Inside…

The IRM Quarterly

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photo by Christoph Geiß

Taras Pokhil follows Rick Oches and Bernie Housen in wrapping up three years of IRM postdoctoral work and moving on to the next stage of his career, with best wishes from all of us at the IRM.

Postdoctoral Transitions II

Taras Pokhil
IRM / Seagate Technology, Inc.

Three Great Years at the Best Laboratory I Ever Saw.

I came to the IRM nearly three years ago in October 1994. In October this year I will start my new career at Seagate Technology. My years at the IRM have been three great years in my life. Unfortunately my English is not good enough to describe my feelings about the IRM (It is easy to feel but hard to describe with words). It was great luck for me to work and to communicate every day with Bruce Moskowitz, Subir Banerjee, Jim Marvin, Mike Jackson, Bernie Housen (my officemate for three years), Chris Hunt (former IRM manager), David Williamson, Christoph Geiss and everybody at the IRM. I was also very fortunate to collaborate with Sherry Foss, Roger Proksch and some other nice people from Magnetic Microscopy Center. I hope that in my new job at Seagate I will have a chance to come back to the IRM (at least sometimes) as a visitor to do some measurements and, which is more important, to meet the IRMers.

Maybe this is enough lyricism. I am not a writer so let's get to business. What did I do for three years at the IRM: As a micromagnetic person at the IRM I was fortunate to work on different projects, studying micromagnetism and micromagnetic dynamics in various objects. My main and favorite tool in working on this projects was Magnetic Force Microscope. Here is a brief description of some of these projects:

Magnetic domains and domain walls in pseudo-single-domain particles (with Bruce Moskowitz).

We studied magnetic domain and domain wall structures in pseudo-single-domain grains (5-20 μm) of magnetite (Fe_3O_4) using magnetic force microscopy. Many of the observed micromagnetic features can be explained by the magnetostatic effects of surfaces and grain edges and interactions within and between walls. Domain walls were frequently subdivided into 1-3 opposite polarity segments separated by Bloch lines, although some walls contained no Bloch lines. Subdivided walls display a characteristic zigzag structure along the easy axis direction, where zigzag angles can be as high as 20°-40° (Fig. 1). The zigzagging structure, in addition to wall segmentation, further minimizes the magnetostatic energy of the walls. Bloch lines can be (de)nucleated during wall displacement or after repeated alternating field (AF) demagnetization. Within individual walls, the number of Bloch lines and their pinning locations were found to vary after repeated AF demagnetization demonstrating that walls, like individual grains, can exist in several different local energy minima. The number of Bloch lines appears to be independent of domain state, but frequently the polarity of the wall was coupled with the direction of magnetization in the adjoining domains, such that wall polarity alternates in sign between adjacent walls across an entire grain. Even after the domain magnetization is reversed, the same sense of wall chirality is maintained across the grain producing unique grain chiralities. For one particular grain (Fig. 2) which has quite an unusual domain structure (step-like walls or even "box" domains) it was possible to reconstruct a likely three-dimensional (3-D) domain structure. The body and surface structures result primarily from a

Taras Pokhil

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Visiting Fellows' Reports

With autumn imminent and winter looming ahead, it is pleasant to look back over the warm months of the recent past. Spring and summer at the *IRM* included return visits from Adrian Muxworthy, studying the effects of low-temperature transitions on remanence in multidomain magnetite, and Andrei Kosterov, investigating the usefulness of high-temperature hysteresis as a tool for screening samples to be used in Thellier paleointensity work.

Adrian Muxworthy
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Metastability of partial thermoremanent magnetizations in multidomain magnetite

My objectives on my second visit to the IRM within a year, were to study the behaviour and stability of thermoremanences in multidomain magnetite to cooling below the acquistion temperature, and to examine various low-temperature properties of magnetite.

Two areas of magnetite's thermoremance stability were examined; firstly the stability of partial TRM's to cooling below the acquisition temperature to approximately 140 K *i.e.*, just above the Verwey transition (118-122 K), and secondly the stability of these same partial TRM's to cooling through the Verwey transition. The first part of the experiment followed on from the observation initially reported by McClelland and Sugiura (1987), where partial TRM's induced in multidomain magnetite were found to reduce in intensity after cooling below the acquisition temperature to room temperature. Previously I had observed a similar decrease in magnetisation when cooling TRM's (T_C to room temperature) and partial TRM's from room temperature down to above the Verwey transition. On this visit I measured a complete record from T_C to 70 K and back up to T_C again. Above room temperature the samples were measured on the microVSM, below the MPMS was used. A decrease was observed from the minimum acquistion temperature all the way down to the Verwey transition, however only in a few random samples was the gradient steady across the transfer from microVSM and MPMS. For increasing temperature *i.e.*, from the MPMS to the microVSM, the smoothness in the curves across the transfer was generally better.

On cooling through the Verwey transition, the behaviour of the thermoremanences showed a dependency on the nature of the acquistion *e.g.* acquired from T_C to T_2 or from T_1 (< T_C) to T_2. There was also some grain size dependency up to 50 microns. From 70 K to the Verwey transition, the heating curves were approximately reversible with the cooling curves. On heating from the Verwey transition to T_C, the magnetisation was found to be fairly stable up to approximately 500 C, where it gradually demagnetised on approach to T_C.

I also examined some fundamental magnetic properties of my samples and of magnetite. I measured the susceptibility between 20 K and room temperature. The larger grained samples (50-150 microns) displayed a fairly sharp transition at 118-126 K, with an increase in susceptibility of almost 100 % during heating. There was a small frequency dependence across this transition, though this dependency was not found at other temperatures. The single domain samples showed no low-temperature transition.

Using the older VSM with the low-temperature liquid nitrogen dewar, I measured the hysteresis parameters for a range of grain sizes at room temperature down to 77 K. It was found for the large multidomain samples, as expected from previous studies *e.g.* Schmidbauer and Keller (1996), that these parameters were strongly affected by the first magnetocrystalline constant isotropic point (130 K), and not the Verwey transition. The difference in transition temperature for the susceptibility and the hysteresis parameters is probably due to the latter being a large field property whereas the susceptibility is a low field property.

I measured the Mössbauer spectrum of pure magnetite as a function of temperature. At 120 K and below the hyperfine splitting attributed to the iron ions on the B sublattice *i.e.* Fe^{2+} and Fe^{3+}, were clearly distinguishable, at 125 K and above they were indistinguishable. It was hoped that more information about the reduction of electron mobility on cooling through the Verwey transition would be revealed, however it was not to be.

Many thanks to the IRM for their help, time and especially their patience.

Andrei Kosterov
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Thermal variation of hysteresis in volcanic rocks and the performance of the Thellier paleointensity method.

My main objective at the IRM was to investigate a relationship between the samples' behavior during Thellier paleointensity experiments and variation of their hysteresis properties with temperature. During my previous informal visit to IRM in June 1996, I noticed that some samples of the Early Jurassic Lesotho basalt, which failed to yield paleointensity estimates, reveal very distinctive variation of hysteresis parameters with temperature. A small but irreversible drop of coercive force was observed on heating up to 175°C, while no other changes occurred up to the temperatures as high as 475°C. As well, the relationship between coercive force and saturation remanence was not constant in the whole temperature range between room T and 400°C, as might be expected if the domain structure was stable during heating.

Thus, the main goal of my new visit to IRM was to carry out similar experiments on a more representative collection of volcanic rocks, studied previously with the Thellier method. The collection included paleomagnetic samples of various ages, from Quaternary to Early Jurassic, and also some samples of historic lavas from Mount Etna, for which the Earth's field intensity is known from the direct observations. Another goal was to further characterize the magnetic mineralogy of the samples by means of low temperature hysteresis measurements and thermal demagnetization of the SIRM given at 15 K.

VF Reports *continued on page 8…*

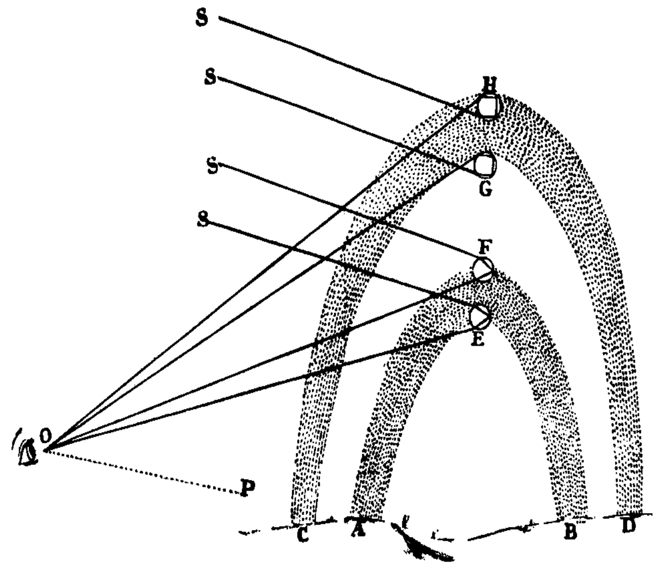

FIG. 15.

"Thus shall there be made two Bows of Colours, an interior and stronger, by one Reflexion in the Drops, and an exterior and fainter by two; for the Light becomes fainter by every Reflexion. And their Colours shall lie in a contrary Order to one another, the red of both Bows bordering on the Space GF, which is between the Bows. ...all the Drops in the Line OE shall send the most refrangible Rays most copiously to the Eye, and thereby strike the Senses with the deepest violet Colour in that Region. And in like manner the Angle SFO ... shall be the greatest in which the least refrangible Rays after one Reflexion can emerge out of the Drops, and therefore those Rays shall come most copiously to the Eye from the drops in the Line OF, and strike the Senses with the deepest red Colour in that Region." From Opticks (4th edition)*, 1730; by Sir Isaac Newton*

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 are included; 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 subjected to Procrustean editing and condensation 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 3700 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the* IRM Quarterly *are always welcome.*

Biogeomagnetism

Dickson, D. P. E., *et al.*
Properties of magnetoferritin: a novel biomagnetic nanoparticle, *Nanostruct. Mater., 9* (1-8), 595-598, 1997.

Mössbauer spectra obtained at low temperatures and in large applied magnetic fields clearly show that the magnetoferritin core is quite different to that of ferritin. The changes in the spectra with increasing applied field indicate that the core is a ferrimagnet and lead to the conclusion that the magnetoferritin core is very similar to the mineral maghemite.

Geomagnetism, Secular Variation and Reversals

Chiari, G., and R. Lanza
Pictorial remanent magnetization as an indicator of secular variation of the Earth's magnetic field, *Phys. Earth Planet. Inter., 101* (1-2), 79-83, 1997.

Magnetic measurements carried out on murals of known date painted between 1740 and 1954 showed that the haematite pigment conferring their red colours carried remanent magnetization. The mean direction was well defined and consistent with that of the Earth's magnetic field at the time of painting, as deduced from the Historical Italian Geomagnetic Catalogue.

Vlag, P., N. Thouveny, and P. Rochette
Synthetic and sedimentary records of geomagnetic excursions., *Geophys. Res. Lett., 24* (6), 723-726, 1997.

The geomagnetic excursion recorded in the sediments of Lac St. Front (Massif Central, France) is characterized by shallow and negative inclinations followed by a younger steep inclination interval. In the corresponding interval of the nearby Lac du Bouchet only steep inclinations are found. Sedimentary records of the Mono Lake excursion show similar inclination patterns (Coe and Liddicoat, 1994). Similarities between synthetic records and the excursional records of Lac St. Front-Lac du Bouchet and Mono Lake suggest that the latter are more or less affected by vector addition of two non-antipodal directions.

Worm, H.-U.
A link between geomagnetic reversals and events and glaciations, *Earth Planet. Sci. Lett., 147* (1-4), 55-67, 1997.

The apparent duration of geomagnetic polarity events in Arctic Ocean sediments is much longer than in sediments from lower latitudes. Because sedimentation rates in the Arctic Ocean were increased during glaciations, the exaggerated proportion of reverse polarities in sediments from high latitudes suggests a link between glaciation and field reversals. All events and reversals younger than 2.6 Ma may have occurred during periods of global cooling or during cold stages, although some are still too poorly dated for a definite correlation. A mechanism for field reversals may be the acceleration of the Earth's rotation, caused by lowering of the sea level during glaciations. The short duration of events also implies that the geomagnetic field can reverse an order of magnitude faster than commonly assumed.

Magnetometry

Cotteverte, J.-C., *et al.*
Laser magnetometer measurement of the natural remanent magnetization of rocks, *Appl. Phys. Lett., 70* (23), 3075-3077, 1997.

A laser magnetometer permits the rapid measurement of rock magnetizations of less than 1 Am^{-1} in a laboratory without the need of any magnetic shielding or cryogenic facilities. Moreover, the laser magnetometer is experimentally shown to be able to measure the distribution of magnetization in spatially inhomogeneous samples.

Modeling and Theory

Balcells, L., O. Iglesias, and A. Labarta
Normalization factors for magnetic relaxation of small-particle systems in a nonzero magnetic field, *Physical Review B (Condensed Matter), 55* (14), 8940-8944, 1997.

For relaxation experiments in magnetic systems that can be characterized in terms of an energy barrier distribution, proper normalization of the relaxation data is needed whenever curves corresponding to different temperatures are to be compared. These normalization factors can be obtained from experimental data by using the $T\ln(t/\tau_0)$ scaling method without making any assumptions about the nature of the energy barrier distribution. The validity of the procedure is tested using a ferrofluid of Fe_3O_4 particles.

Hrouda, F., V. Jelinek, and K. Zapletal
Refined technique for susceptibility resolution into ferromagnetic and paramagnetic components based on susceptibility temperature-variation measurement, *Geophys. J. Int., 129* (3), 715-719, 1997.

The temperature variation of magnetic susceptibility can be used for the separation of ferromagnetic and paramagnetic susceptibility components. The method assumes a hyperbolic dependence of paramagnetic susceptibility and assumes that the ferromagnetic susceptibility varies linearly with temperature in the resolution interval, as indicated by the investigation of monomineralic ferromagnetic fractions.

Wright, T. M., W. Williams, and D. J. Dunlop
An improved algorithm for micromagnetics, *J. Geophys. Res., 102*

Abstracts *continued on page 4...*

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(B6), 12085-12094, 1997.

An improved micromagnetic model results in higher resolution by the use of a Fourier transform algorithm and by implementing the model on a parallel computer. The improved model enables equilibrium magnetization states to be predicted using a resolution of 64*64*64 subcubes to a grain in 16 hours of CPU time; this compares with a resolution of 12*12*12 in 24 hours of CPU time for previous models. High-resolution models allow the examination of multidomain states in materials such as magnetite and different sized grains or assemblages of interacting grains.

Mössbauer Spectroscopy

Betteridge, S., *et al.*
An investigation of the magnetic moment orientations in recording media using polarized Mössbauer spectroscopy, in *International Conference on the Applications of the Mössbauer Effect. ICAME-95*, edited by I. Ortalli, pp. 251-254, Soc. Italiana di Fisica, Bologna, Italy: 1996., Rimini, Italy, 10-16 Sept 1995.

The polarized source Mössbauer spectroscopy technique provides information on the in-plane angle of the magnetic moments in a sample, as well as on the out-of-plane angle which can also be obtained using conventional Mössbauer spectroscopy. Results show significant differences in the degree of alignment in various samples of both maghemite and iron metal recording tape.

Diamandescu, L., D. Mihaila-Tarabasanu, and S. Calogero
Mössbauer study of the solid phase transformation alpha -FeOOH to Fe_2O_3, *Materials Chemistry and Physics, 48* (2), 170-173, 1997.

The solid phase transformation alpha -FeOOH to alpha -Fe_2O_3 was investigated by means of Mössbauer transmission spectroscopy of powder samples previously annealed between 200 and 300° C. The reaction isotherms, rate constants and the activation energy of the process were determined.

Nakamura, S., *et al.*
Precise Mössbauer parameters of the high temperature phase of Fe_3O_4., *J. Phys. Soc. Jpn., 66* (2), 472-477, 1997.

Mössbauer parameters of the high temperature phase of Fe_3O_4 have been precisely determined as functions of temperature. The measurements were carried out by using a stoichiometric single crystal in applied magnetic field up to 15 kOe. The values of isotropic hyperfine fields and isomer shifts at room temperature for A- and B-sites agree with those of typical 3+ and 2.5+ Fe ions, respectively, while the values of e2qQ/2 and magnetic dipole field for B-site are too small for purely ionic state. The difference between the isomer shifts of A- and B-sites, however, becomes small above around 500-600 K. This corresponds to the contribution of A-site Fe to the electrical conduction above this temperature range. Both the absorption line width and e2qQ/2 value of the B-site spectrum increase noticeably below around 300 K. We consider that this feature indicate the change of the electronic states, or the formation of large polarons.

Vandenberghe, R. E., T. Becze-Deak, and E. De Grave
The Morin transition in hematite: another approach for the Mössbauer spectral analysis, in *International Conference on the Applications of the Mössbauer Effect. ICAME-95*, edited by I. Ortalli, pp. 207-210, Soc. Italiana di Fisica, Bologna, Italy: 1996., Rimini, Italy, 10-16 Sept 1995.

The Morin transition in an untreated and an annealed sample of Merck hematite has been studied using Mössbauer spectroscopy with ascending temperature scan. The spectra have been analysed according to a distribution of magnetic hyperfine fields linearly correlated with the quadrupole shift. From the analysis it turns out that in addition to the antiferromagnetic and weakly-ferromagnetic states more than one intermediate state is present instead of a gradually varying one as claimed before.

Paleoclimate and Proxy Records

Jelinowska, A., P. Tucholka, and K. Wieckowski
Magnetic properties of sediments in a Polish lake: evidence of a relation between the rock-magnetic record and environmental changes in Late Pleistocene and Holocene sediments, *Geophys. J. Int., 129* (3), 727-736, 1997.

In a Late Pleistocene and Holocene sedimentary sequence from Lake Bledowo (central Poland), the most important mineral magnetic change was authigenetic formation of ferrimagnetic greigite, Fe_3S_4, during the beginning of lacustrine conditions (±12 000 yr BP). Variations of ferrimagnetic iron oxide size are related to early diagenetic processes.

Yamazaki, T., and N. Ioka
Cautionary note on magnetic grain-size estimation using the ratio of ARM to magnetic susceptibility., *Geophys. Res. Lett., 24* (7), 751-754, 1997.

Rock-magnetic study of deep-sea surface sediments from the Pacific Ocean showed that ARM/χ depends strongly on χ , the concentration of magnetic minerals, and on the R value of Cisowski [1981], an index of the strength of magnetic interactions. This result demonstrates that ARM/χ can be influenced significantly by magnetic interactions in natural sediments. Previous interpretations of ARM/χ variations on magnetic grain-size without consideration of magnetic interactions may not be valid.

Paleointensity

Brassart, J., *et al.*
Absolute paleointensity between 60 and 400 ka from the Kohala Mountain (Hawaii), *Earth Planet. Sci. Lett., 148* (1-2), 141-156, 1997.

Successful paleointensity estimates obtained for eight lava flows are found to be in good agreement with previous absolute paleointensities obtained from other areas. The results are also consistent with the synthetic curve (Sint-200) of relative paleointensity obtained for the past 200 ka from deep-sea sediment cores. There is thus no reason to infer the presence of large non-dipole fields in the vicinity of Hawaii.

Lanci, L., and W. Lowrie
Magnetostratigraphic evidence that ‘tiny wiggles’ in the oceanic magnetic anomaly record represent geomagnetic paleointensity variations, *Earth Planet. Sci. Lett., 148* (3-4), 581-592, 1997.

A 40 m long core (the Massicore) drilled through Early Oligocene marlstone and limestone contains a complete magnetostratigraphy that matches the geomagnetic polarity sequence from chron C16n to chron C12r. The ratio NRM/ARM, used as a proxy for relative variation of paleomagnetic field intensity, has minimum values close to the reported positions of cryptochrons in the marine record. The Massicore results favour the interpretation that ‘tiny wiggles’ represent paleointensity variations of the geomagnetic field rather than unresolved short polarity chrons.

Thomas, D. N., T. C. Rolph, and D. F. Friel
Permo-Carboniferous (Kiaman) palaeointensity results from the western Bohemian Massif, Germany, *Geophys. J. Int., 130* (1), 257-265, 1997.

Thellier palaeointensity analyses were carried out on samples from three quartz porphyry intrusions dated at 280-275 Ma, in the main part of the Permo-Carboniferous (Kiaman) Reversed Superchron (P-CRS). Palaeointensity values range from 6.6 μT to 22.1 μT, with a mean value of 12.0±1.3 μT, which has a corresponding VDM value of $(3.0\pm1.2)*10^{22}$ A m^2. This suggests that the geomagnetic field strength recorded by the quartz porphyries is only 37% of the current value, supporting recent studies that report a field strength of 25-40% of the present-day value during the P-CRS.

Properties and Synthesis of Magnetic Minerals

Jonsson, T., *et al.*
Energy barrier distribution of a noninteracting nano-sized magnetic particle system, *J. Magn. Magn. Mater.*, *168* (3), 269-277, 1997.

AC-susceptibility and magnetic relaxation data are analysed to determine the distribution of energy barriers (E_b) of an assembly of small magnetic particles. The assembly, a dilute frozen ferrofluid, consists of spherical nano-sized maghemite (gamma -Fe_2O_3) particles with a median diameter of 70 Å. Assuming a direct proportionality between E_b and particle volume, the volume distribution is found to be described by a normalised gamma distribution. The system is not adequately described by the commonly adopted log-normal distribution function, which comparably should yield an excess amount of large particle sizes. From the analyses, accurate values of the Arrhenius law prefactor ($tau_0=4*10^{-10}$ s) and the magnetic anisotropy constant are derived.

Linderoth, S., J. Z. Jiang, and S. Mrup
Reversible alpha -Fe_2O_3 to Fe_3O_4 transformation during ball milling, *Mater. Sci. Forum*, *235-238*, 205-210, 1997.

The transformation of hematite to magnetite by high-energy ball milling in a sealed container has been studied by Mössbauer spectroscopy and X-ray diffraction. Mechanisms for this transformation are critically discussed. The dominant mechanism is concluded to be due to bond breaking during the high energy ball milling followed by release of the oxygen from the vial. The reverse transformation, magnetite to hematite, is demonstrated to occur by ball milling in air.

Park, J.-H., *et al.*
Single-particle gap above the Verwey transition in Fe_3O_4, *Physical Review B (Condensed Matter)*, *55* (19), 12813-12817, 1997.

The Verwey transition in magnetite, Fe_3O_4, has been studied using temperature-dependent high-resolution photoemission spectroscopy. On heating through the transition temperature T_V the band gap is not collapsed, but is merely reduced by 50 meV, showing that a metal-insulator transition does not occur. The change in the gap is perfectly consistent with the two orders of magnitude conductivity jump at T_V. Thus even above T_V short-range charge ordering rather than site equivalency dominates the single-particle excitations and the electrical properties.

Takacs, L., H. Dlamini, and H. Pollak
Effect of composition on the solid state reaction of magnetite with Al and Mg induced by mechanical alloying, in *International Conference on the Applications of the Mössbauer Effect. ICAME-95*, edited by I. Ortalli, pp. 149-152, Soc. Italiana di Fisica, Bologna, Italy: 1996., Rimini, Italy, 10-16 Sept 1995.

The reduction of magnetite by Al and Mg has been induced by mechanical alloying. Milling initiates self propagating thermal “explosion” in these systems after some incubation period. Mössbauer spectroscopy and X-ray diffraction have been used to investigate the reaction products. The shortest incubation time before explosion was measured close to the stoichiometric composition for the reduction of magnetite by Al but far from stoichiometry when Mg was used.

Tanaka, K., *et al.*
Preparation and magnetic properties of glass-ceramics containing magnetite microcrystals in calcium iron aluminoborate system, *J. Magn. Magn. Mater.*, *168* (1-2), 203-212, 1997.

Calcium iron aluminoborate glass with Al_2O_3-rich composition is suitable for the preparation of magnetite-based glass-ceramics with controlled magnetic properties. The crystallite size of magnetite is determined by Al_2O_3 content. The lattice constant of the magnetite microcrystals increases with crystallite size. These experimental facts suggest that an aluminum oxide cluster is the nucleus for the magnetite. The coercive force increases with the crystallite size of magnetite, reaching a maximum value, 640 Oe, when the crystallite size is 23 nm.

Remanence Acquisition and Alteration

Kirker, A. I., and E. McCelland
Deflection of magnetic remanence during progressive cleavage development in the Pembrokeshire Old Red Sandstone, *Geophys. J. Int.*, *130* (1), 240-250, 1997.

Remanence components within kink bands are deflected by an amount related to the amount of kinking. The maximum principal susceptibility axis lies in the bedding plane and is deflected by the same amount or slightly more than the bedding. In contrast, the degree of remanence deflection is systematically less than the relative dip of the kink. These observations indicate that: (1) the remanence is syn-folding and has subsequently been rotated within the kink bands, mostly like a passive marker; (2) oversteepening due to pressure solution provides only a small contribution to the excess of the kink dip over the remanence deflection.

Kodama, K. P.
A successful rock magnetic technique for correcting paleomagnetic inclination shallowing: case study of the Nacimiento Formation, New Mexico., *J. Geophys. Res.*, *102* (B3), 5193-5205, 1997.

An inclination shallowing correction technique assumes that shallowing is directly related to changes in remanence anisotropy. The remanence anisotropy is also a function of the magnetic anisotropy of the individual magnetic grains. The Nacimiento Formation has a primary remanence with a well-constrained age, magnetic overprints are minimal, and inclination is shallow by 7° to 8°. The characteristic remanence from 20 Nacimiento sites was corrected using the anisotropy of anhysteretic remanence. Two techniques resulted in similar values for individual particle anisotropy and similar inclination shallowing corrections. The inclination-corrected formation mean direction was indistinguishable from the direction predicted by North America’s Paleocene paleopole.

Snowball, I. F.
Gyroremanent magnetization and the magnetic properties of greigite-bearing clays in southern Sweden, *Geophys. J. Int.*, *129* (3), 624-636, 1997.

Single-domain (SD) greigite particles carries a stable chemical remanent magnetization (CRM), which coexists with a detrital remanent magnetization (DRM) carried by magnetite, and also acquires a gyroremanent magnetization (GRM) during alternating-field (AF) demagnetization. The low-coercivity DRM carried by magnetite was mistaken for a ‘viscous’ component in earlier paleomagnetic studies, and the former debate about the record of the Gothenburg Flip may have been based on erroneous palaeomagnetic interpretations or non-reproducible results.

Xu, W., *et al.*
Electron microscopy of iron oxides and implications for the origin of magnetizations and rock magnetic properties of Banded Series rocks of the Stillwater Complex, Montana, *J. Geophys. Res.*, *102* (B6), 12139-12157, 1997.

The origins of multiple magnetizations of the Archean Stillwater Complex have been investigated through scanning electron microscopy and scanning transmission electron microscopy observations of mineralogical relations, using representative samples from nine sites in mafic Banded Series rocks. On the basis of directional grouping and demagnetization behavior, three magnetizations have been recognized. The natural remanent magnetization is typically dominated by only one of these magnetizations and multicomponent behavior in individual specimens is rare.

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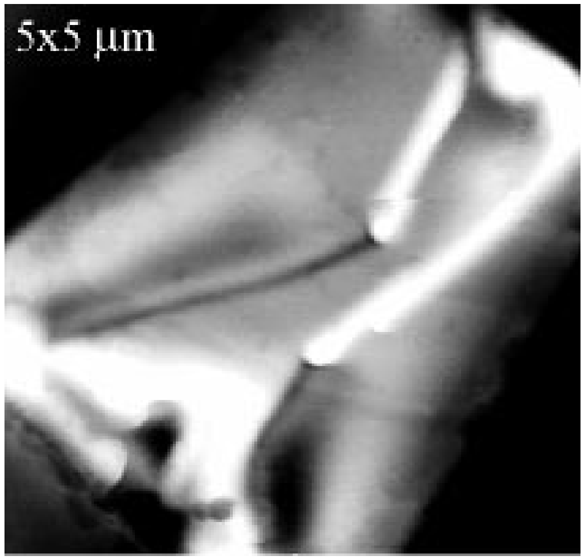

Figure 1. MFM image of subdivided domain walls in a magnetite grain. The black and white segments within the walls correspond to opposite polarity Bloch wall segments. The walls zigzag at the location of Bloch lines with zigzag angles of 20°-40°.

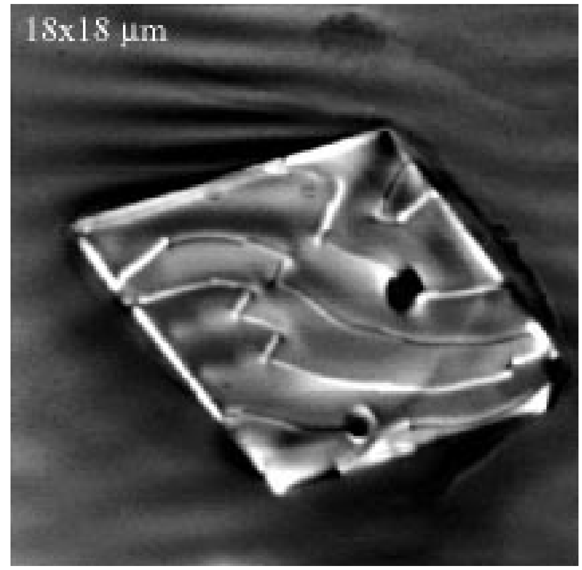

Figure 2. MFM image of step-like domain walls in a magnetite grain. We explained these "strange" step-like walls using a model in which we assumed that domain magnetization is inclined to the grain surface.

combined volume magnetostatic interaction between all grain surfaces and magnetocrystalline anisotropy. Finally, commonly observed open-flux features within the interior of grains or along grain edges terminating planar domains are inconsistent with the prediction of edge closure domain formation based on recent 2-D micromagnetic models. Our observations suggest that 3-D micromagnetic models are required to model results even for grains larger than 1 μm.

A combined magnetooptic-magnetic force microscope (with Roger Proksch).

We have combined a Magnetic Force/ Atomic Force Microscope (MFM/AFM) with a Magneto-optic (MO) microscope. This instrument combines the high spatial resolution of the MFM/AFM and its capability to correlate magnetic structure with the structure of the sample surface with the real-time imaging capabilities and large field of view of the MO microscope. Our MO/MFM setup is based on the Nanoscope III Multimode™ MFM/AFM (Digital Instruments, Santa Barbara, CA). Currently, the spatial resolution of the MO microscope is about 3 μm and polarization sensitivity is on the order of 0.5 degrees. Using this instrument, we observed domain structures in Co/Pd multilayer films. We found that in a film with 20 Co/Pd layer pairs and 16 nm total thickness, nucleation of domains during sample remagnetization occurs repeatedly in the same points, and that displacement of domain walls is unidirectional (Fig. 3). The high topographic resolution of the AFM allowed us to show that domains nucleate at small defects on the sample surface. The depth of the defects is 1-2 nm, they are 20-30 nm

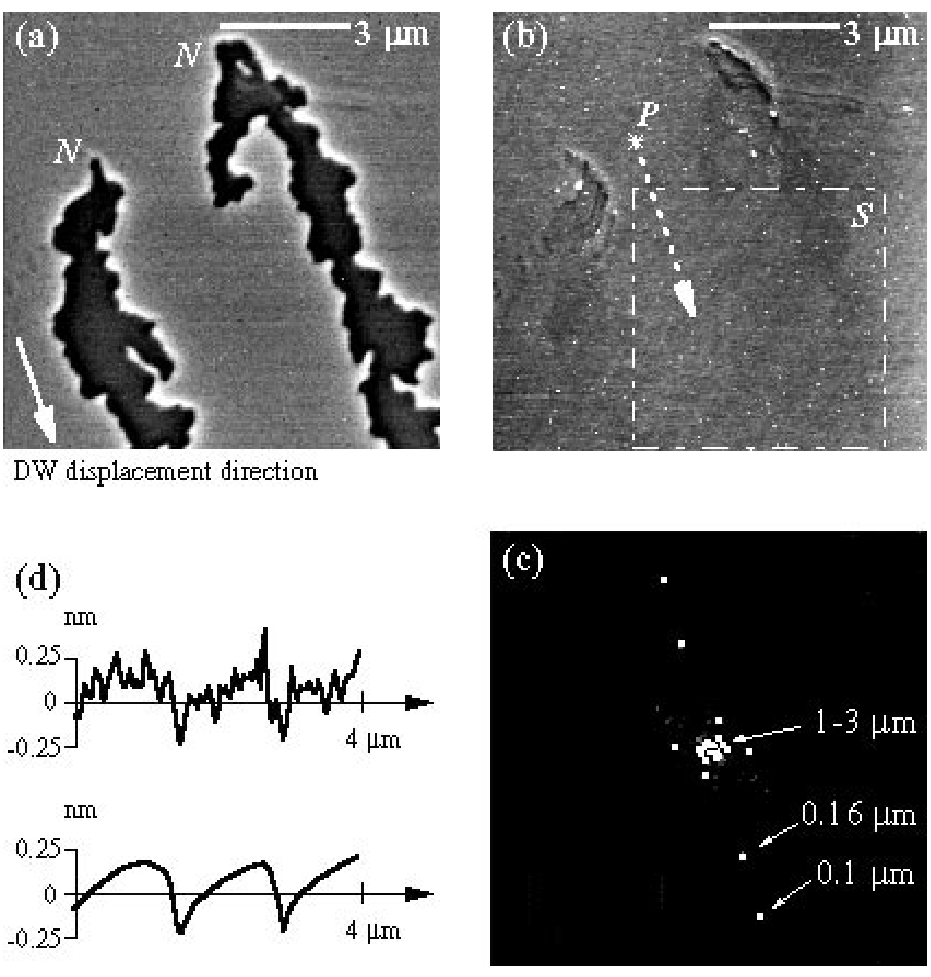

Figure 3. (a) MFM image of the domains in 16 nm thick Co/Pd multilayer film; (b) AFM image of the same area of the film surface; (c) 2D Fourier spectrum of the surface area S *outlined in (b); (d) AFM profile of the surface and smoothened AFM profile taken along the line* P *shown in (b). It is seen in the images (a) and (b) that domains were nucleated at small elongated defects on the film surface (nucleation points are marked with* N*). The 2D Fourier spectrum (c) indicates that the surface has an anisotropic structure. The points in the spectrum corresponding to the short wavelength are located on the line which is parallel to the direction of the displacement of domain walls. The AFM profile of the surface (d) shows that the local slope of the surface in the direction of domain wall displacement is lower than in the opposite direction.*

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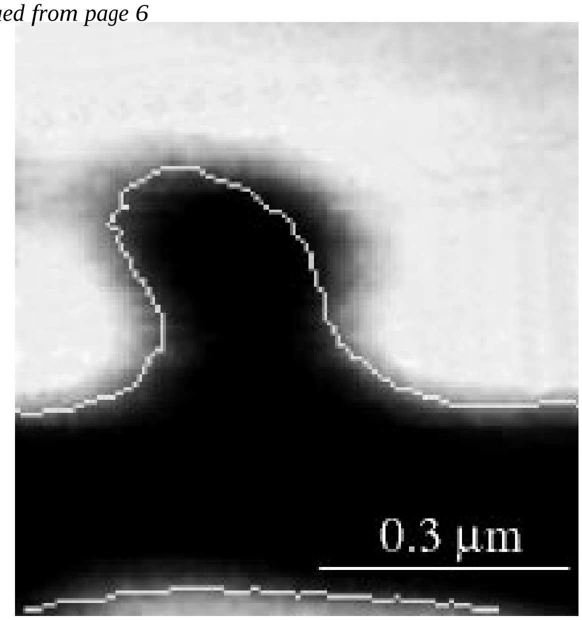

Figure 4. MFM image of a domain wall in a TbFe film in an external field of 200 Oe showing the reversible displacement of the DW segment. The curvature of the segment of the domain wall changed in the field. The white line shows the position of the domain wall without the external field. The size of the image is 0.5x0.5 mm.

wide and up to 500 nm long. The unidirectional displacement of the domain walls was found to correlate with the anisotropic structure of the sample surface.

Domain wall displacements in amorphous films and multilayers.

The magnetic force microscope (MFM) was used to study the displacement of domain walls (DW) in amorphous TbFe alloy films and Co/Pd multilayer films with high spatial resolution. The reversible bending of domain wall segments pinned to defects and irreversible, jump-like displacement of domain wall segments were imaged with the MFM in an applied magnetic field. The maximum reversible displacement of domain walls was 50-100 nm and the length of the segments which reversibly curved in the field was about 150 nm (Fig. 4). Measurement of the change in radius of curvature of a DW segment in response to an applied field allowed estimation of the DW energy density and self-demagnetizing field of the film acting on the DW. The DW energy density for the TbFe films was about 1 erg/cm^2. It was shown that the self-demagnetizing field acting on a domain wall depends on the domain structure surrounding the studied DW segment. For instance, for a film with saturation magnetization 100 G and thickness 80 nm which exhibited a maze-like domain structure, the demagnetizing field varied from 100 G in the center of a maze-like domain to 400 G near the edge of a domain. The irreversible displacement of a DW was not a continuous process. The 200 - 400 nm long DW segments exhibited jump-like motion over distances of 100-150 nm.

Experimental Micromagnetism of Magnetite and Maghemite (with Bruce Moskowitz and George Skidmore (Magnetic Microscopy Center))(in progress).

We are studying the interrelation between micromagnetic structure and macroscopic magnetic behavior in magnetite, maghemite, and phase coupled particles using magnetic force microscopy and magnetic property measurements. Crystallographically oriented arrays of magnetic oxide particles to be studied with the MFM are produced using molecular beam epitaxy and photolithography. These microfabrication techniques can synthesize arrays of single crystalline, single phase and phase coupled particles with good control over shape, size, and crystallographic orientations. In this way, a systematic study of intrinsic domain patterns, domain wall structures, and other micromagnetic features as a function of particle size, crystallographic orientation, and exchange coupling (for phase coupled particles) within the pseudo-single-domain size range (for magnetite 0.5 - 10 µm) will be accomplished. Complementary magnetic property measurements will be made to reveal how micromagnetic structures identified with the MFM are manifested in macroscopic magnetic properties. The goal of the project is to improve the knowledge of magnetic behavior of small magnetic particles similar to those that are commonly found in nature and are the main carriers of magnetic remanence in rocks.

At Seagate I will take part in the development of advanced magneto-resistive heads (giant magneto-resistance (GMR) heads) for hard drives. So I will still be working in magnetism, but more applied magnetism than I did at the IRM. I will have to prepare GMR thin film systems and study the remagnetization processes in these samples. So I hope that I will have enough formal reasons (I will definitely have a lot of informal reasons) to come back to the IRM as a short term local visitor.

Matuyama, Motonori

b. Oct 25, 1884, Uyeda
d. Jan 27, 1958, Yamaguchi

Matuyama's career encompassed a wide range of geophysical research, including early papers on seismology and glacial ice deformation. His most influential work, however, was related to the Earth's gravity field and to the natural remanence of rocks. He is credited with being the first to suggest that minute features in the gravity field could reveal subsurface structure. His landmark 1929 paper relating remanent polarity and age of basalts from Japan, China and Korea, provided crucial evidence for the reality of field reversals, and a foundation for modern magnetostratigraphy.

Fall & Winter Visiting Fellows

The Visiting Fellow proposals for fall and winter (northern hemisphere), 1997-1998, encompassed a wide variety of applications. Based on evaluations by the IRM's Review and Advisory Committee (RAC), the following applicants and their respective projects have been selected:

Jennifer Boryta, *Department of Hydrology, University of Arizona*: Identification of titanomagnetite in sandstones

R. Douglas Elmore, *School of Geology & Geophysics, University of Oklahoma*: Rock magnetic characterization of CRMs

Zhichun Jing, *Archeometry Laboratory, University of Minnesota - Duluth*: Environmental magnetic studies of archeological sediments from North China Plain

Juan Cruz Larrasoana, *Laboratory of Paleomagnetism, Institute of Earth Sciences Jaume Almera*: Rock magnetic study of marine Eocene marls from the southwestern Pyrenees, Spain

Neil Linford, *Ancient Monuments Laboratory, English Heritage*: Characterizing the magnetic mineralogy and grain size distribution of archeological sediments

Suzanne McEnroe, *Norwegian Geological Survey, Trondheim*, and Laurie Brown, *Department of Geosciences, University of Massachussetts-Amherst*: Rock magnetic studies in support of aeromagnetic anomaly interpretations

Michael Urbat, *Paleomagnetic Laboratory Fort Hoofdijk, University of Utrecht*: Untangling diagenetic effects on the NRM in marine sediments

IRM Welcomes Post-Docs

The folks at *IRM* are pleased to welcome David Williamson back for a second year of research funded by the French Centre National de la Récherche Scientifique (CNRS), and to extend a warm welcome to new Post-doctoral Fellow Pieter Vlag, who finished his dissertation at the Université d'Aix-Marseille, on the paleomagnetism and rock magnetism of Lac St-Front. Look for more information about their research in a future *Quarterly*!

...Visiting Fellow Reports

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The results I have obtained are however somewhat puzzling. With a very few exceptions, remanence is carried by a near magnetite phase with Curie points around 580°C, and pronounced Verwey transition in the temperature range 100-120 K. All samples yielded room temperature hysteresis parameters compatible with the presence of predominantly PSD grains. At the same time, only for a part of samples with poor behavior in the Thellier experiments does the coercive force show an irreversible behavior at moderate temperatures, like that observed previously on the Lesotho basalt. For the others, with equally poor Thellier results, the variation of the coercive force, as well as of the other hysteresis parameters, is perfectly reversible, at least up to 450°C. Particularly striking are the results obtained on Etna samples: no considerable difference was observed in the high-temperature hysteresis behavior of samples yielding correct and wrong (up to 50 per cent too high) paleointensities respectively, and for both groups of samples all hysteresis parameters appear to vary almost reversibly with temperature. These results suggest that provoked by heating transformation of domain structure is but one of several possible mechanisms causing failure of Thellier experiments, whilst other mechanisms exist that do not manifest themselves in the irreversible evolution of hysteresis parameters with temperature.

I would like to thank the IRM staff for their helpfulness and hospitality. I appreciate the courtesy of Annick Chauvin, Peter Riisager, Mireille Perrin, Manuel Calvo and Michel Prévot who kindly donated me the samples used in this study.

Collectors Series #6. Clip and save! Collect them all!

Photo courtesy of Prof. Masayuki Torii

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

The *IRM* staff consists of Subir Banerjee, Professor/Director; Bruce Moskowitz, Associate Professor/Associate Director; Jim Marvin, Senior Scientist; Mike Jackson, Senior Scientist/Facilities Manager, and Peat Solheid, Scientist.

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

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