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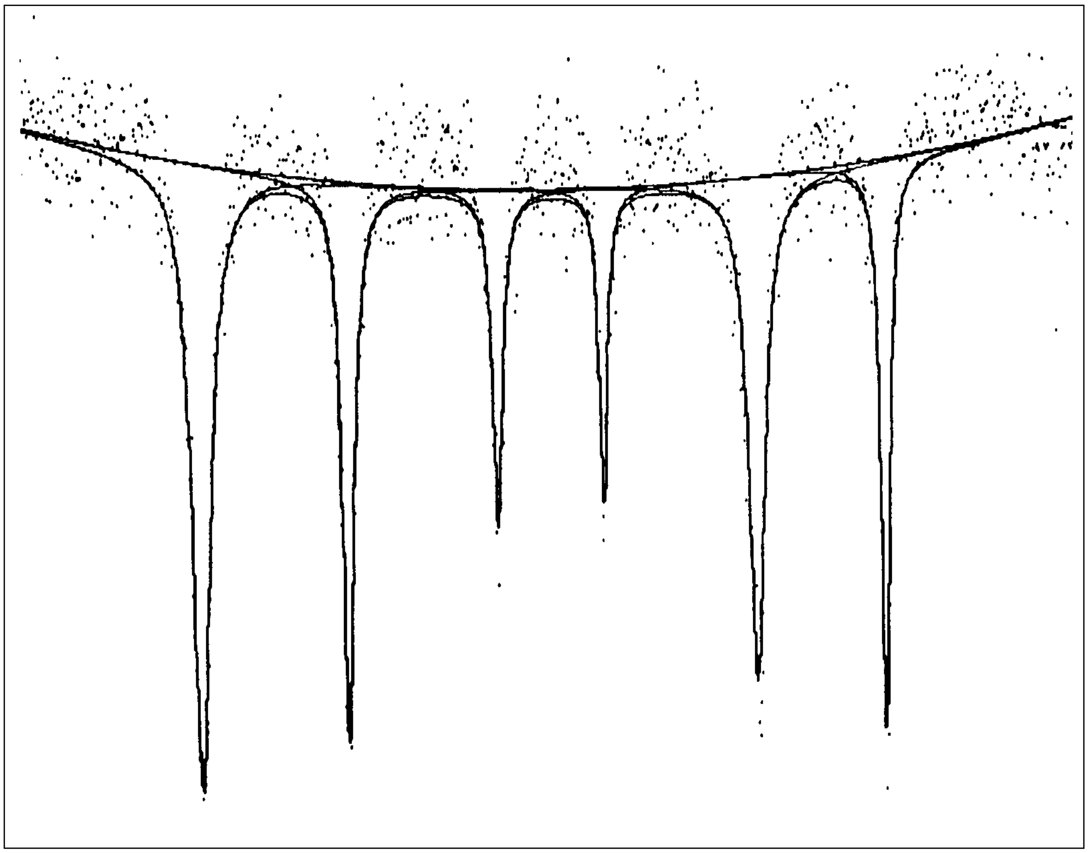


Mössbauer: Marvelous Measurements of Magnetic Minerals

Chris Hunt
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 third 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 Mössbauer Spectrometer:*

THE MÖSSBAUER

Parts of a Mössbauer spectrometer were donated to the *IRM* in May 1991 by the 3M Corporation of St. Paul. Now, after more than a year of tinkering with upgrade parts and software from Ranger Scientific in Texas, adapting the lab for use of radioactive materials, designing and building lead shielding for the instruments, working out safe sample- and source-changing procedures, training staff in safety procedures, obtaining the requisite radiation safety certification, and ordering the ^{57}Co source—the most expensive few milligrams of anything any of us has ever purchased (gold and platinum are bargains by comparison!)—after all of this, the Mössbauer is up and running. Its purpose, for rock- and paleomagnetists, is to distinguish among familiar magnetic minerals such as magnetite, maghemite, or hematite. It accomplishes this task by characterizing the iron atoms within any of these solids in terms of chemistry, valence state, particle size, lattice distortion or asymmetry, degree of magnetic ordering, and cation distribution in ferrimagnets.

Applications

Mössbauer spectroscopy can yield quantitative estimates of the various proportions of different magnetic minerals in a sample. The relative strength of each spectrum type is always roughly proportional to the amount of corresponding material (*i.e.*, to the number of atoms in a given configuration); thus one eliminates the problem inherent in trying to determine mineral assemblages by using magnetic parameters which vary over orders of magnitude (*cf.*, J_s = 90 A·m^2/kg [90 emu/g] for magnetite and J_s = 0.4 A·m^2/kg [0.4 emu/g] for hematite). By comparing Mössbauer spectra, one can determine the relative proportions of iron atoms in various conditions (*i.e.*, one can see the amount of magnetite *vs*. the amount of hematite that is present in a given sample, or the relative number of Fe^{3+} atoms in A sites as compared to B sites).

At a given temperature between 4 K and ambient, sufficiently small magnetic grains can change from being thermally stable (yielding a multi-line spectrum) to being Mössbauer-superparamagnetic (yielding a single-line spectrum). Thus, the results obtained from measuring spectra as a function of temperature can be deconvolved into a grain-size distribution.

How?

A Mössbauer Spectrometer takes advantage of the Mössbauer Effect, which was first discovered and investigated in 1958 by a graduate student called Mössbauer (or Mößbauer, for you purists) who ensured his future

continued on page 6...

Visiting Fellows' Reports

We enjoyed working this fall with Visiting Fellow Mr. Clive ***Roberts****, from Open University in Milton Keynes, Buckinghamshire, England, who studied dike swarms from Lundy Island in the Bristol Channel. In addition to the official Fellow, we welcomed an informal visitor, Ms.* ***Janet Pariso****, from the University of Washington in Seattle, who worked on the magnetic properties of rocks from ODP Hole 504B just before she left for another ODP cruise to the eastern Pacific. We have enticed both visitors to contribute a summary of work done here at the* **IRM***:*

Clive Roberts
Open University,
England

Tertiary magmatism in the Bristol Channel, southwest England

Lundy Island, in Great Britain's Bristol Channel, is postulated to be a remnant of an active Lower Tertiary volcano—part of the British Tertiary Volcanic Province. It is made mostly of granite, but many mafic dikes, visible in the coastal cliffs, cut the granite. The planed island surface is covered by up to three meters of soil, peat, and bracken, so the dikes cannot be seen from above. Associated positive gravity and magnetic anomalies point to the presence of one or more possible magma-source chambers offshore.

A ground-based proton magnetometer survey was made 1) to determine the trends of the dikes, 2) to ascertain whether the dikes cropping out in the western cliffs extend through the island to crop out along the eastern coast (in which case a geological map of the implied field relations of the mafic dikes could be produced), and 3) to extrapolate the Island's dike trends back to a common center of volcanic activity in the Bristol Channel.

The initial determination of the dike trends was accomplished by setting up an accurate grid network for the survey, and by prospecting for paired anomaly profiles. Eventually, 2-D and 3-D computer modelling of regional gravity and magnetic data will be used to unravel some of the complex geological history of the area.

The three-week visit to the *IRM* was directed primarily towards anisotropy of magnetic susceptibility (AMS) studies of both basic and intermediate dikes, with a view towards studying magma pathways and discriminating between laminar and turbulent flow during dike emplacement. Subsequent analysis of the Curie-temperature determinations, hysteresis loop parameters, and anhysteretic remanent magnetization (ARM) properties will also allow relative grain-size determinations and qualitative mineralogical identifications to be made.

Janet Pariso
University of
Washington

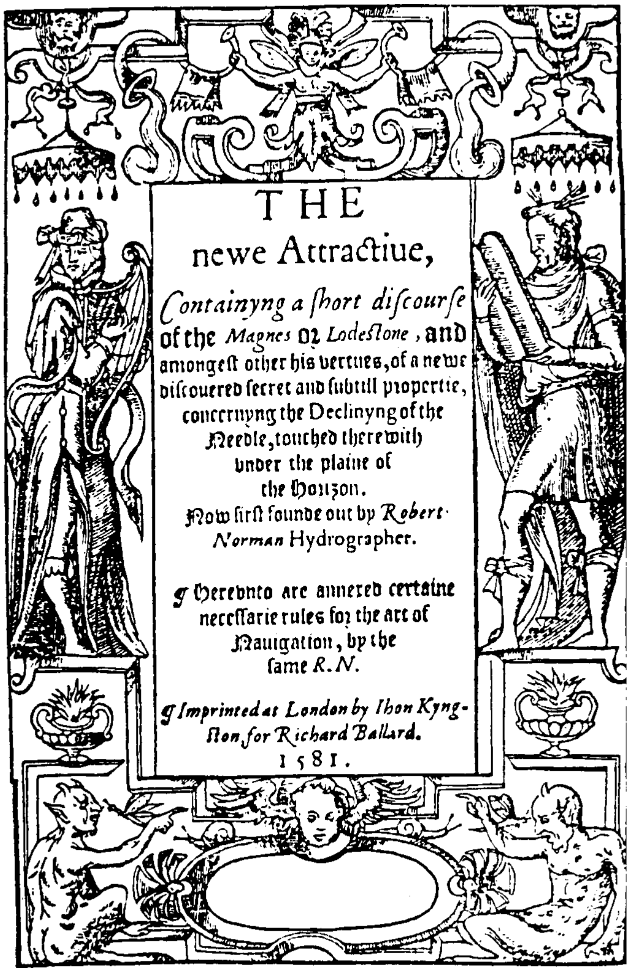
Magnetic properties of altered dike rocks from the oceanic crust

My visit to the *IRM* focused on developing a better understanding of the effect of alteration on the remanent magnetization of oceanic crust. It involved two different suites of samples, both from relatively young upper oceanic crust.

The first samples were recovered from ODP Hole 504B, the deepest hole in the oceanic crust, and the only hole to clearly penetrate the sheeted dike complex. These samples were of basaltic dikes which have a complicated alteration history including both the high-temperature, deuteric oxidation (> 600 ˚C) and the hydrothermal alteration (200–400 ˚C) of primary titanomagnetite. Within the kilometer-thick section which has been drilled in the dikes to date, the effect of these two alteration processes on titanomagnetite grains is observed to have significant downhole variation. Although the final mineral formed during both of these processes is low-titanium magnetite, the optical grain-size is generally quite different. In an effort to constrain the magnetic grain-size which results from the combination of these two processes, I measured hysteresis loop parameters on approximately 25 samples using both the Vibrating Sample Magnetometer (VSM) and the Alternating Gradient Force Magnetometer (MicroMag). In general, the results from the two magnetometers were in good agreement. However, for a few of the coarser-grained diabase samples, the small sample size required by the MicroMag proved to be inadequate to represent the bulk magnetic properties of the rock.

In addition to Curie temperatures and room-temperature hysteresis loops, I also measured hysteresis loops on two samples at 200 ˚C (the current equilibrium temperature at the bottom of Hole 504B). For these samples, there is virtually no difference in the magnetic hysteresis properties between room temperature and 200 ˚C. This important result argues that, in this particular case, the room-temperature hysteresis loop measurements can be viewed as a reasonable guide to the *in situ* magnetic properties of these rocks. The hysteresis loop parameters and Curie temperatures will be correlated with detailed opaque mineralogical studies to understand the effect of variable alteration—both type and degree—on the ability of these rocks to carry remanent magnetization.

The second suite of samples I studied was of oceanic basalts recovered during a University of Hawaii dredging program on the East Pacific Rise. This field program, led by Rodey Batiza, recovered an age-progressive suite of samples (from 0 to 2 Ma) along three different spreading segments of the East Pacific Rise. As a means of constraining the rate of progressive low-temperature oxidation at a fast spreading ridge, I measured the Curie temperature of basalt samples of different ages. In addition, I used the MicroMag to run hysteresis loops on these samples. The Curie temperature and hysteresis loop data will be combined with paleomagnetic measurements in order to examine the effect of progressive oxidation on the magnetic behavior these samples. ■



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Norman Hydrographer.

¶ Hereunto are annexed certaine
neceſſarie rules for the art of
Nauigation, by the
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¶ Imprinted at London by Ihon Kyng-
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Title page from Norman's The newe Attractive, *1581.*

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 geology and geophysics 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 nearly 1800 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the* IRM Quarterly *are always welcome.*

Alteration/CRM

Beske-Diehl, S. J., and H.-L. Li
Magnetic properties of hematite in lava flows from Iceland: response to hydrothermal alteration, *J. Geophys. Res., in press*, 1992.
Changes occur in the magnetic properties of low-Ti hematite in Icelandic subaerial basalts when Ti migrates from the lattices during low-temperature metamorphism (< 300 °C). But, observations show that field-controlled chemical remanent magnetization does not form during Ti migration, suggesting that seafloor basalts undergoing the same processes may also faithfully retain primary directions of remanence.

van Velzen, A. J., and J. D. A. Zijderveld
A method to study alterations of magnetic minerals during thermal demagnetization applied to a fine-grained marine marl (Trubi formation, Sicily), *Geophys. J. Int., 110*, 79-90, 1992.
Alteration of magnetic minerals during thermal demagnetization can be studied by monitoring changes in the coercivity spectrum of an isothermal remanent magnetization (IRM) during stepwise thermal demagnetization. The procedure allows one to determine alteration temperatures, coercivities, and blocking temperatures of the magnetic minerals involved. The method is demonstrated with samples of fine-grained marine marls from the Pliocene Trubi formation in Sicily.

AMS

Cogné, J.-P., and S. Canot-Laurent
Simple shear experiments on magnetized wax-hematite samples, *Earth Planet. Sci. Lett., 112*, 147-159, 1992.
During deformation of hematite-bearing paraffin wax samples, hematite platelets progressively rotate, as measured by the anisotropy of magnetic susceptibility (AMS). Because the principal susceptibility directions tend to parallel the corresponding principal strain directions, and because AMS intensity increases with increasing strain, support is given to the idea that the hematite population develops a preferred orientation by progressive rigid rotation within the paraffin matrix.

Jackson, M. J., *et al.*
Experimental deformation of synthetic magnetite-bearing calcite sandstones: effects on remanence, bulk magnetic properties, and magnetic anisotropy, *J. Geophys. Res., in press*, 1992.
A quantification has been made of the effects of experimental deformation on the magnetic properties of a set of synthetic magnetite-containing "calcite sandstones." A comparison of data for samples deformed under higher and lower differential stresses indicates that remanence reorientation and susceptibility anisotropy are controlled primarily by bulk strain, whereas coercivity and anhysteretic anisotropy are controlled predominantly by microstrain or intragranular stress.

Pfleiderer, S., and H. C. Halls
Magnetic pore fabric analysis: verification through image auto-correlation, *J. Geophys. Res., in press*, 1992.
The average orientation and shape anisotropy of pore bodies in sandstones was studied by impregnating porous samples with ferrofluid and then measuring their anisotropy of magnetic susceptibility (AMS). Because the AMS fabric compared well with the pore shape observed in thin section, the method represents a powerful tool to analyze the pore fabric of sedimentary rocks and to study its effects on petrophysical properties.

Richter, C.
Particle motion and the modelling of strain response in magnetic fabrics, *Geophys. J. Int., 110*, 451-464, 1992.
Quantitative correlations between magnetic fabric, single-grain anisotropy, and preferred grain orientation are investigated using computer modelling. The influences on the magnetic fabric of various initial fabric patterns and imposed strains are simulated by using multiparticle systems represented by their magnetic anisotropy tensor. Each mineral grain is numerically reoriented under coaxial deformation conditions. The calculated strain versus magnetic fabric curves are discussed.

Biomagnetism

Diaz Ricci, J. C., and J. L. Kirschvink
Magnetic domain state and coercivity predictions for biogenic greigite (Fe_3S_4): a comparison of theory with magnetosome observations, *J. Geophys. Res., in press*, 1992.
Lack of information about greigite and the discovery of a greigite-precipitating bacterium prompted the authors to make theoretical calculations of the expected size and shape of single-domain particles. Evolution is expected to select for single-domain size particles. Results suggest that bacterial greigite is near the single-domain–superparamagnetic boundary, and could thus be mistaken for large multi-domain magnetite in alternating field demagnetization studies.

Meldrum, F. C., B. R. Heywood, and S. Mann
Magnetoferritin: in vitro synthesis of a novel magnetic protein, *Science, 257*, 522-523, 1992.
Ferritin, an iron-storage protein, consists of a spherical polypeptide shell (apoferritin) which surrounds a 6-nm inorganic core of ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$). By reconstituting apoferritin under controlled conditions, discrete 6-nm spherical single crystals of magnetite were synthesized. The resulting magnetic protein, "magnetoferritin," could have uses in biomedical imaging, cell labeling, and separation procedures.

Climate

Herbert, T. D.
Paleomagnetic calibration of Milankovitch cyclicity in Lower Cretaceous sediments, *Earth Planet. Sci. Lett., 112*, 15-28, 1992.
Bedded pelagic limestones of the Lower Cretaceous Maiolica formation display rhythmic bedding in sections where the magnetic reversal sequence is clearly correlated to marine magnetic anomalies. Carbonate couplets have a mean period of 23.5 ka, and prominent modulations in bedding thickness ("bundling") have a mean period of 117 ka. The close match of sedimentary periodicities to orbital Milankovitch cycles implies that the carbonate bedding reflects climatic forcing.

Marzocchi, W., F. Mulargia, and P. Paruolo
The correlation of geomagnetic reversals and mean sea level in the last 150 m.y., *Earth Planet. Sci. Lett., 111*, 383-393, 1992.
The correlation between mean sea level and the rate of occurrence of geomagnetic reversals is statistically analyzed. A highly negative significant correlation (significance level <0.01) is found only with those long-term sea-level variations that follow the non-stationarities in the rate of occurrence of geomagnetic reversals by about 6–9 Ma. This correlation suggests a link between crustal and deep interior Earth processes.

Nurgaliyev, D. K.
Solar activity, geomagnetic variations, and climate changes, *Geomagn. Aeron. (transl. of Geomagn. Aeron.), 31*, 14-18, 1991.
Relationships between changes of the climate and the magnetic field of the Earth are established by comparing paleoclimatic data with geomagnetic data for the last approximately 25,000 years and during one Late Permian reversal. Possible mechanisms for the influence on climate of the variations and geomagnetic field reversal are discussed.

Schneider, D. A., D. V. Kent, and G. A. Mello
A detailed chronology of the Australasian impact event, the Brunhés-Matuyama geomagnetic polarity reversal, and global climate change, *Earth Planet. Sci. Lett., 111*, 395-406, 1992.
An examination of two high-sedimentation rate, deep-sea sediment cores (which record the Australasian impact with well-defined microtektite layers, the Brunhés-Matuyama polarity reversal with strong and stable remanent magnetizations, and global climate with oxygen isotope variations in planktonic foraminifera) suggests that there is insufficient evidence to demonstrate a causal link between impacts and geomagnetic reversals.

Tarduno, J. A.
Magnetic susceptibility cyclicity and magnetic dissolution in Cretaceous limestones of the southern Alps (Italy), *Geophys. Res. Lett., 19*, 1515-1518, 1992.
Cyclicity of magnetic susceptibility values, in limestones which record a Barremian reversed interval can be correlated with the 100-kyr Milankovitch cycle. A number of "paleomagnetic barren" intervals—those lacking any mineral with a stable remanent magnetization—may be the result of the selective dissolution of magnetite related to increases in organic carbon. Such dissolution may explain certain patterns of magnetization and remagnetization observed in other carbonates.

Wang, Y., *et al.*
Rescaled range analysis of paleoclimatic proxies, *Can. J. Earth Sci., 29*, 296-300, 1992.
It was postulated that popular paleoclimate indicators—*e.g.*, oxygen-isotope ratios from deep-sea cores, and magnetic susceptibility of loess sediments—might respond to climatic variations in different ways. If so, it could be inferred that they might possess different long-term characteristics, which could be detected by re-scaled range (R/S) analysis. In fact, analysis yielded Hurst exponents of about 0.8 for oxygen-isotope records, and about 0.9 for loess susceptibility sequences.

Crustal Sources

Markovsky, V. S., B. G. Yakovlev, and V. S. Sukach
Concerning magnetization sources of the depth zones of the Earth crust (on the example of the granulite facies rocks of the Enderby Land and the Ukrainian Shield), *Geofiz. Zh. (J. Geophys.), 11*, 85-90, 1989.
The genetic peculiarities and the stability of the mineral parageneses of a collection of Early Precambrian mafites from the Ukrainian Shield and from Enderby Land (Antarctica) have been analyzed as a function of temperature and oxygen fugacity. This analysis, along with a study of the magnetic properties of the above minerals, established that the magnetization of these rocks is associoated with magnetite which is coeval with granulite-facies metamorphic transformations.

Inclination Shallowing

Abrahamsen, N.
On farsidedness of palaeomagnetic poles: magnetic refraction, sediment compaction, and dipole offset, *Stud. Geophys. Geod., 36*, 26-41, 1992.
An examination is made of three possible mechanisms of systematic inclination-shallowing: magnetic refraction, compaction, and dipole off-set. Attention is given to the magnetic refraction error which originates from the shape anisotropy of two-dimensional bodies. A standardized simple refraction correction is suggested, which may apply to simple two-dimensional bodies, such as volcanic dikes, sills, and lava flows, as well as baked clays and slags from fireplaces, walls, and kilns.

Sun, W.-W., and K. P. Kodama
Magnetic anisotropy, SEM, and x-ray pole figure goniometry study of inclination shallowing in a compacting clay-rich sediment, *J. Geophys. Res.*, *in press*, 1992.
Synthetic sediments and natural marine sediments were compacted by pressures consistent with burial depths of up to 500 m. The observed shallowing of magnetic-remanence inclination was modeled for the various compaction regimes. The model's randomizing/disturbance process (early compaction) caused slightly more than half of the inclination-shallowing observed; magnetite-clay attachment (late compaction) caused the remainder of the inclination decrease.

Laboratory Techniques

Ibrahim, M. M., J. Zhao, and M. S. Seehra
Determination of particle size distribution in an Fe_2O_3-based catalyst using magnetometry and x-ray diffraction, *J. Mater. Res.*, *7*, 1856-1860, 1992.
Data from magnetization versus temperature (5–400 K), magnetization versus field (up to 5.5 T) [sounds like they used an MPMS Superconducting Susceptometer!—Ed.], and x-ray line-broadening are used to derive particle-size distributions for an Fe_2O_3-based catalyst. The results are compared with published Mössbauer measurements on the same sample: all techniques yield sizes between 35 and 115 Å.

Stephenson, A.
Three-axis static alternating-field demagnetization of rocks and the identification of NRM, GRM, and anisotropy, *J. Geophys. Res.*, *in press*, 1992.
It is shown that even "perfect" AF demagnetizing equipment can impart a gyroremanent magnetization (GRM) under certain conditions. Thus, the "spurious" remanences previously attributed by others to shortcomings in instrumentation are almost certainly of gyromagnetic origin. It is demonstrated that by suitable treatment of the data, GRM can be identified and used to provide information about the anisotropy of the rock.

Vajda, P.
Investigation of the possibility to determine the palaeointensity of the thermoremanently magnetised synthetic magnetite by the method of anhysteretic magnetising, *Stud. Geophys. Geod.*, *36*, 51-56, 1992.
The paleointensity of synthetic magnetite, which had been thermoremanently magnetized in a known laboratory field, was determined from the behavior of the anhysteretic magnetization curves, suggesting a method to measure the paleointensity of natural rock samples.

Williams, W., R. J. Enkin, and G. Milne
Magntic domain wall visibility in Bitter pattern imaging, *J. Geophys. Res.*, *in press*, 1992.
A theoretical analysis of the imaging properties of the Bitter pattern method is made. An analytic expression for the magnetic fields due to Néel and Bloch walls was used to determine the colloid density (and hence the optical contrast) that collects on the grain surface due to the these fields. The results show that 180° Néel and Bloch walls of equal width should be equally well imaged, but since Néel walls are generally wider than Bloch walls, they should be significantly more visible.

Paleomagnetism

McIntosh, W. C., *et al*.
Calibration of the latest Eocene-Oligocene geomagnetic polarity time scale using $^{40}Ar/^{39}Ar$ dated ignimbrites, *Geology*, *20*, 459-463, 1992.
High-precision $^{40}Ar/^{39}Ar$ sanidine dating and a paleomagnetic study of 37–27 Ma ignimbrites are used to provide age-control for several late Eocene-Oligocene geomagnetic polarity reversals. Correlations with the geomagnetic polarity time scale (GPTS) indicate an Eocene-Oligocene boundary age near 33.4 Ma, which is some 0.3–0.6 Ma younger than the boundary ages previously indicated by other GPTS calibrations based on terrestrial and marine sedimentary sequences.

Tarduno, J. A.
Reversed polarity characteristic magnetizations in the Albian Contessa section, Umbrian Apennines, Italy: implications for the existence of a mid-Cretaceous mixed polarity interval, *J. Geophys. Res.*, *97B*, 241-271, 1992.
Paleomagnetic and paleontologic data have been obtained for a previous 14-Ma gap in the record, and they reveal several intervals of reversed characteristic remanent magnetization (ChRM) which is carried by hematite. If the reversed ChRM is a primary magnetization, then similar reversed intervals should be found worldwide. If the ChRM is a result of later remagnetization, then the record is subject to misinterpretation, since magnetization patterns which resemble polarity intervals can be produced.

Physics

Shvets, I. V., *et al*.
Progress towards spin-polarized scanning tunneling microscopy, *J. Appl. Phys.*, *71*, 5489-5499, 1992.
The main problems in operating a spin-polarized scanning tunneling microscope are addressed. Techniques were found for fabricating antiferromagnetic tips made of Cr, MnNi, and MnPt, and preparating clean (100) surfaces of magnetite. In addition, low-energy electron diffraction patterns and atomic resolution STM results were obtained on Fe_3O_4(100) using iron and tungsten tips.

Ziolo, R. F., *et al*.
Matrix-mediated synthesis of nanocrystalline γ-Fe_2O_3: a new optically transparent magnetic material, *Science*, *257*, 219-223, 1992.
A new magnetic material with appreciable optical transmission in the visible region at room temperature has been isolated as a γ-Fe_2O_3–polymer nanocomposite. The magnetization of the nanocomposite is greater, by more than an order of magnitude, than those of the strongest room-temperature transparent magnets, $FeBO_3$ and FeF_3.

Reversals/VGP Paths

Clement, B. M.
Evidence for dipolar fields during the Cobb Mountain geomagnetic polarity reversals, *Nature*, *358*, 405-407, 1992.
Comparisons are made among five reversal records: two North Atlantic records bounding the Cobb Mountain subchron (1.1 Ma ago), a volcanic record from Tahiti, and two new records of the Cobb Mountain subchron from the western Pacific. The results reveal striking similarities in the sequences of transitional VGPs, suggesting the presence of large-scale symmetries in these fields, and providing evidence of dipolar transitional fields during the Cobb Mountain reversals.

Constable, C.
Link between geomagnetic reversal paths and secular variation of the field over the past 5 Myr, *Nature*, *358*, 230-233, 1992.
The author shows that a non-zonal bias, similar to that observed in the transition paths (antipodal longitudinal bands) of VGPs during field reversals, is evident in the data on secular variation of the field over the past 5 Ma. These results, which are valid even after normalization according to site locations, suggest that the time-averaged field does indeed contain persistent (but not constant) non-zonal contributions.

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...*Mössbauer* continued from page 1
fame and funding by lending his name to the phenomenon. Samples are subjected to γ-rays, which, when certain quantum mechanical conditions obtain, are absorbed by the nuclei—a detector measures how many γ-rays of a given energy are absorbed. Different absorption spectra, which are plots of the number of counts as a function of γ-ray energy, are characteristic of various the iron mineralogies, lattice types, and other properties of the sample. The specific spectrum obtained depends on the status of the nuclear energy levels of the nuclei in the sample. Various changes in nuclear energy levels can be categorized as "Isomer Shift" (due to chemical factors), "Quadrupole Splitting" (due lattice distortion or asymmetry), or "Hyperfine Interaction" (due to magnetic fields). Each of these nuclear interactions results in a different Mössbauer spectrum, with superposition of any combination possible. [The diagram on the cover is not, by the way, meant to represent the typical form taken by water in Minnesota at this time of year, but rather it is just such a Mössbauer spectrum].

Principles of Operation

As outlined above, Mössbauer spectroscopy involves the resonant absorption of a γ-ray photon by a nucleus, wherein the nucleus is excited from the nuclear ground state to the first excited state. Taking the ground state energy to be zero and the first excited state energy to be E_1, absorption occurs when the photon energy $h\nu = E_1$, where h is Planck's constant and ν is the photon frequency. For ^{57}Fe, E_1 is 14.4 keV—the energy of a γ-ray. But, if a gas of ^{57}Fe nuclei in the ground state is exposed to photons with energy $h\nu = E_1$, no γ-rays are absorbed and no nuclei are excited. Because photons carry momentum, and because momentum is conserved when photons are absorbed, the nucleus must recoil in order to conserve momentum. If the nucleus recoils, it acquires kinetic energy, and this energy can only have come from the γ-ray. In other words, some of the γ-ray energy would have to be used to impart kinetic energy to the recoiling nucleus, leaving less than the original 14.4 keV for excitation of the nucleus. Because there would no longer be enough energy for excitation, the γ-ray could not be absorbed.

Mössbauer's great discovery was a quantum mechanical phenomenon: if the target nuclei are embedded in a solid, then there is a certain probability that the entire solid, and not just the individual nucleus, can take up the recoil momentum when a γ-ray is absorbed. In this case, because the recoil kinetic energy is effectively zero, no γ-ray energy is used up in imparting momentum. The entire photon energy E_1 is thus available for nuclear excitation, and the γ-ray can be absorbed.

Because the energy levels of the nuclear states are shifted under certain conditions, it is useful to vary the energy of the γ-rays by a small amount to see resonant absorption at slightly different energies in the neighborhood of 14.4 keV. The γ-ray energy can be adjusted by Doppler shifting—the changing-pitch-of-a-passing-police-car phenomenon. The energy shifts involved are so small that moving the source of photons relative to the ^{57}Fe nuclei in the solid need be only a few millimeters per second—no speeding tickets here! Energy shifts in Mössbauer spectra are given in terms of their Doppler velocity.

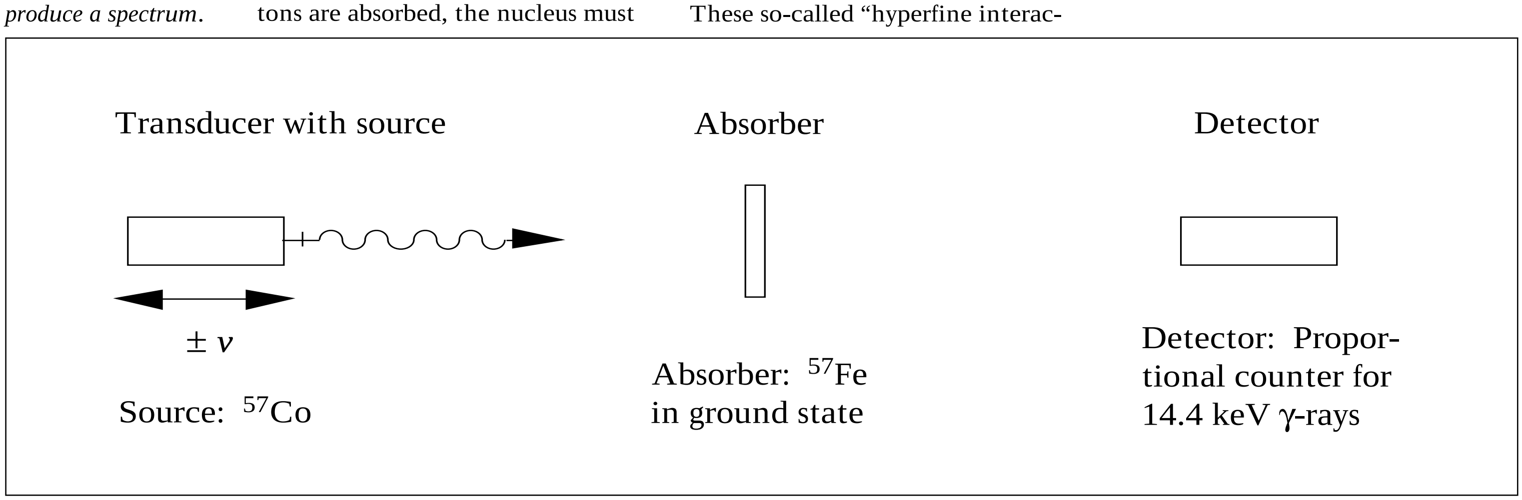
What makes the Mössbauer effect interesting is that the energies of the nuclear sub-levels can change when there are interactions between the nuclear sub-levels and the electronic environment within the solid in which the nuclei are embedded. These so-called "hyperfine interac-

...*Abstracts* continued from page 5
Langereis, C. G., A. A. M. van Hoof, and P. Rochette
Longitudinal confinement of geomagnetic reversal paths as a possible sedimentary artifact, *Nature*, *358*, 226-230, 1992.
It is shown that longitudinal confinement of VGPs can result from the smoothing of non-antipodal stable directions just before and after a geomagnetic reversal because of the filtering effect of the remanence acquisition process in sediments. The origin of this non-antipodality is still uncertain and must remain speculative until there become available more reversal records that include sufficiently long pre- and post-transitional intervals.

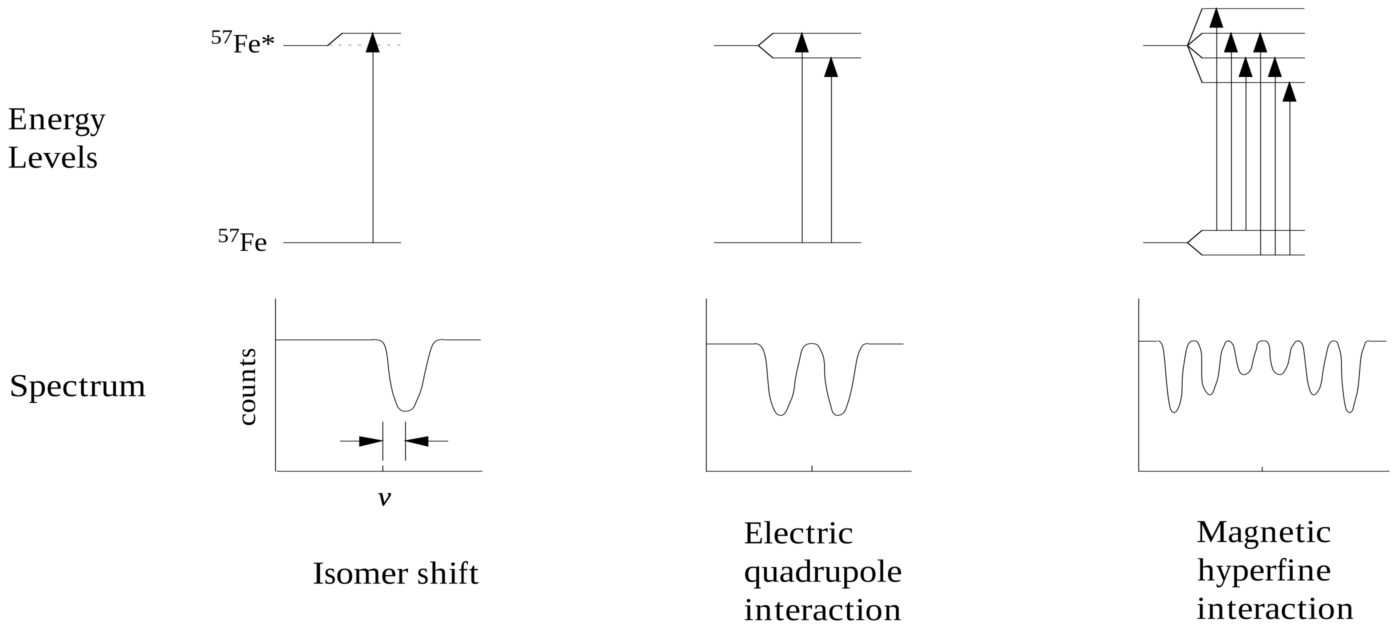
Secular Variation

Bloxham, J.
The steady part of the secular variation of the Earth's magnetic field, *J. Geophys. Res.*, *in press*, 1992.
The secular variation of the Earth's magnetic field results from the effects of both magnetic induction in the fluid outer core and magnetic diffusion in the core and in the mantle. The steady core flows for the periods 1690–1840 and 1840–1990 are calculated: over 90% of the variance of the time-dependent field can be explained by simple steady core flow, with the remainder due to non-steady flow and magnetic diffusion rather than to torsional oscillations.

Bloxham, J., and A. Jackson
Time-dependent mapping of the magnetic field at the core-mantle boundary, *J. Geophys. Res.*, *in press*, 1992.
Almost all the available geomagnetic field data from the last 300 years is used to produce two time-dependent maps of the field at the core-mantle boundary, one for the period 1690–1840 and the other for 1840–1990. The model used for calculations fits the magnetic observatory data better than any previous one, and the map exhibits much of the structure in the field and its secular variation that had been identified in earlier studies. ■



Schematic set-up of a Mössbauer Spectrometer. The 14.4-keV γ-rays come from the radioactive decay of ^{57}Co to ^{57}Fe. The γ-ray energy is then swept by Doppler-shifting. The detector tallies the γ-rays that are not absorbed by the target. Counts are sorted by energy to produce a spectrum.



Energy level diagrams and corresponding spectra for the three most common interactions. A given sample may yield a spectrum which is a superposition of any combination of these spectra.

tions" result in line-shifts or splittings in the Mössbauer spectrum, which give information about the electronic environment. There are three important hyperfine interactions:

1) The *Isomer Shift* arises because the ground and the first excited nuclear states have different sizes, and hence slightly different energy shifts when placed in the potential well caused by the electrons in the solid. If the potential well is changed by changing the electronic environment, there will be a shift of the centroid of the Mössbauer resonance. In practise, this occurs when the source and absorber have different chemical environments. For example, if the source is ^{57}Co dissolved in copper metal, and the absorber is ^{57}Fe dissolved in copper metal, the spectrum is a single line centered at $v = 0$. However, if the absorber is ^{57}Fe dissolved in palladium metal, stainless steel, or some other cubic metal, the spectrum is a single line shifted from $v = 0$. If the absorber contains Fe^{2+}, the isomer shift will be about 1.4 mm/sec; if Fe^{3+}, it will be about 0.4 mm/sec. Most isomer shift measurements are quoted relative to ^{57}Fe in iron metal.

2) An *Electronic Quadrupole Interaction* occurs for ^{57}Fe nuclei in low symmetry electronic environments, and is due to the interaction between the nuclear electric quadrupole moment and the electronic electric field gradient at the nucleus. This interaction affects only the excited state and splits the energies of its sub-levels into two pairs, but does not change the centroid of the spectrum; this results in a two-line Mössbauer spectrum. In general, Fe^{3+} salts have small electric field gradients and correspondingly small electric quadrupole interactions (~0.7 mm/sec), whereas Fe^{2+} salts have large electric field gradients and correspondingly large electric quadrupole interactions (~3.0 mm/sec).

3) The *Magnetic Hyperfine Interaction*, or Zeeman Effect, occurs when there is a magnetic field acting on the ^{57}Fe nucleus. The field can be externally generated in a magnet, or it can occur as a result of unpaired electron spins in a magnetically ordered solid. Since both the ground and the first excited nuclear states have magnetic dipole moments, all of the sub-levels have different energies in the magnetic field. This results in a six-line spectrum, with the overall spread of the splitting determined by the magnitude of the magnetic field at the nucleus.

It is possible to have all three interactions operating simultaneously (as in hematite). Or, if the solid under investigation has inequivalent iron sites (as in magnetite), or is a mixture of materials, one will find a superposition of spectra, with relative intensities roughly proportional to the relative amounts of the materials in the sample.

Nitty Gritty

A sample consists of a few tens of milligrams of a magnetic separate. The sample is affixed to the millimeter-size holder and attached to the end of the sample rod. The assembly is inserted into the machine, and the Doppler driver is turned on. A computer controls the driver motion such that the velocity, which is measured with a laser interferometer, changes linearly with time. The computer also keeps track of detector counts, depositing them in the bins appropriate to their Doppler-shifted energies. The detectors are allowed to accumulate counts until a good signal-to-noise ratio is achieved. The actual time required can be anything from an hour or so to days, depending upon the number of iron atoms in the sample and the patience of the operator. The temperature can be changed from 4 K to ambient. When our vertical spectrometer is also up and running, it will be possible to apply an external magnetic field of 5 T (50,000 Oe) to externally induce the Magnetic Hyperfine Interaction, but this will not happen until we get the money for another ^{57}Co source (Spring–Summer 1993?). The count data are stored in a file, and software permits both easy plotting of the resulting spectrum and effortless curve-fitting for analytical interpretation [see cover].

Pluses and Minuses

Mössbauer spectrometry can be maddeningly slow, especially after being able to do less-than-a-minute hysteresis loops on the MicroMag next door. In addition, there is always a small non-zero hazard when working with radioactive materials. [The lead shielding does cut the harmful γ-rays from the 50 mCi source down to below background levels, but because ^{57}Co has a half-life of 270 days, the source must be

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changed every couple of years.] On the other hand, the advantages of Mössbauer spectroscopy are that it is relatively non-destructive of samples, it can quantify the relative proportions of magnetic materials in a solid, and it's truly a you-set-it-up-and-walk-away-while-it-does-all-the-work sort of machine: it not only drives the Doppler shifters and collects all the data, but its software also takes care of the considerable (and formidable!) calculations and data-manipulation.

Now, you may remember that, in past issues of this newsletter, you were told that you'd have, in the next issue, an answer to the burning question, "Why do all new pieces of equipment at the *IRM* begin with the letter 'M'?" Well...you shouldn't believe everything you read—even in the *IRM Quarterly*! Your scheming editor has chosen to keep you on the edge of your seat, to hone your interest in the next issue to a razor-sharp point, and generally to annoy you further by refusing to cooperate once again. But, he will reveal all in the next issue after an article on the Magnetic Force Microscope! This time it's a promise. ▬

Meeting Update

Subir Banerjee
IRM

Sixth Northeastern Paleomagnetic and Rock-Magnetic Workshop

Ann Arbor, 17 October 1992

Thirty-three faculty members from several institutions gathered at Ann Arbor on October 17, 1992 for the Sixth Northeastern Paleomagnetic and Rock-Magnetic Workshop. (Holding a "northeastern" conference in Michigan was a delightfully fruitful exercise in stretching geographical terminology!) Of the eighteen presentations made, seven dealt with rock magnetism, and most included additional microprobe work and electron microscopy to confirm the compositions and grain-sizes inferred from the quick, but qualitative, rock-magnetic techniques. Analysis of multi-component remanent magnetization remains a major focus, but now multidisciplinary efforts have greatly expanded to include more rock-magnetic techniques than in the old days, when a few "obligatory" IRM-acquisition and Curie-point determinations were made on only two or three samples. The meeting was held in a laboratory, and this contributed to the friendly, but appropriately critical, atmosphere. We strongly urge such local get-togethers and, of course, personal visits to the *IRM* from the participants. [See the following announcement—Ed.] ▬

IRM Visiting Fellowships: Application Deadline is December 18, 1992

Applications are invited for visiting fellowships (regular and student) lasting between one and three weeks during the period from March 1–August 31, 1993.

"We know that the center of the Earth is a fiery molten mass, but it's not good to dwell on it."

Topics for research are open, although fellows are encouraged to take advantage of the focus for cooperative research chosen for the year. During 1992–93, the emphasis is on the connections between paleomagnetic observations and the fundamentals of rock magnetism. Short proposals (two pages of single-spaced text plus necessary figures and tables) are due by **December 18, 1992** for consideration by our Review and Advisory Committee (RAC). Successful applicants will be notified on February 15, 1993.

A limited number of travel grants (of $500) are available for researchers who have no existing financial resources. No funds are available for per diem expenses.

For information about proposal preparation, and for the required application forms, just call, fax [new verb], e-mail [another new verb], or write the *IRM*. ▬

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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The *IRM Quarterly* is published four times a year by the staff of the *IRM* with editorial and layout assistance from **Freddie Hart**. If you or someone you know would like to be on [or off] 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:

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