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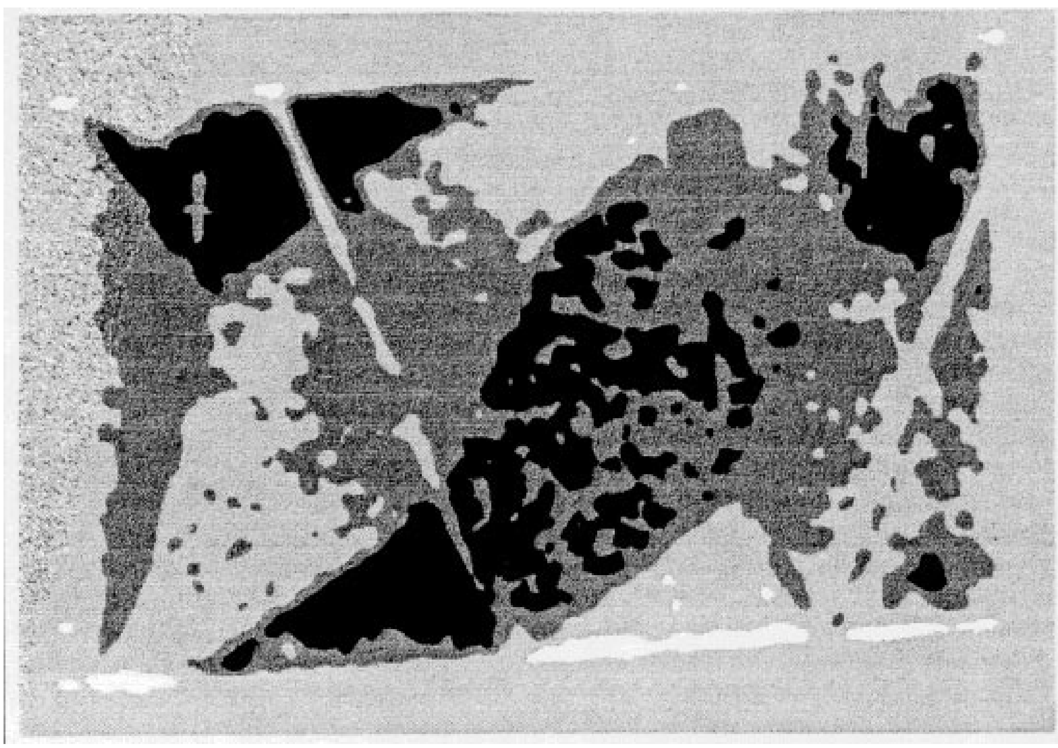

MOKE Magnifies Magnetic Moments [Magnificently!]

Chris Hunt
Sanghamitra Sahu
IRM

The arrival of several new pieces of equipment during the past year has added significantly to the capabilities of the IRM. *This article is the second in a series that will explain their usefulness as well as how to use them. We thus hope both to remove some of the mystique that surrounds them, and to foster ideas for new experiments afforded by their existence. This time, it's the MOKE system:*

THE MOKE

Our new Magneto-Optic Kerr Effect (MOKE) system, which consists of a Leitz Orthoplan microscope and many peripheral parts, is now going through its break-in period. The primary use of the MOKE is to create images of magnetic domains. The behavior of domains and domain walls, and even the direction of magnetization, can then be directly investigated in real time, as an applied field is varied.

Applications

The observation of magnetic domains is of fundamental importance for understanding macroscopic magnetic properties and for analysis of micromagnetic structures. For example, MOKE microscopy, in conjunction with MicroMag measurements of magnetization, can explain the roles played by microstructure and second phases in controlling the stability of remanence in single grains. MOKE observations by others have even shown the behavior of individual domains while a sample undergoes a hysteresis loop. With our MOKE, we have had success in obtaining domain images from Permalloy (Ni-Fe alloy) wafers [as shown at left]. Currently, we are adapting the microscope for the more demanding problem [see below] of domain observations in titanomagnetite.

How?

A MOKE imaging system takes advantage of the Kerr Effect, in which the plane of polarization of incident light is rotated a small amount after being reflecting from a polished surface which has a magnetic moment. Using crossed-polars, this rotation results in magnetized areas of a sample appearing as bright and dark areas. Higher magnetization results in more rotation and a brighter image. By comparing gray-scale variations, the magnetization direction within domains can be analyzed qualitatively—even quantitatively in certain cases. When used in conjunction with a furnace and a stage magnet, the domain state of a sample can be watched in nearly real time as the sample undergoes hysteresis or goes through its Curie point. Digital processing can result in images such as that shown above.

Principles of Operation

The Kerr Effect comes about when a linearly polarized electromagnetic wave is reflected from the surface of a magnetized material. One can take a Phreshman Physics view of what happens when light strikes the surface (*i.e.*, a simplified-and-therefore-not-very-precise-under-heavy-scrunity-but-nevertheless-satisfyingly-sensible-and-certainly-more-comprehensible-than-Quantum-Mechanics view [but, if you're a die-

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Visiting Fellows' Reports

We have enjoyed working with two Visiting Fellows this summer. At the end of July, Mr. ***David Grimley****, from the University of Illinois, researched loess and paleosol from the midwest. Dr.* ***Franz Heider****, from Universität München, flew over in August to measure single magnetite crystals. In addition to the official Fellows, we have welcomed several informal visitors, plus half a dozen less-than-one-day visitors who wanted to inspect our facilities. For example, in early June some travelers from Germany made an appearance to measure single hornblende crystals: Dr.* ***Horst-Ulrich Worm****, from the Bundesanstalt für Geowissenschaften und Rohstoffe in Einbeck, and Ms.* ***Dietlinde Friedrich****, from Universität Göttingen. Later in the month, Mr.* ***Bernie Housen*** *and Dr.* ***Carl Richter****, from the University of Michigan, drove all night to measure anisotropy of magnetic susceptibility. We have enticed each visitor to contribute a summary of work done here at the* **IRM***:*

David Grimley
University of Illinois

Magnetic Properties of Loess/Paleosol Sequences in Southwestern Illinois and Eastern Missouri

After a few initial setbacks, my two-week venture at the *IRM* was tremendously successful. Measurements of the mass susceptibility of remolded loess in the laboratory are in excellent agreement with variations in volume susceptibility with depth as measured in the field with a portable instrument. This confirmation gives stratigraphic significance to high and low susceptibility zones within the Peoria Loess and Roxana Silt (both of Wisconsinan age). These susceptibility zones can be correlated over several counties in southwestern Illinois and eastern Missouri. Regional extensions of these correlations are possible in the future.

Based on over 175 ARM and k_{fd} determinations as well as on several hysteresis loops and one Curie temperature, it seems that susceptibility zones in relatively unaltered loesses (CB or C horizons) are caused by concentration changes in silt-sized magnetite. This is in good agreement with previous analyses and observations of the magnetic extracts. The ultimate cause for stratigraphic changes in magnetite concentration may be related to changing ice margins or changing source areas of glacial erosion during the late Quaternary.

Ratios of k_{ARM}/k were found to increase sharply in the Roxana Silt relative to the overlying Peoria Loess. The change is interpreted as a reflection of a greater concentration of single-domain magnetite grains in the clay fraction of the Roxana Silt. ARM measurements of particle size fractions support this hypothesis.

The frequency dependence of susceptibility, k_{fd}, is generally less than 1.5% in relatively unaltered loesses, but ranges from 1.5% to 5.0% in the A and Bt horizons of several modern Alfisols and Mollisols, from 3% to 7% in the Bt horizon of three Sangamon Geosols (developed into Illinoian loess), and from 4% to 8% in the Bt horizon of one Yarmouth Geosol (developed into a Pre-Illinoian loess). Hysteresis loops indicate that superparamagnetic grains in the strongly developed soils contribute significantly to susceptibility.

The data acquired at the *IRM* will be further interpreted in conjunction with optical microscopy, SEM, and XRD measurements of the magnetic fractions along with other mineralogical and grain-size determinations at the University of Illinois. Many thanks to the *IRM* staff and students for patiently training me on the equipment and for having enlightening magnetic discussions.

Franz Heider
Universität München,
Germany

Magnetic properties of single magnetite crystals

Until now, magnetic hysteresis properties could only be measured on bulk samples containing hundreds of magnetite grains in dispersion. Lack of sensitivity made measurement of small single crystals on a Vibrating Sample Magnetometer impossible. But, the Alternating Force Gradient Magnetometer (MicroMag), available at the *IRM*, allows the investigation of single magnetite crystals over a range of grain sizes.

The smallest hydrothermally grown magnetite for which a hysteresis loop was obtained had a diameter of 20 µm. Handling particles of this size without loosing them is quite a challenge. One of the questions I had was whether individual particles show the same properties as the bulk sample or whether particles of the same size can have different saturation remanences and coercive forces. Finding that not all magnetites of one size were equal, but that some were harder than others, was one interesting aspect of this work. The largest grains measured were 300 µm in size, whose magnetization was near the upper end of the sensitivity scale of the MicroMag.

In general the parameters H_c and M_{rs} showed the expected size dependence known from bulk measurements. Surface irregularities of the crystals seem to influence magnetic properties. Surprisingly, the coercivity of remanence did not show a strong grainsize dependence. The question of local energy minimum states (LEM) and their influence on the coercivity of remanence measured on a single grain will be discussed in a poster at the 1992 Fall AGU meeting.

I also used the Quantum Design Superconducting Susceptometer (MPMS) for low-temperature measurements on ODP Leg 120 sediments. A saturation IRM (not to be confused with the *Institute for Rock Magnetism*[!]) was induced at 6 K and monitored during warming up to 300 K. From previous $M_s(T)$ measurements and TEM work, we knew that the sediments contain basaltic volcanic ashes with titanomagnetite inclusions. The low-temperature measurements were intended to find out whether there was any magnetite of biogenic or other origin in the sediments. Unfortunately, there was no Verwey transition in the vicinity of 110 K. In order to see a nice Verwey transition, I did a low temperature demagnetization of an IRM on some home-grown multidomain magnetites during my last day in Minneapolis.

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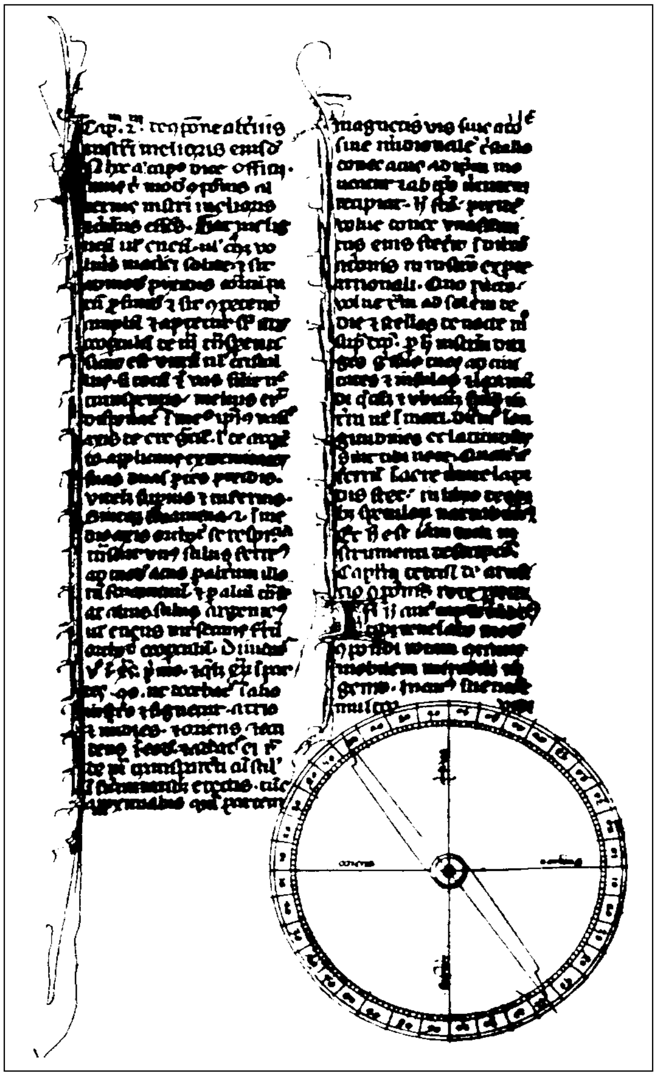

From the Epistola de Magnete *by Petrus Peregrinus, 1269.*

Current Abstracts

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 geological journals will be included, but special emphasis is given to current articles from physics, chemistry, and materials science journals. Most abstracts are culled 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 edited for the* IRM Quarterly. *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 1700 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the* IRM Quarterly *are always welcome.*

Anomalies

Petronotis, K. E., R. G. Gordon, and G. D. Acton
Determining palaeomagnetic poles and anomalous skewness from marine magnetic anomaly skewness data from a single plate, *Geophys. J. Int., 109*, 209-224, 1992.
A method is presented for simultaneously determining both paleomagnetic poles and anomalous skewness from the observed skewness of marine magnetic anomalies. Skewness is estimated by comparison of observed anomalies with a synthetic anomaly. The inversion procedure determines the paleomagnetic pole and the anomalous skewness that give the best fit to the observed effective remanent inclinations, as inferred from the observed phase shift.

Yanez, G. A., and J. L. LaBrecque
Age dependent 3-D magnetic modeling of the North Pacific and North Atlantic oceanic crust at intermediate wavelengths, *J. Geophys. Res., 97B, in press*, 1992.
Three-dimensional magnetic modeling shows that the source for the intermediate-wavelength magnetic anomaly pattern consists primarily of an age-dependent thermoremanent magnetization (TRM) in layer 2, plus a combination of a chemical remanent magnetization (CRM) in the altered upper oceanic crust, and a thermoviscous remanent magnetization (TVRM) in the slowly-cooling lower crust and upper mantle.

Chemistry

Dhara, S., *et al.*
Structural and magnetic properties of chemically vapour deposited iron oxide thin films, *Thin Sol. Films, 209*, 116-121, 1992.
Measurements made during the transformation of α-Fe_2O_3 to both γ-Fe_2O_3 and Fe_3O_4 by a reduction-oxidation process provide new information about microstructural changes, about changes in magnetic properties, and about the mechanism and kinetics of the reaction.

Ivanov, P., and M. Mikhov
The transformation γ-Fe_2O_3–α-Fe_2O_3: Experiment and model, *J. Magn. Magn. Mater., 104-107*, part 1, 417-418, 1992.
The kinetics of the gamma–alpha transformation in Fe_2O_3 in a homogeneous magnetic field were studied by magnetic phase analysis. A model for the elementary transformation process is proposed and then used to discuss the kinetic curves obtained.

Data Manipulation

Le Goff, M., B. Henry, and L. Daly
Practical method for drawing a VGP path, *Phys. Earth Planet. Inter., 70*, 201-204, 1992.
A statistical method is proposed for smoothing polar wander paths and for giving their confidence limits by the mean of successive ellipses. An elementary tensorial calculation gives the parameters of the confidence ellipse around a vectorial weighted mean. This model can also be used for other statistical tests, wherever the rotational symmetry hypothesis is not consistent (*e.g.*, in the fold test).

Werner, T., and M. Jelenska
The applicability of two computer techniques to separate the remanent magnetization (RM) components acquired in laboratory fields, *Phys. Earth Planet. Inter., 70*, 194-200, 1992.
Kirschvink's principal component analysis (PCA) technique, and Stupavsky and Symons' method for the analytical modelling of demagnetization data were used to resolve laboratory components of TRM and ARM. These remanences were applied in different directions to natural rock samples which had overlapping blocking-temperature and/or coercivity spectra.

Dating

Baksi, A. K., *et al.*
$^{40}Ar/^{39}Ar$ dating of the Brunhés-Matuyama geomagnetic field reversal, *Science, 256*, 356-357, 1992.
Astronomical forcing frequencies observed in the oxygen isotope record have suggested that the age of the Brunhés-Matuyama reversal is 780 ka; the $^{40}K/^{40}Ar$-based estimate has been 730 ka. Results from $^{40}Ar/^{39}Ar$ incremental heating studies on a series of Hawaiian lavas give an age of 783 ± 11 ka, in agreement with the astronomically derived value. This suggests that the astronomically-based technique is a viable tool for dating young sedimentary sequences.

Cande, S. C., and D. V. Kent
A new geomagnetic polarity time-scale for the late Cretaceous and Cenozoic, *J. Geophys. Res., 97B, in press*, 1992.
An analysis of marine magnetic profiles from the world's ocean basins was used to construct a magnetic polarity time-scale for the late Cretaceous and Cenozoic. A composite geomagnetic polarity sequence was derived, based primarily on data from the South Atlantic, with fine-scale information derived from faster-spreading ridges in the Pacific and Indian Oceans. The time-scale was generated by using a spline function to fit age-calibration points to the composite polarity sequence.

Nakanishi, M., K. Tamaki, and K. Kobayashi
A new Mesozoic isochron chart of the northwestern Pacific Ocean: Paleomagnetic and tectonic implications, *Geophys. Res. Lett., 19,* 693-696, 1992.
All the currently available data was used to complete a Mesozoic isochron chart of the northwestern Pacific Ocean. The chart provides the first whole view of the Mesozoic MMA lineations in this region, and yields essential information for understanding the problems of the Mesozoic magnetostratigraphic time-scale and the evolutionary history of the Pacific plate.

Geology

Krs, M., *et al.*
Magnetic properties and metastability of greigite-smythite mineralization in brown-coal basins of the Krusné hory Piedmont, Bohemia, *Phys. Earth Planet. Inter., 70,* 273-287, 1992.
Under oxidizing conditions, heat treatment of greigite caused changes in magnetic parameters. Between 320˚C and 380˚C, a self-reversal of remanence was probably associated with the formation of pyrrhotite, and pyrite and marcasite were produced. At temperatures above 400˚C, bisulfides decomposed, and various types of Fe_2O_3 were formed. At the highest temperatures, only α–Fe_2O_3 was seen.

Magnetic Fabric

Ernst, R. E., and W. R. A. Baragar
Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm, *Nature, 356,* 511-513, 1992.
Continental flood basalts, and their associated swarms of mafic dikes, are thought to result from melting in mantle plumes. Magnetic anisotropy measurements on dike swarms show that magma generated in the mantle plume flowed vertically, up to a point about 500 km below the surface, and then radiated out horizontally for about 2100 km, with the transition corresponding to the outer bounds of melt generation in the mantle plume.

Henry, B.
Modelling the relationship between magnetic fabric and strain in polymineralic rocks, *Phys. Earth Planet. Inter., 70,* 214-218, 1992.
When uniaxial paramagnetic minerals dominate the magnetic fabric of a rock, Borradaile *et al.*'s procedure for isolating the magnetic fabric of anisotropic monocrystals can be used to obtain the magnetic properties equivalent to those of a theoretical equivalent mineral. Finite strain and orientation tensors may thus be determined from magnetic fabric measurements of polymineralic rocks.

Models

Sinito, A. M., and J. F. Vilas
Model of geomagnetic paleosecular variation for the Northern Hemisphere, *Stud. Geophys. Geod., 35,* 334-343, 1991.
A model of geomagnetic paleosecular variations which uses radial drifting and oscillating dipoles, and which has been shown to be appropriate for the Southern Hemisphere, is applied to the Northern Hemisphere. After a new parameter fitting, the theoretical results of the model are compared with the paleomagnetic data of Lac de Bouchet (France), and the Black Sea, with good results.

New Techniques

Funaki, M., *et al.*
The S pole distribution on magnetic grains in pyroxenite determined by magnetotactic bacteria, *Phys. Earth Planet. Inter., 70,* 253-260, 1992.
One-micron-size, north-seeking bacteria were used to identify the domain patterns on a polished surface of magnetite-rich pyroxenite. Bacteria formed clusters in a number of areas when the sample had an NRM, and at one side of the sample when it had an SIRM, but formed no clusters after AF demagnetization.

Kwon, T. M., M. S. Jhon, and T. E. Karis
A device for measuring the concentration and dispersion quality of magnetic particle suspensions, *IEEE Trans. Instr. Meas., 41,* 10-16, 1992.
The orientation of magnetic particles, which are entrained in an extensional flow field, can be detected with a weak magnetic sensing field. This method can be useful in determining the particle flocculation aspect of dispersion quality. A similar technique can also be used to measure the particle concentration in a quiescent flow.

Paleoclimate

Hus, J. J., and J. Han
The contribution of loess magnetism in China to the retrieval of past global changes—some problems, *Phys. Earth Planet. Inter., 70,* 154-168, 1992.
Despite problems in locating the Brunhés-Matuyama boundary at two sites, paleosols may nevertheless be differentiated from the parent loess not only by their high magnetic susceptibility, but also by their enhanced remanence properties. These contrasts result mainly from concentration changes of the inherited magnetic minerals, grain-size changes, and authigenic formation of magnetic minerals—all of which are linked to climate-controlled soil formation processes.

Maher, B. A., and R. Thompson
Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols, *Quat. Res., 37,* 155-170, 1992.
Electron microscopy of magnetic extracts is used to estimate the major magnetic components in Chinese loess and paleosol. Lithogenic magnetites (> 2 µ) dominate the coarse-grained magnetic fraction, while the remaining ultrafine magnetic material consists mostly of inorganically precipitated soil magnetites. Because pedogenic magnetite is the major magnetic contributor, these sequences record a very high-resolution magnetic stratigraphy, directly related to changing climate.

Paleointensity

Cande, S. C., and D. V. Kent
Ultra-high resolution marine magnetic anomaly profiles: A record of continuous paleointensity variations?, *J. Geophys. Res., 97B, in press,* 1992.
Comparison of a distinctive pattern of small-scale marine magnetic anomalies (25-100 nT amplitude, 8-25 km wavelength) from sites in the Indian Ocean and in the Pacific Ocean demonstrates that this pattern of "tiny wiggles" is a high-resolution recording of paleo-dipole field behavior. "Tiny wiggles" are most likely caused by paleointensity fluctuations of the dipole field, and are a ubiquitous background signal to most magnetic anomaly profiles from fast-spreading ocean basins.

Sherwood, G. J., and J. Shaw
The relationship between magnetic field strength and reversal frequency: Preliminary palaeointensity results from the Cretaceous Quiet Zone, *Stud. Geophys. Geod., 35,* 325-333, 1991.
Despite predictions that the geomagnetic field strength should be at its highest during periods of low reversal frequency, paleointensity estimates obtained from basaltic lavas from Israel and India—which were erupted during the 35 Ma Cretaceous Quiet Zone—indicate that the mean virtual dipole moments from the two areas are about 75% of the current value, suggesting that there is no simple relationship between the time-averaged strength of the dipole and the frequency of reversals.

Physics

Hu, Z., et al.
The investigation of magnetite microcrystals, *Hyperfine Interactions*, *68*, 421-424, 1992.
Mössbauer spectroscopy, x-ray diffraction work, and transmission electron microscopy were used to investigate four magnetite samples with average particle sizes of 72, 88, 100, and 110 Å. The experimental results show that the anisotropy energy constant K increases as the particle size decreases. For a given sample, the value of K drops suddenly around the Verwey transition temperature T_v, and then remains constant to temperatures well above T_v.

Fannin, P. C., B. K. P. Scaife, and S. W. Charles
Measurements of the AC and zero-frequency susceptibility of colloidal suspensions of magnetite as a function of frequency and particle volume fraction, *Magnetohydrodyn.*, *27*, 50-54, 1991 (*transl. of Magnit. Gidrodin.*, *27*, 58-61, 1991).
Kirkwood's theory of dielectric polarization is used to discuss the non-linearity of the frequency dependence of the real component of complex AC susceptibility for seven ferrofluid samples of magnetite as a function of particle volume fractions. The peaks in the imaginary component are thought to be evidence of the presence of aggregates of smaller particles.

Mahmood, S., *et al*.
Mössbauer study of Fe_3O_4 fine particles, *Magnetohydrodyn.*, *27*, 34-38, 1991 (*transl. of Magnit. Gidrodin.*, *27*, 40-43, 1991).
Mössbauer spectroscopy was used to study fine particles of Fe_3O_4 at room temperature. The spectra of coated, uncoated, and annealed samples were all magnetically split in an applied field of 4.4 kOe (0.44 T). The angles between the applied field and the hyperfine field were less than 30 degrees for all samples.

Tanner, B. K.
Time-dependent magnetization in the 1D spin glass Fe_2TiO_5, *J. Magn. Magn. Mater.*, *104-107*, 1611-1612, 1992.
The time dependence of the isothermal remanence magnetization (IRM) of flux-grown single crystals of the 1D spin glass Fe_2TiO_5 has been measured at 4.2 K. For short magnetization time t_0 and long measurement time t, deviation from logarithmic decay was found. The complete data set has been fit, with excellent agreement, to a theoretical model which predicts a decay of the IRM varying as $ln(l + t_c/t)$, where t_c is the critical time, proportional to t_0.

Pressure/Stress/Strain

Borradaile, G. J.
Deformation of remanent magnetism in a synthetic aggregate with hematite, *Tectonophys.*, *206*, 203-218, 1992.
Because a hematite-calcite aggregate, bonded with Portland cement, deforms triaxially in a ductile fashion at room temperature, it is a good textural analog of natural, penetratively-strained, hematite-bearing rocks. The paleomagnetic implications for changes in inclination and intensity of an isothermal remanent magnetization (IRM) are explored.

Kapicka, A.
Magnetic susceptibility under hydrostatic pressure of synthetic magnetite samples, *Phys. Earth Planet. Inter.*, *70*, 248-252, 1992.
Artificial specimens containing magnetite of various grain sizes and in different concentrations were used to study the behavior of 15 directional susceptibilities under hydrostatic pressure of up to 20 MPa (0.2 kbar). With increasing pressure, a moderate but systematic and reversible decrease of all directional susceptibilities was detected, which can probably be attributed to decreased mobility of the domain walls.

Remagnetization

Jackson, M. J., W.-W. Sun, and J. P. Craddock
The rock magnetic fingerprint of chemical remagnetization in midcontinental Paleozoic carbonates, *Geophys. Res. Lett.*, *19*, 781-784, 1992.
A paleomagnetic and rock magnetic survey of Paleozoic carbonates from the midcontinental U.S. shows that Permian remagnetizations can often be recognized by a ratio of ARM/J_{rs} exceeding 0.1. This reflects the presence of a significant fraction of very fine-grained magnetite (a few hundred Ångströms) spanning the superparamagnetic-single domain (SP-SD) threshold.

Reversals

Herrero-Bervera, E., and M. A. Khan
Olduvai termination: Detailed palaeomagnetic analysis of a north central Pacific core, *Geophys. J. Int.*, *108*, 535-545, 1992.
A study of the terminal Olduvai subchron normal-to-reverse polarity transition (1.77 Ma) shows that, 1) although the dipole component still constrains the VGP to the longitudinal band of the Americas, the transition field is dominated by quadrupole terms; and 2) the 10,000-year transition was accompanied by a decrease in field intensity.

Valet, J.-P., *et al*.
Palaeomagnetic constraints on the geometry of the geomagnetic field during reversals, *Nature*, *356*, 400-407, 1992.
Records of geomagnetic field reversals over the past 12 Ma are consistent with the simplest models, in which a field, reminiscent of the non-dipole component of the present-day field, becomes dominant.

Rock Magnetism

Dekkers, M. J., and P. Rochette
Magnetic properties of CRM in synthetic and natural goethite: Prospects for a NRM/TRM ratio paleomagnetic stability test?, *J. Geophys. Res.*, *97B*, in press, 1992.
Goethite was synthesized and allowed to grow under controlled field conditions in order to compare the magnetic properties of the resulting grain-growth CRM with TRM. It is encouraging that both the CRM/TRM ratio in synthetic samples, and the NRM/TRM ratio in natural samples, decrease with increasing grain size. However, more experimental research is necessary before the potential of the CRM/TRM technique can be fully realized.

Gapeev, A. K., and V. A. Tselmovich
The microstructure and domain structure of multiphase oxidized titanomagnetites, *Phys. Earth Planet. Inter.*, *70*, 243-247, 1992.
When non-magnetic lamellae in multiphase oxidized titanomagnetites were thinner than 0.1 μ, the titano-magnetite grains demonstrated multidomain behavior independent of the size of the interlamellar regions (cells). When the lamellae were thicker than 0.1 μ, the domain state depended on the size of the cells. Single-domain behavior was exhibited for cell sizes less than 1×1 μ; larger cells had multidomain properties.

Hejda, P., et al.
Some magnetic properties of synthetic and natural haematite of different grain size, *Phys. Earth Planet. Inter.*, *70*, 261-272, 1992.
Magnetic properties of hematite, ranging in grain size from 0.5 μ to 120 μ, are examined. The samples show 1) an increase in the initial remanence value J_r [pseudo-NRM of artificial samples] with decreasing grain size, 2) similar responses to AF demagnetization except for the soft 0.5 μ sample, 3) similar IRM acquisition curves, and 4) diverse and complicated AMS behavior.

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…VF Reports continued from page 2

Thanks to the supportive members of the *IRM*, the measurements went very smoothly without any of the usual catastrophes encountered in experimental work. Having spent 12 days at the *IRM* with multiple experiments going at the same time, I collected half a year's worth of data. The support from and the discussions with Bruce, Subir, Chris, Jim, and Paul were highly appreciated. A research stay at the *IRM* is highly recommended, not only to get away from phone calls and paper work in your home department, but to use some state-of-the-art equipment which really works.

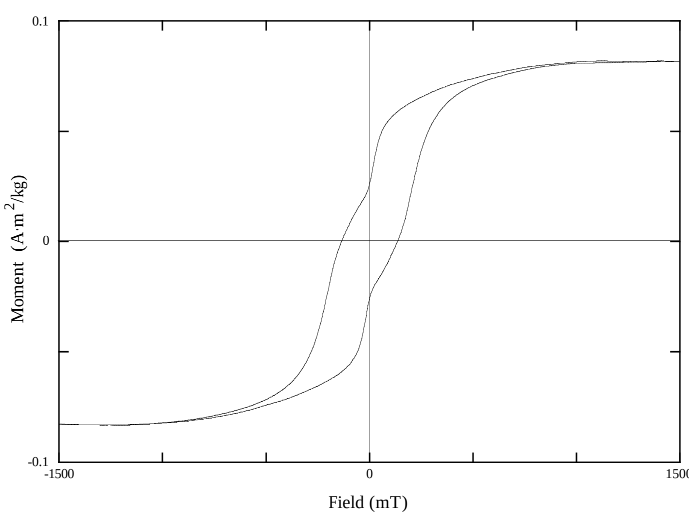
P.S. After having been ahead of schedule for the first time in years, my last two days were spent canoeing in northern Minnesota.

Rock magnetic applications for structural geology (with weird hysteresis loops)

Bernie Housen
Carl Richter
University of Michigan

During our informal visit to the *IRM*, Carl Richter and I worked on two applications of magnetic anisotropy for structural geology. The first project involved measurement of the bulk-rock hysteresis of samples to obtain the high-field (paramagnetic) susceptibility. These results are being used to evaluate various methods of separating the ferrimagnetic, paramagnetic, and diamagnetic contributions to AMS, most notably our current work refining the cryogenic susceptibility technique of Schultz-Krutisch and Heller (1985). The second project involved the development of a new technique for measuring rock fabrics via magnetic susceptibility. We are currently in the process of digesting our data. We would like to thank Jim Marvin for modifying the AMS control software so that we could measure susceptibility in 3565 [sic!] orientations.

I also conducted a hysteresis study of magnetic separates from the Martinsburg Formation. In addition to "normal" and wasp-waisted hysteresis loops, loops with kinked or pinched ends were observed, which I termed "sausage-shaped" loops. An explanation of the cause of this behavior awaits further study. Another unusual hysteresis loop was observed in a marble ultramylonite from the Bancroft shear zone in Ontario. This "hummingbird-shaped" loop is shown in the figure. Using the MPMS, I conducted a magnetic moment *vs.* temperature experiment on this sample, heating from 5 K to 300 K in a 10 Oe field. I found an abrupt drop in moment between 30 K and 35 K, which I attribute to the second-order transition observed in pyrrhotite. The origin of the kink in the hysteresis loop is as yet unexplained. I would like to thank Chris Hunt for conducting the hysteresis measurements on the MicroMag, and for his hospitality during our visit. *continued on page 8…*



"Hummingbird" hysteresis loop

"Hummingbird-shaped" hysteresis loop from a marble ultramylonite from the Bancroft shear zone in Ontario.

…Astracts continued from page 5

Hoffmann, V.
Greigite (Fe_3S_4): Magnetic properties and first domain observations, *Phys. Earth Planet. Inter., 70*, 288-301, 1992.
The ferrimagnetic iron sulfide greigite (Fe_3S_4) has been recognized as a rare but important carrier of magnetic remanence in young sediments. In this study, magnetic measurements were made in order to try to establish a relationship between grain size and domain state. Using the Bitter method and the magneto-optical Kerr effect, the domain structures were observed to be very complicated, probably because of high magnetostriction.

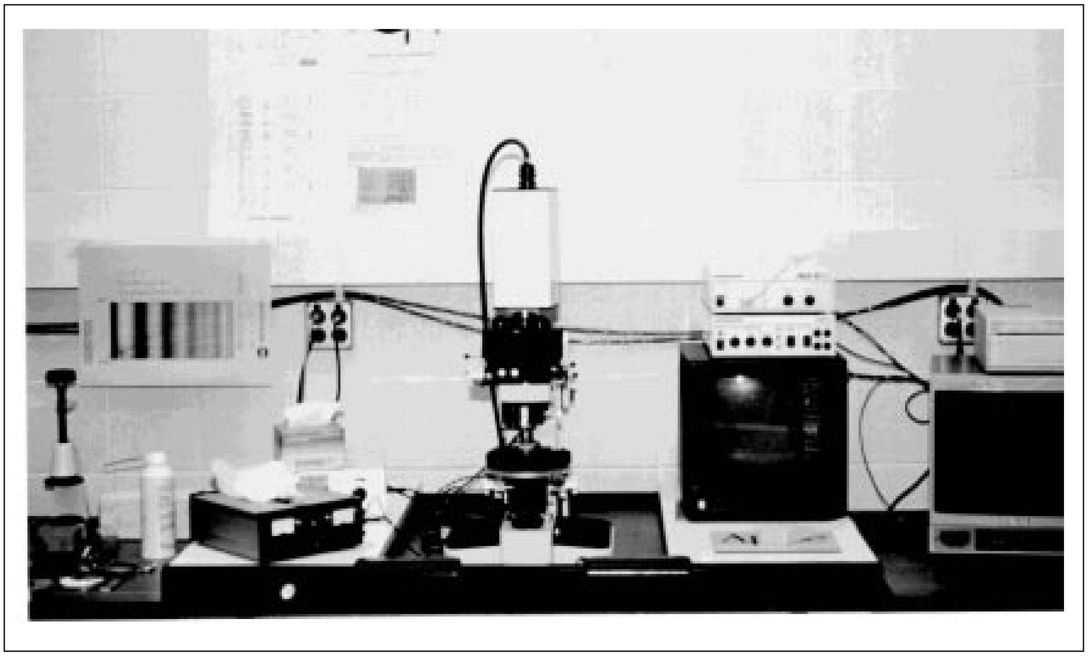
Self-Reversal

Hoffman, K. A.
Self-reversal of thermoremanent magnetization in the ilmenite-hematite system: Order-disorder, symmetry, and spin alignment, *J Geophys. Res., 97B, in press*, 1992.
A model is proposed for the process by which certain members of the ilmenite-hematite solid solution series acquire reverse TRM. It is shown that details of the superexchange-controlled spin-ordering between cation-ordered regions in the crystal lattice and their ferrimagnetic Fe-rich cation-disordered boundaries, and the behavior of this ordering while cooling in a magnetic field, are responsible for the self-reversal.

Zapletal, K.
Self-reversal of isothermal remanent magnetization in a pyrrhotite (Fe_7S_8) crystal, *Phys. Earth Planet. Inter., 70*, 302-311, 1992.
Room-temperature isothermal remanent magnetization (IRM) was measured on powder and massive specimens of Fe_7S_8 crystals. Self-reversals of IRM were revealed in a massive crystal fragment after magnetization in magnetic fields of the order of 10-100 mT. This might be explained by the fact that a twinning plane perpendicular to the c´-axis contained both IRM vectors, and that each twin had a very low coercivity.

Viscous Remanence

Pozzi, J. P., and G. Dubuisson
High temperature viscous magnetization of oceanic deep crustal- and mantle-rocks as a partial source for Magsat magnetic anomalies, Geophys. *Res. Lett., 19*, 21-24, 1992.
High-temperature measurement of viscous magnetization on oceanic deep-crustal and mantle rocks, extrapolated to geological times, suggests that the viscous magnetization acquired since the last reversal of the Earth's magnetic field may be of the order of magnitude of the induced magnetization above 200˚C, and possibly predominant near 500˚C. ■



Above: The MOKE system. Below: The Kerr Effect—E *and* N *are the electric field vectors of the incident and normally reflected light beams, respectively.* K *is the electric field vector of the reflected light beam which originated from the domain magnetization. Two domains with antiparallel homogeneous magnetizations are indicated by black and white. [From Appel, E., V. Hoffmann, and H. C. Soffel, Magneto-optical Kerr effect in (titano)-magnetite, pyrrhotite, and hematite,* Phys. Earth Planet. Inter., 65*, 36-42, 1990.]*

...MOKE continued from page 1

hard egghead and really want the full-bore Quantum-Mechanical explanation of the Kerr effect—to the extent that Q.-M. can provide anything truly "satisfying"—see Argyres, P. N., Theory of the Faraday and Kerr effects in ferromagnetics, *Phys. Rev.*, *97*, 334-345, 1955. The explanation given below is adapted from Appel, E., V. Hoffmann, and H. C. Soffel, Magneto-optical Kerr effect in (titano)magnetite, pyrrhotite, and hematite, *Phys. Earth Planet. Inter.*, *65*, 36-42, 1990]). Anyway, here is that simplified view of the Kerr Effect: The incoming oscillating electric field vector E exerts a force F on electrons in the material, causing them to vibrate in the plane of polarization of the incoming wave (according to $F = qE$, where q is the electric charge of the electron [remember this stuff?]). The vibrational motion of the electrons in the presence of the magnetic field of the sample B results in a pseudo-Lorentz force (according to $qv \times B$, where v is the pseudo-velocity of the electrons in response to E) in the direction mutually perpendicular to both the magnetization M of the material and the electric field E of the incoming wave. This results in the reflected wave acquiring a small E component (called the Kerr component K) in this direction. The plane of polarization of the resultant reflected wave is thus rotated with respect to the incoming wave. The magnitude of the component of M perpendicular to the direction of E of the incoming wave will determine the amount of rotation. The sign of this component will determine the direction of rotation. Finally, the amplitude of K is proportional to the spontaneous magnetization of the material M_s (*i.e.*, the magnetization within a magnetic domain).

Nitty Gritty

Samples consist of polished surfaces of either bulk samples or powders which have been embedded in epoxy. The application of the magneto-optical Kerr Effect to such geologically-interesting low-M_s materials as ferrimagnetic minerals requires extremely smooth and stress-free surfaces; thus, sample preparation requires patience and finickiness. Kerr rotations are less than 30° for Permalloy, about 1° for magnetite, and less than 1° for titanomagnetite.

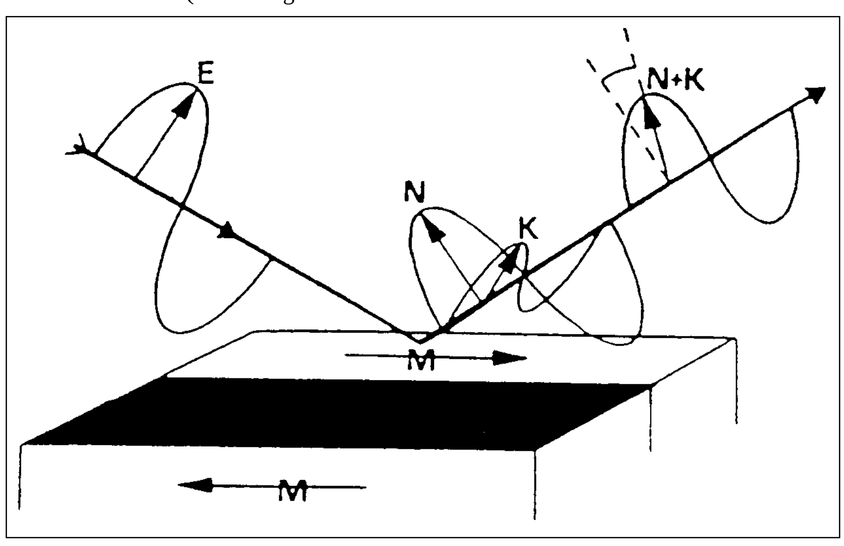
The system consists of a reflected-light polarizing microscope, a video camera, a digital image processor, a computer, and two image display monitors. The microscope uses an ordinary incandescent light source for strongly magnetized domains (as in iron or Permalloy), and a brighter xenon light source for weakly magnetized domains (as in magnetite or titanomagnetite). The optical components typically consist of a 10x eyepiece with an objective no greater than 50x for up to 100x magnification.

The very small Kerr contrasts can be enhanced by digital image processing. First, the image formed by the microscope is detected by the video camera. Then, the video signal is digitized and massaged by the image processor. The resulting image can then be displayed or stored in the computer memory. Employing digital image processing at video rates allows the observation of magnetic domains and domain walls in real time. The image can be enhanced by first recording the illuminated surface in a saturated state as a reference image without magnetic contrasts, and then subtracting this reference image from subsequent images where domain contrasts are present. The result is a high-contrast difference image, which represents the individual magnetic domains as different shades of gray. Noise can be further reduced by averaging difference images of the same domain structure.

Pluses and Minuses

Because the MOKE displays information about magnetization direction and intensity within domains, it has an advantage over the classic Bitter pattern technique, which is limited to observations of stray fields along domain walls. The chief disadvantages of the MOKE are the technical difficulties involved in creating highly polished samples, battling with a very complex optical system, working typically at the limits of detectability, and finding relatively strong samples.

So why *do* all of our new pieces of equipment begin with the letter "M"? Stay tuned 'til the next issue and the article on the Mössbauer!



. . . VF Reports continued from page 6

Magnetic anisotropy of hornblende single crystals

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For fabric analysis of rock from the German Continental Deep Drilling Program (KTB), measurements of the anisotropy of magnetic susceptibility (AMS) are routinely employed. During the study of amphiboles, an inconsistency was discovered between theoretical and observed AMS. Microscopic and x-ray texture analyses indicated that, for some amphiboles, a high proportion of hornblende crystals are well-aligned along their c- and b-axes. Based on previous literature data, a well-developed prolate AMS ellipsoid should be expected for hornblende crystals aligned along their c-axes. However, the experimentally determined AMS ellipsoid was clearly oblate. Neither remanence measurements nor electron microscopy revealed significant proportions of ferrimagnetic minerals. The concentration of other silicates with oblate anisotropies was also much too low to explain the observed AMS. Therefore, it was planned to study the magnetic properties of hornblende in more detail. Seventeen single crystals were collected from different localities around the world and taken to the *IRM*. Initially, all the samples were characterized by magnetization measurements with the VSM. Non-linearities in the M-H curves and hysteresis loops in 8 of the 17 samples indicated the presence of significant contaminations by ferrimagnetic minerals. Hence, these samples were excluded from further investigations. The remaining pure hornblendes were characterized for their magnetic anisotropy properties in the temperature range 10 K to 290 K using the MPMS susceptometer. The susceptibility values of the sample suite span more than an order of magnitude, which is probably dependent on iron content (to be determined). Most hornblende crystals possess equally large susceptibilities parallel to the b- and c-axes, with smaller values parallel to the a´´-axis, thus giving rise to oblate anisotropy ellipsoids! To complicate matters, for the two hornblendes with the weakest susceptibilities, the c-axis forms the direction of smallest magnetization. Clearly, our analyses of AMS data involving hornblende-carrying rocks have to be reinterpreted.

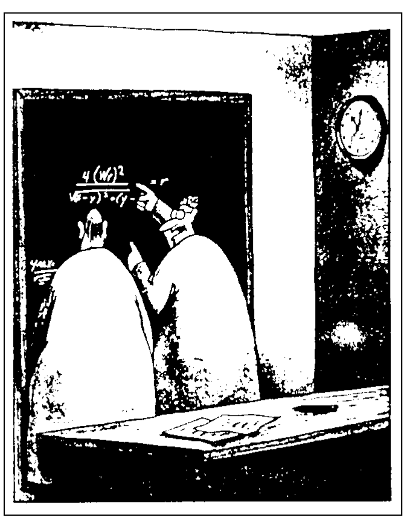
Other projects at the *IRM* involved using the Roly Poly [our affectionate and descriptive name for the AMS device—ed.] to measure AMS at different temperatures (liquid nitrogen, dry ice, RT) in order to separate paramagnetic from ferrimagnetic contributions. Hysteresis loops were measured on cuttings and drill cores from the KTB drill hole in order to characterize magnetic hardness as a function of depth. And finally, employing the SRM, a paleomagnetic study was done on weakly magnetic—but very stable—lamprophyres, also from the KTB site. ■

Santa Fe Conference A Success

An *IRM*-sponsored workshop on "The Effects of Chemical Change on Magnetization" was held at St. John's College Conference Center in Santa Fe, NM from August 13 through August 16; about fifty rock- and paleomagnetists from the U.S. and Canada participated.

By the end of the meeting, the overwhelming consensus was that the conference was a great success. Individual sessions were lively, invigorating, and even downright rowdy at times. Valuable input—including some much-needed eye-opening reality checks—came from outside the rock- and paleomagnetic community in the form of guest speakers Don Canfield (iron and sulfides in sedimentary environments), Lynton Land (stable isotope geochemistry), Jill Banfield (electron microscopy), Roger Proksch (magnetic force microscopy), and Mike Singer (soil formation processes). Thanks to the willingness of *all* participants to engage in frank and open exchanges, comprehensive and in-depth discussions on topics at the frontiers of rock magneic research were possible. And the setting in the hills overlooking Santa Fe was pretty good, too!

Look for a brief report on the workshop in an upcoming issue of *Eos*, and a longer report for general distribution in time for the Fall AGU Meeting. ■



"Yes, yes, I know *that, Sidney. . .*every*body knows* that*!. . .But look: Four wrongs* squared, *minus two wrongs to the fourth power, divided by this formula,* do *make a right."*

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 during the following half year. Shorter, less formal visits are arranged on an individual basis through the laboratory manager.

The *IRM* staff consists of Subir Banerjee, Director; Bruce Moskowitz, Associate Director; Jim Marvin, Senior Scientist; and Chris Hunt Scientist and Lab Manager.

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