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Inside…

2008 International Conference on Rock Magnetism

The courtyard of the beautiful Institute d'Études Scientifiques de Cargèse, filled with happy rock magnetists. (Photo courtesy of Steve Constable.)

Julie Bowles
IRM

Spring in Corsica is beautiful, and the success of the 2008 International Conference on Rock Magnetism (June 2 – 8) was evidenced by the fact that over 100 scientists chose to spend those beautiful days inside a dark conference room, discussing the latest research in rock magnetism. Held at the beautiful *Institute d'Études Scientifiques de Cargèse*, the meeting was designed in part as a celebration of the career of Subir Banerjee, founder of both the IRM and the Santa Fe Conference series. The wide range of research discussed reflected that encompassed by Subir's career, an overview of which was provided as a conference kick-off by Bruce Moskowitz. Starting with his first published paper in 1960 in the field of seismology and spanning everything from mineral physics and magnetism to lunar paleointensity to environmental magnetism and nanobiogeomagnetics, Subir has made fundamental contributions to each of the sub-disciplines represented by the sessions at Cargèse.

This summary cannot possibly cover all the excellent science presented at the meeting, but will try to give a feel for the amazing breadth of topics covered. That breadth may have been the single most impressive aspect of the meeting. Where else can a single discipline also make contributions to paleoclimatology, environmental science, tectonics, planetary science, chemistry, physics, and biology?

The entire program and abstract volume can be downloaded from the conference website (www.irm.umn.edu/Cargese/).

Rock and Mineral Magnetism

The first morning featured two companion talks given by Suzanne McEnroe et al. and Dave Dunlop and Özden Özdemir on open questions and challenges in mineral (McEnroe) and rock (Dunlop/Özdemir) magnetism. McEnroe discussed some unanswered questions, including the age and source of magnetism in the ocean crust; the source of continental deep-crustal anomalies; and temperature and pressure effects on mineral exsolution systems. Exciting new research bearing on these (and many other) questions is being carried out at the intersection of rock and mineral magnetism with numerical modeling, laboratory synthesis and new magnetic microscopy and micro-analytical techniques that allow us to address problems at a scale not previously possible. Dunlop and Özdemir focused on open questions related to remanence acquisition; low-temperature transitions and "transition remanence"; poorly-understood behavior at the SD-2D transition; and the interpretation of grain-size distributions and mixtures on Day plots. McEnroe further pointed out that in addition to fundamental scientific challenges, we also face funding challenges – and opportunities. She suggests developing community-based projects or strategies as an approach to exploit potential funding sources.

Early results were presented on two efforts to use precisely synthesized material to study magnetostatic and coupled/exchanged interactions. Maike Lübbe, Michael Winklhofer et al. described a controlled laboratory synthesis of hematite-ilmenite multilayers, designed to understand the effect of layer thickness on the properties of lamellar magnetism. Wyn Williams et al. presented early results from the synthesis of precise nano-particle

cont'd. on p. 9…

Visiting Fellows' Reports

FORC diagrams and low-temperature measurements of biogenic and non-biogenic magnetites

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Part 1: Formation of magnetite in cultured *Magnetospirillum gryphiswaldense*

The first set of samples was provided by Damien Faivre from the University of Bremen and consisted of cultured *Magnetospirillum gryphiswaldense* at various stages of their development. They were grown following an assay in which the iron uptake is used only for magnetite formation and not for cell growth. This enabled me to follow the magnetite formation independently from growth.

I measured room-temperature FORC diagrams for samples that had spent respectively 2, 3, 5 and 8 hours in their growth medium. According to what TEM images had previously shown, the FORC diagrams show a very clear evolution from a mainly superparamagnetic (SP) (though very noisy) pattern to a mainly single-domain (SD) pattern, but still containing some SP particles.

Part 2: Magnetic characterization of biotic and abiotic nanomagnetite

The second set of samples were nanomagnetites chemically produced from lepidocrocite and nanomagnetite biogenically produced by the iron-reducing bacterium *Shewanella putrefaciens*. The main goal of this study was to look at differences between the magnetic properties of the two kinds of samples by various methods, including X-ray spectroscopy methods and FORC diagrams. Since the particles were mainly SP at room temperature, the FORC measurements had to be done at low temperature (down to 20 K). Both samples had very similar FORC diagrams, SP-like as expected. The progressive blocking of the magnetization when the temperature is decreased is easily seen on the FORC diagrams (Fig.2), and could be used to determine the grain size distribution.

Thanks very much to Mike, Peat and Brian for the technical help, and to Thelma, Amy and Ioan for their help with sample preparation.

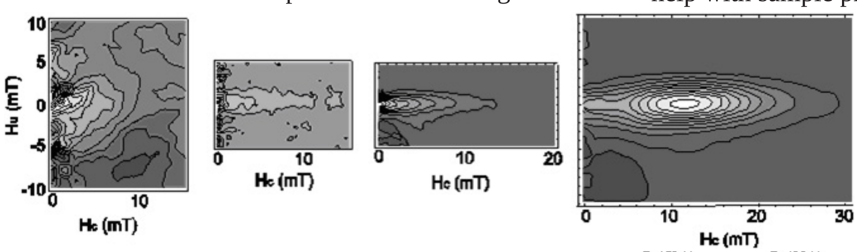

Figure 1: FORC diagrams of the time-course series of M. gryphiswaldense after: a: 1h30; b: 3h; c: 5h; d: 8h in the growth medium. The 4 FORC diagrams are at the same scale. SF=4.

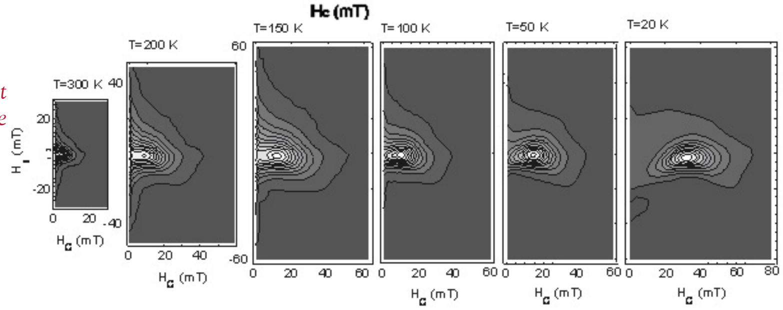

Figure 2: Top: FORC diagrams measured at different temperatures, for a magnetite sample produced with the abiotic method. SF=2.

Direct measurement of hematite individual particle anisotropy using thermal fluctuation tomography: comparison to other techniques and implications for inclination shallowing in red bed DRMs

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Methods to correct for the observed inclination shallowing in sedimentary rocks have been proposed that are based on either models of the geomagnetic field (Tauxe and Kent, 2004; Kent and Tauxe, 2005) or on magnetic anisotropy (Jackson et al., 1991; Tan and Kodama, 2003). One limitation of the anisotropy method has been the isolation and determination of the magnetic carrier's individual particle anisotropy (*a* factor). Our red bed inclination shallowing corrections of the Carboniferous Shepody Fm. of New Brunswick and Nova Scotia have been dependent on estimates of hematite's individual particle anisotropy using data fit to theoretical correction curves and by spatial analysis of the distribution of corrected paleomagnetic directions and poles. We have also developed a technique for extracting the magnetic mineralogy in a sample and preferentially make a direct measure of individual particle anisotropy of specular hematite. Measured values are consistent with our previous estimates.

In order to improve our understanding of red bed DRMs and inclination shallowing, I went to the IRM in the attempt to apply the thermal fluctuation tomography technique of Jackson et al. (2006) to measure hematite's particle anisotropy in red beds. Application of the technique has requirements that aren't strictly met by most red bed formations. Most importantly, a single magnetic mineralogy is required, while the Shepody Fm. red beds contain a mixed magnetic mineralogy of specular hematite, magnetite, maghemite, goethite and pigmentary hematite, as indicated by IRM acquisition modeling and thermal demagnetization of three orthogonal IRMs. Thermal fluctuation tomography also requires high temperature measurements, which pose the problem of thermochemical alteration at the required Néel temperatures. In view of these complications, the challenge was to work through some of the steps towards a quantitative estimate of particle anisotropy.

Focus was placed on magnetic separates in an attempt to limit the effects of thermochemical alteration. Rock-magnetic measurements were compared to those performed on whole-rock samples. High temperature hysteresis loops performed on the high-temperature vibrating sample magnetometer (VSM) and high temperature susceptibility measurements performed on the high-temperature kappabridge suggest that magnetic separates start altering at higher temperatures than whole rock samples (~550°C as opposed to ~450°C), making them potentially more useful for thermal fluctuation tomography. Heating and cooling sweeps between 20 K and 300 K performed on an MPMS show smoother signals from the magnetic separates. The contribution of hematite in separates, however, is extremely low and appears to have been dampened by the extraction process, which preferentially selects magnetite. The presence of goethite is also suggested.

As a combination of the thermal alteration observed and the mixed mineralogy present in the samples, together with the very weak hematite signal obtained from the separates, attempts at thermal fluctuation tomography modeling gave very poor results. While at the IRM, however, I was able to make important measurements on the VSM and MPMS that helped me further characterize the mineralogies and properties of a broader collection of red bed samples from the Maritime Provinces of Canada, including FORC diagrams. These results have unequivocally proven the presence of primary magnetite in red beds whose primary remanence is carried by specularite (Shepody Fm) and in red beds whose remanence is carried by magnetite with secondary chemically grown hematite present (Deer Lake Group, Newfoundland).

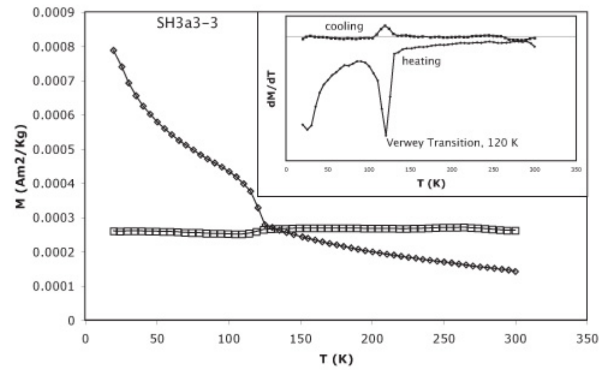

Figure 1: Low temperature MPMS, heating and cooling curves between 20 K and 300 K of a whole rock specimen of the Shepody Fm. whose characteristic remanence is carried specular hematite, showing a very strong magnetite signal. The inset shows the derivative of the curves with the Verwey transition indicated.

My time at the IRM was a great learning experience and I am grateful to all the IRM staff for the opportunity I was offered and for the generous help and expertise provided.

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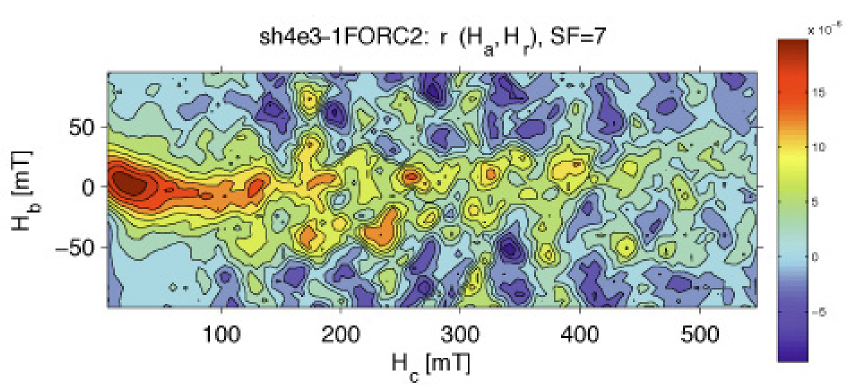

Figure 2: FORC diagram of a whole-rock specimen of the Shepody Fm. whose characteristic remanence is carried by hematite, indicating a contribution to the remanence that is dominated by magnetite.

Imaging of experimentally shocked pyrrhotite

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The remanent magnetization of many extraterrestrial materials, including meteorites and planetary surfaces, has often been used to infer the magnetic histories of their parent bodies. However, many materials are known to demagnetize due to shock (see e.g. Nagata, 1971; Pohl, et al., 1975). An appreciation of the effects that impact-related shocks have had on the magnetic signatures in these rocks is critical to our understanding of the magnetization of these materials.

Unmagnetized regions of crust surrounding large impact craters on Mars have been attributed to low pressure (a few GPa) shock-demagnetization of the magnetic carriers. Although the precise nature of the magnetic minerals in the Martian crust remains debated, pyrrhotite ($Fe_{1-x}S$, $0<x<0.125$) is the primary magnetic phase in Martian basaltic shergottites (Rochette, et al., 2001). Hydrostatic pressure experiments on pyrrhotite (Rochette, et al., 2003) indicate complete demagnetization of high-field isothermal remanent magnetization (IRM) at ~3 GPa. Shock experiments corroborate this result (Louzada, et al., 2007). However, at higher pressures, shock demagnetization is less efficient and the total moment may even increase at shock pressures above 10 GPa (Louzada, et al., *in prep.*).

Shock (and high static pressure) in magnetic minerals is often accompanied by permanent increases in coercivity and saturation IRM (e.g. Louzada, et al., 2007; Gilder and Le Goff, 2008). Proposed mechanisms for this increase in single domain like behavior (or hardening) are: 1) a decrease of grain size via microfracturing, 2) changes in magnetostriction and/or magnetocrystalline energies, and 3) domain restructuring and wall nucleation as a result of increased crystal defects (Borradaile and Jackson, 1993; Gilder, et al., 2004; Gilder and Le Goff, 2008; Kontny, et al., 2007).

In this study we collected Bitter pattern and Magnetic Force Microscope images of shocked pyrrhotite to: 1) characterize the distribution of magnetic pyrrhotite in the natural samples, and 2) investigate the effects of shock on this distribution.

The natural pyrrhotites used in this study are mixtures of hexagonal (antiferromagnetic) and monoclinic (ferrimagnetic) pyrrhotite, with domain sizes ranging from single to multidomain (Louzada, et al., 2007). Bitter images of unshocked samples (Fig. 1a) show that the monoclinic pyrrhotite is confined to lamellae (dark grey/black) inside a hexagonal matrix (featureless grey). In monoclinic pyrrhotite, the domains are simply

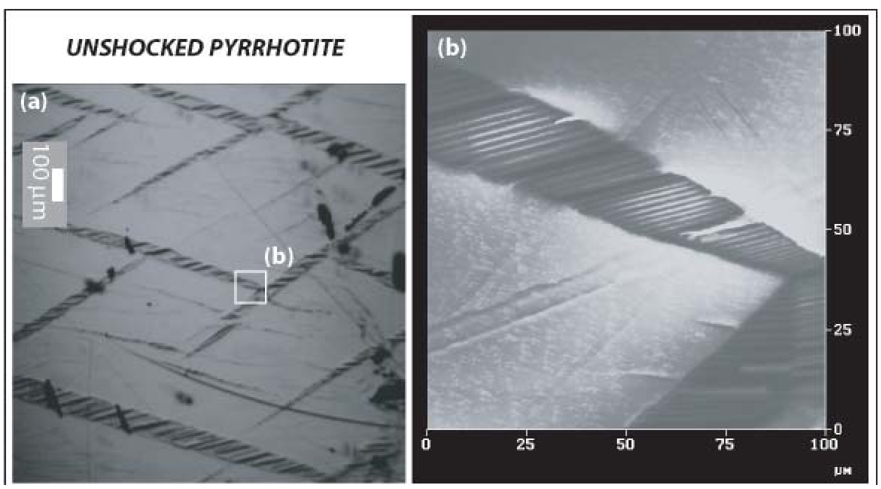

Figure 1. (a) Bitter pattern image of unshocked, unmagnetized pyrrhotite. The direction of view is approximately perpendicular to the c-axis. (b) MFM detail image of the boxed region in (a). Bright and dark areas are regions where the magnetization is directed out of and into the sample respectively.

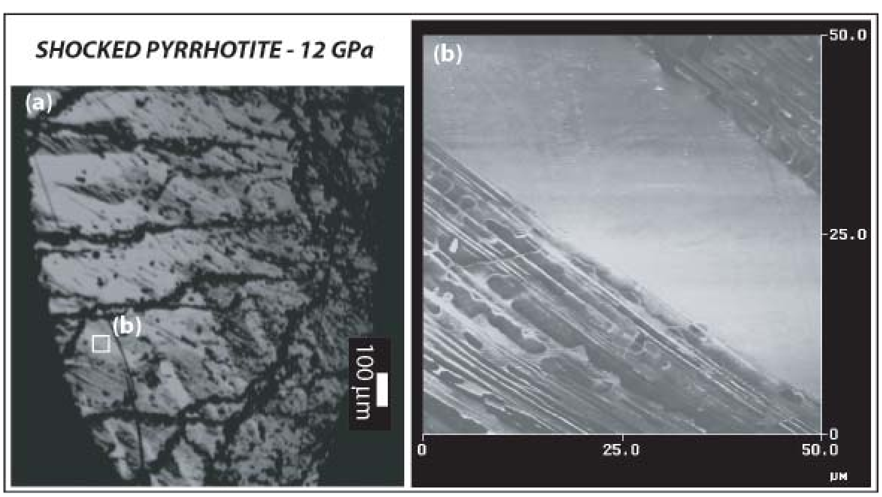

Figure 2. (a) Bitter pattern image of shocked (12 GPa) recovered pyrrhotite AF demagnetized to 85 mT. The direction of view is the same as in Figure 1. Fractures appear as black, roughly linear features, predominantly radially oriented from right to left. (b) MFM detail image of the boxed region in (a).

organized with straight parallel walls (Fig. 1b), typical of demagnetized pyrrhotite (Halgedahl and Fuller, 1981). The post-shock sample (Fig. 2a) is much fractured and the domains are disrupted (Fig. 2b). The undulating, non-planar domain walls are reminiscent of domain wall pinning in pyrrhotite with a thermal remanence (Halgedahl and Fuller, 1981). Domain restructuring due to new defects or microfractures in the crystal, and effective domain size reduction, are likely responsible for the observed magnetic hardening. Shock-induced nano-structures, analogous to planar deformation features in shocked quartz, have also been observed in strongly magnetized pyrrhotite from Bosumtwi crater, Ghana (Kontny, et al., 2007).

We conclude that shock-induced permanent changes in magnetic properties of magnetic minerals preclude the use of meteorite remanences as reliable paleointensity indicators.

TIPS for producing clean images on the MFM: 1) take care older polishing slurries do not leave a colloid residue, 2) wipe samples down with ethanol (not acetone), and 3) scan at a 45° angle.

Thank you to the IRM staff for a very enjoyable visit, in particular Mike, Julie, Josh, Bruce, and Peat.

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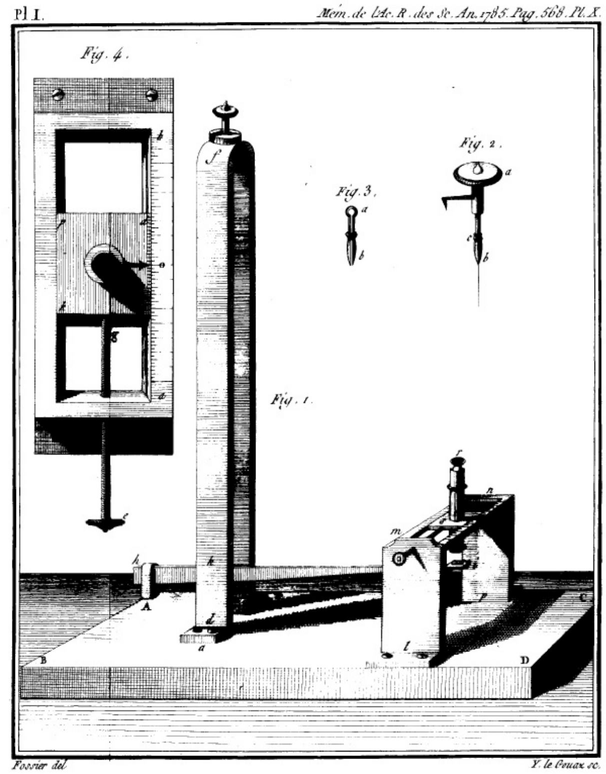

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Current Articles

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.

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2008 Conference on Rock Magnetism, *continued from page 1...*

arrays using electron-beam lithography of iron thin film. The goal is to better understand magnetostatic interactions by precisely controlling particle size and spacing, combining observations with micromagnetic modeling.

Two talks delved into recent advances in our understanding of disordered systems. France Lagroix discussed order/disorder transitions in the hematite-ilmenite solid solution series and recent experiments aimed at understanding the magnetic phase diagram of the system. She questioned the use of the term 'superparamagnetic' for states with only short range, but no long range ordering. Karl Fabian commented that he has adopted the term PM´ to denote such states (e.g. IRM Quarterly v. 17 no. 4). Later in the day, Candice Viddal and Roy Roshko discussed recent modeling work where they found that a Preisach system of interacting nanoparticles may display low-temperature behavior that had previously been linked only to spin glass.

Karl Fabian et al. discussed the state of our understanding behind theories of thermal remanence (TRM), thermochemical remanent magnetization (TCRM), and detrital remanence (DRM) with respect to recovering accurate paleointensity determinations. Lisa Tauxe and Ritayan Mitra took this further and presented an experimental and theoretical study of the role that flocculation plays in DRM acquisition, including its influence on inclination error and DRM linearity with respect to field strength.

Extraterrestrial Magnetism

Jérôme Gattacceca and Ben Weiss gave nice overviews of the challenges and opportunities in recovering paleofield information from meteorites. Most meteorites have undergone some kind of shock and/or thermal event and (as pointed out in the question-and-answer period) may also have been contaminated by exposure to strong magnets on Earth. Considerable effort is currently being applied toward differentiating a shock magnetization or a viscous magnetization acquired on Earth from a primitive TRM. With care in addressing some of these issues we can begin to learn about paleofields in the early solar system, planetary evolution, and early planetary dynamos.

Best quote of the meeting: *(photo courtesy of Enver Murad)*

"Follow your star, but keep a flashlight handy."*
-- Subir K. Banerjee, June 4, 2008

** flashlight = basic physics and geology*

In other talks, Stuart Gilder et al. reported on an experimental examination of pressure effects on titanomagnetite magnetization, which has implications for deeply-rooted crustal anomalies both on Earth and other planets. Saturation remanence and coercivity both increase with increasing applied pressure load, and the magnitude of the effect increases with increasing Ti content. Pierre Rochette et al. compared the magnetic properties of lunar materials derived from both meteorites and sample return. Minoru Uehara and Norihiro Nakamura used a magneto-impedance magnetic microscope to measure fine-scale variations in magnetization of a piece of chondrite.

Paleofield Behavior and Records

John Tarduno examined the role that paleomagnetism can play in establishing dynamo evolution, but the search continues for materials (such as certain single crystals) that are both thermally and chemically stable over the relevant time scales. A better understanding of geodynamo evolution may also play a role in understanding atmospheric evolution; the presence or absence of a strong field can affect the degree to which atmosphere is swept away by the solar wind.

cont'd. on p. 10…

Several talks explored the differences between dipole and non-dipole field behavior. One of the most basic tenets of paleomagnetism assumes that when averaged over a sufficiently long time interval, the Earth's magnetic field can be represented by a geocentric axial dipole (GAD). Catherine Constable presented ongoing efforts to model paleomagnetic field behavior over millennial to million year time scales and examined the structure and persistence of departures from GAD: the non-axial dipole (NAD) components. Even after averaging over 5 Ma, some zonal structure is observed in the field, and this result appears to be robust.

Roman Leonhardt, Karl Fabian et al. have used a Bayesian inversion technique on several high-resolution paleomagnetic records to develop a different model of field morphology. The model shows some similarities and differences in field evolution between an excursion (Laschamp) and the last reversal. While in both cases reverse flux patches at the core-mantle boundary move poleward from near the equator, only in the case of the reversal do these patches cross the inner-core tangent cylinder. They also find that during the excursion, both dipolar and non-dipolar components decrease at approximately the same rate while during the reversal there is a relative increase in the non-dipolar component.

Ken Hoffman and Brad Singer argued for a magnetic source separation whereby the dipole field is generated in the deep core and the non-dipole field is produced in the shallow outer core and is strongly influenced by core-mantle interactions. They proposed the new term Shallow-Core Generated (SCOR) field to denote this component that is predominantly (but not completely) non-dipolar and suggested it is this SCOR field that dominates during both reversals and excursions. They observe that VGPs in a set of Tahiti lavas are clustered near Western Australia (a flux lobe in a 400 yr field model) during both the last reversal and an excursion (Big Lost).

Possible orbital influences on the geodynamo were discussed by Mike Fuller, who is interested in the relatively recent revival of the idea of precession as a possible power source for the geodynamo. Paleomagnetic data over the past 5 Ma may support links to excursions and reversals that occur preferentially at certain points in the obliquity cycle. In addition, recent laboratory studies have shown that precession combined with rotation can lead to core convection. Nicolas Thouveny reviewed in more detail a potential coincidence between dipole lows and the obliquity signal. He presented data suggesting dipole lows and excursions preferentially occur during interglacials. He additionally pointed out that though sedimentary records may be biased by paleoenviornmental contamination, both ^{10}Be data and marine magnetic records show similarities with the marine sedimentary records, suggesting a real link between orbital variations and the geomagnetic field.

The session finished up with several talks on paleointensity methods. Mark Dekkers presented some recent results using the multi-specimen parallel pTRM method. Ron Shaar described using a set of well-characterized synthetic slags to evaluate Thellier methods and interpretation. Andrew Biggin discussed possible reasons for consistent differences between some microwave and traditional thermal Thellier experiments.

Environmental Magnetism

Topics in this session ranged from using magnetic proxies to uncover paleoenvironmental conditions, to magnetism in modern land use and pollution monitoring. Barbara Maher discussed some of the efforts involved in using magnetic proxies to trace East Asian monsoon intensity in loess. With the recognition that the interpretation of magnetic soil enhancement as a rainfall proxy varies with soil type, and when combined with δ^{18}O records from Chinese speleothems, a more complex picture of monsoon variations becomes evident. Ted Evans gave a more

One of many extra-curricular meetings of magnetic minds. (Photo courtesy of Enver Murad.)

historical overview of loss magnetism and the evolution of our understanding of loess as both a geomagnetic and paleoclimatic recorder.

Richard Reynolds et al. described an application currently employed by land-use managers in the western U.S. whereby magnetic properties are used as a proxy for atmospheric dust-derived nutrient loads in the soil. Dust accumulation and erosion in soils can be mapped using susceptibility, and changes in land-use practices can be tied to effects on nutrient load.

A recurring theme in the session was using magnetism as a tracer for natural vs. anthropogenic input to a system. Christine Franke et al. examined sediments from the Seine River with the aim of developing magnetic fingerprints for different geologic and anthropogenic inputs and processes. Leonardi Sagnotti used magnetism as tracer of airborne particulate matter in a study of air pollution monitoring.

Biogeomagnetism and Nanomagnetism

The final session focused on two fields which have been rapidly growing in recent years. Yohan Guyodo discussed complex behaviors observed in nanoparticles of iron oxyhydroxides that point to nanoclusters of material. These presence or absence of these clusters may play a role in the how the particles evolve in soil via chemical or biological mediation.

Richard Pattrick et al. described the technique of x-ray magnetic circular dichroism as applied to geomagnetic minerals. This technique can provide quantitative information on cation valence state and coordination, as well as the distribution of vacancies in ferri- and ferromagnetic minerals.

Richard Frankel reviewed current understanding of and open questions regarding magnetosomes and magnetotaxis in bacteria. Michael Winklhofer presented recent work on understanding the physical basis of magnetic sense in animals. Results of a study in birds shows that they use an inclination compass that allows them to sense increasing or decreasing inclination, but not polarity.

In addition to the main sessions, two afternoons were devoted to mini-courses in Mössbauer spectroscopy (Enver Murad) and magnetic microscopy (Bruce Moskowitz and Richard Harrison). Notes from these courses can be found on the conference website: www.irm.umn.edu/Cargese/. A morning poster session rounded out the talks and re-emphasized how broadly encompassing our field is.

Special thanks are due to the organizing committee, who put in many long hours ensuring that the meeting went smoothly: Pierre Rochette (CEREGE, France); Mike Jackson, Bruce Moskowitz, and Joshua Feinberg (IRM, US); Fabio Florindo (INGV, Italy); and Andrew Roberts (Univ. Southampton, UK).

And of course the meeting would not have been possible without the conference sponsors: National Science Foundation (NSF, USA); Centre National de la Recherche Scientifique (CNRS, France); and the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Italy).

Charles-Augustin de Coulomb
b. 14 June, 1736, Angoulême, France
d. 23 August, 1806, Paris, France

Trained as an engineer, Charles-Augustin de Coulomb spent the early part of his career in the military, including nine years in the West Indies. During this time he was in charge of the construction of Fort Bourbon and gained significant practical experience in engineering, structural design, and mechanics that would influence his later theoretical writings and research. After returning to France in 1772, he was able to devote more time to his scientific work, and one of his earliest efforts described a magnetic compass capable of measuring diurnal variations in the magnetic field. This memoir claimed the *Grand Prix* of the *Académie des Sciences* in 1777 and was the beginning of his work with the torsion balance. Further work with the torsion balance led to his formulation of 'Coulomb's Law' describing the inverse-square law of attraction and repulsion between charged bodies. Coulomb went on to write seven treatises on electricity and magnetism, and presented at least 25 other papers on magnetism, friction, materials strength, torsion, hydraulics, mechanics, and ergonomics at the *Académie*. The SI unit of electric charge was ultimately named after Coulomb.

2008 Visiting Fellows

July - December

Charles Aubourg, *University Cergy Pontoise*, P-transition in immature claystones

Amy Chen, *Ludwig-Maximilians University*, Low-temperature hysteresis, remanence, and susceptibility of partially oxidized SD & 2D Fe_3O_4

Annika Ferk, *Montanuniversity Leoben*, Volcanic glass - an ideal recording material? Rock magnetic investigations

Beatriz Ortega, *Universidad Nacional Autonoma de Mexico*, Environmental magnetism record of Holocene from tropical lake sediments on western México: Tacambaro lake

Francesca Saragnese, *University of Turin*, Atmospheric particulate matter revealed by magnetic analysis

Jairo Francisco Savian, *University of São Paulo*, Magnetic Characteristics of Soils Containing Biomineralizations

Xixi Zhao, *University of California, Santa Cruz*, Rock magnetic characterization of sedimentation process and faulting activities of the Nankai Trough

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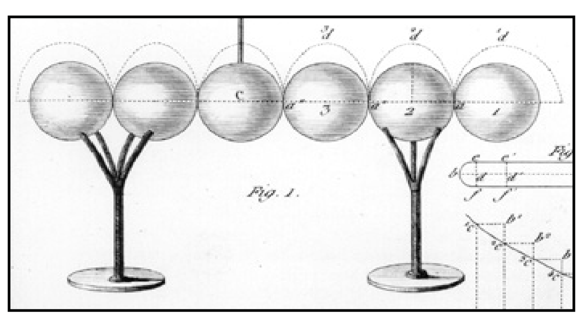

From Coulomb's "Sixth Memoir on Electricity and Magnetism", Mémoires de l'Académie royale des sciences, vol. 91, 617-705, 1788.

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