidence for lamellar magnetism**, *Geophysical Journal International*, *165* (1), 17-31, 2006.

Yu, Y., and L. Tauxe, **Effect of multi-cycle heat treatment and pre-history dependence on partial thermoremanence (pTRM) and pTRM tails**, *Physics of the Earth and Planetary Interiors*, *157* (3-4), 196-207, 2006.

Zhao, X.X., P. Riisager, M. Antretter, J. Carlut, P. Lippert, Q.S. Liu, B. Galbrun, S. Hall, H. Delius, and T. Kanamatsu, **Unraveling the magnetic carriers of igneous cores from the Atlantic, Pacific, and the southern Indian oceans with rock magnetic characterization**, *Physics of the Earth and Planetary Interiors*, *156* (3-4), 294-328, 2006.

Mineral Physics and Chemistry

Bode, M., E.Y. Vedmedenko, K. Von Bergmann, A. Kubetzka, P. Ferriani, S. Heinze, and R. Wiesendanger, **Atomic spin structure of antiferromagnetic domain walls**, *Nature Materials, 5 (6)*, 477-481, 2006.

Bode, et al., use spin-polarized scanning tunnelling electron microscopy to study the spin structure in an anti-ferromagnetic monolayer. Whether the domain walls, with widths of 6-8 atomic rows, have uncompensated magnetic moments depends on their crystallographic orientation.

Fiorillo, F., **Anisotropy and magnetization process in soft magnets: Principles, experiments, applications**, *Journal of Magnetism and Magnetic Materials*, *304* (2), 139-144, 2006.

Gomez, E., J. Roger-Folch, A. Molina, J.A. Fuentes, A. Gabaldon, and R. Torres, **Modelling of magnetic anisotropy in the finite element method**, *Compel-the International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, *25* (3), 609-615, 2006.

Hu, G.L., K. Dam-Johansen, W. Stig, and J.P. Hansen, **Decomposition and oxidation of pyrite**, *Progress in Energy and Combustion Science*, *32* (3), 295-314, 2006.

Huang, Z.G., Z.G. Chen, L.Q. Jiang, Q.Y. Ye, and Q.Y. Wu, **Monte Carlo simulation of magnetization and coercivity of free magnetic clusters**, *Chinese Physics*, *15* (7), 1602-1610, 2006.

Jentzsch, T.L., and R.L. Penn, **Influence of aluminum doping on ferrihydrite nanoparticle reactivity**, *Journal of Physical Chemistry B*, *110* (24), 11746-11750, 2006.

Klotz, S., G. Rousse, T. Strassle, C.L. Bull, and M. Guthrie, **Nuclear and magnetic structure of magnetite under pressure to 5.3 GPa and at low temperatures to 130 K by neutron scattering**, *Physical Review B, 74 (1)*, 2006.

Klotz, et al., studied the spin structure of magnetite from 0-5.3 GPa covering 130 K< T <300 K. The inverse-spinel structure was stable and the long-range ferrimagnetic ordering do not change over the studied P/T range.

Kwon, S.K., S. Suzuki, M. Saito, T. Kamimura, H. Miyuki, and Y. Waseda, **Atomic-scale structure of beta-FeOOH containing chromium by anomalous X-ray scattering coupled with reverse Monte Carlo simulation**, *Corrosion Science*, *48* (6), 1571-1584, 2006.

Lee, S.J., and S. Lee, **The spin structure of maghemite investigated by Fe-57 NMR**, *New Journal of Physics*, *8*, 2006.

Markl, G., F. Von Blanckenburg, and T. Wagner, **Iron isotope fractionation during hydrothermal ore deposition and alteration**, *Geochimica Et Cosmochimica Acta*, *70* (12), 3011-3030, 2006.

Oshima, Y., H. Nojiri, K. Asakura, T. Sakai, M. Yamashita, and H. Miyasaka, **Collective magnetic excitation in a single-chain magnet by electron spin resonance measurements**, *Physical Review B*, *73* (21), 2006.

Pineau, A., N. Kanari, and I. Gaballah, **Kinetics of reduction of iron oxides by H-2 - Part I: Low temperature reduction of hematite**, *Thermochimica Acta*, *447* (1), 89-100, 2006.

Rabenhorst, M.C., and S.N. Burch, **Synthetic iron oxides as an indicator of reduction in soils (IRIS)**, *Soil Science Society of America Journal*, *70* (4), 1227-1236, 2006.

Satoh, A., and M. Ozaki, **Transport coefficients and orientational distributions of spheroidal particles with magnetic moment normal to the particle axis - (Analysis for an applied magnetic field normal to the shear plane)**, *Journal of Colloid and Interface Science*, *298* (2), 957-966, 2006.

Sort, J., K.S. Buchanan, V. Novosad, A. Hoffmann, G. Salazar-Alvarez, A. Bollero, M.D. Baro, B. Dieny, and J. Nogues, **Imprinting vortices into antiferromagnets**, *Physical Review Letters*, *97* (6), 2006.

Wiederhold, J.G., S.M. Kraemer, N. Teutsch, P.M. Borer, A.N. Halliday, and R. Kretzschmar, **Iron isotope fractionation during proton-promoted, ligand-controlled, and reductive dissolution of goethite**, *Environmental Science & Technology*, *40* (12), 3787-3793, 2006.

Nanophase and Disordered Systems

Baruwati, B., K.M. Reddy, S.V. Manorama, and S.S. Madhavendra, **Synthesis of nanostructured hydroxides and oxides of iron: Control over morphology and physical properties**, *Journal of the American Ceramic Society*, *89* (8), 2602-2605, 2006.

de Biasi, R.S., and E.C. Gondim, **Use of ferromagnetic resonance to determine the size distribution of gamma-Fe2O3 nanoparticles**, *Solid State Communications*, *138* (6), 271-274, 2006.

Deb, P., and A. Basumallick, **Structure and properties of iron oxide nanoparticles prepared through a gentle chemistry route**, *Materials and Manufacturing Processes*, *21* (7), 658-661, 2006.

Eisenreich, N., H. Fietzek, M. Juez-Lorenzo, V. Kolarik, V. Weiser, and A. Koleczko, **Influence of nano-particle size on the oxidation behavior of Al, Fe and Cu**, *Materials at High Temperatures*, *22* (3-4), 329-333, 2005.

Frandsen, C., and S. Morup, **Reversible aggregation and magnetic coupling of alpha-Fe2O3 nanoparticles**, *Journal of Physics-Condensed Matter*, *18* (31), 7079-7084, 2006.

Heinrichs, S., W. Dieterich, and P. Maass, **Kinetic growth of nanoclusters with perpendicular magnetic anisotropy**,

The IRM
Quarterly

The *Institute for Rock Magnetism* is dedicated to providing state-of-the-art facilities and technical expertise free of charge to any interested researcher who applies and is accepted as a Visiting Fellow. Short proposals are accepted semi-annually in spring and fall for work to be done in a 10-day period during the following half year. Shorter, less formal visits are arranged on an individual basis through the Facilities Manager.

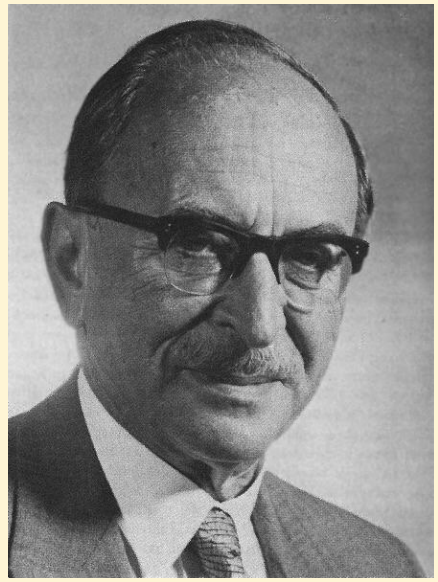
The *IRM* staff consists of **Subir Banerjee**, Professor/Director; **Bruce Moskowitz**, Professor/Associate Director; **Jim Marvin**, Emeritus Scientist; **Mike Jackson**, **Peat Sølheid**, and **Brian Carter-Stiglitz**, Staff Scientists.

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

The *IRM Quarterly* is published four times a year by the staff of the *IRM*. If you or someone you know would like to be on our mailing list, if you have something you would like to contribute (*e.g.*, titles plus abstracts of papers in press), or if you have any suggestions to improve the newsletter, please notify the editor:

Brian Carter-Stiglitz
Institute for Rock Magnetism
University of Minnesota
289 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5049
fax: (612) 625-7502
e-mail: cart0196@umn.edu
www.irm.umn.edu

University of Minnesota



GABOR

From: www.physik.uni-frankfurt.de/~jr/physpicnobel.

University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: irm@umn.edu
www.irm.umn.edu

Nonprofit Org.
U.S Postage
PAID
Mpls., MN
Permit No. 155

Europhysics Letters, *75* (1), 167-173, 2006.

Hernando, A., P. Crespo, M.A. Garcia, E.F. Pinel, J. de la Venta, A. Fernandez, and S. Penades, **Giant magnetic anisotropy at the nanoscale: Overcoming the superparamagnetic limit**, *Physical Review B*, *74* (5), 2006.

Madsen, D.E., S. Morup, and M.F. Hansen, **On the interpretation of magnetization data for antiferromagnetic nanoparticles**, *Journal of Magnetism and Magnetic Materials*, *305* (1), 95-99, 2006.

Tang, B., G.L. Wang, L.H. Zhuo, J.C. Ge, and L.J. Cui, **Facile route to alpha-FeOOH and alpha-Fe2O3 nanorods and magnetic property of alpha-Fe2O3 nanorods**, *Inorganic Chemistry*, *45* (13), 5196-5200, 2006.

Yang, T.Z., C.M. Shen, H.T. Yang, C.W. Xiao, Z.C. Xu, S.T. Chen, D.X. Shi, and H.J. Gao, **Synthesis, characterization and self-assemblies of magnetite nanoparticles**, *Surface and Interface Analysis*, *38* (6), 1063-1067, 2006.

Yang, W.H., C.F. Lee, H.Y. Tang, D.B. Shieh, and C.S. Yeh, **Iron oxide nanopropellers prepared by a low-temperature solution approach**, *Journal of Physical Chemistry B*, *110* (29), 14087-14091, 2006.

Synthesis

Hwang, J.Y., S.Z. Shi, Z.Y. Xu, and K.W. Peterson, **Synthesis of monodispersed iron oxide particles by a large-scale microwave reactor**, *Chemical Engineering Communications*, *193* (12), 1586-1591, 2006.

Mutch, K.J., V. Koutsos, and P.J. Camp, **Deposition of magnetic colloidal particles on graphite and mica surfaces driven by solvent evaporation**, *Langmuir*, *22* (13), 5611-5616, 2006.