Inside...

# The IRM Quarterly

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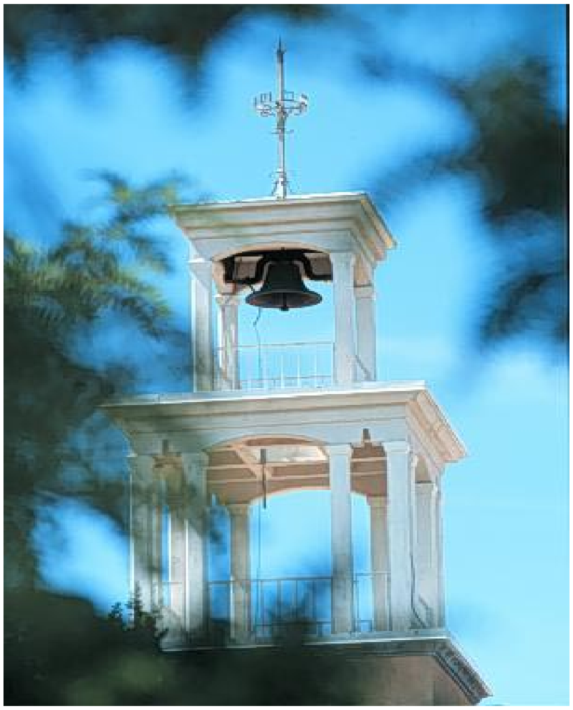

http://www.sjcsf.edu/

*The bell tower at St. John's College in Santa Fe, NM, venue of the IRM-organized Santa Fe Conference on Rock Magnetism*

## Santa Fe V

**Mike Jackson**
*IRM*

*With support from the Earth Sciences Division of the National Science Foundation (NSF), the Fifth Biannual Santa Fe Conference on Rock Magnetism (Santa Fe V) was held at St. John's College, July 20-23, 2000, with thirty-nine participants (including ten students and three invited keynote speakers) from six countries.*

In London in the year 1600, Wm Gilbert published *De Magnete* and Wm Shakespeare published *A Midsummer Night's Dream*. At about the same time, the town of Santa Fe was established. This summer, a 400th anniversary reunion of sorts took place at St John's College, when the Santa Fe Shakespeare Company opened their production of *AMND* during the weekend of the Conference on Rock Magnetism. And despite some moments of chaos for Puck, the foolish mortals, and the rock magnetists alike, all ended well.

The conference was centered on twin themes: (i) The current state of the art in basic rock magnetism (theory and experiment) and (ii) Problems and opportunities in applying the newer theories and techniques to "real-life" problems, such as recognition of nanoscale biomineralized particles and their contributions to sediment magnetism. Following in the tradition of the previous Santa Fe conferences, the format was informal, discussion-oriented, and future-oriented.

Three keynote sessions, featuring invited speakers with both specialized and interdisciplinary expertise, introduced valuable new nonmagnetic analytical methods, and highlighted avenues for future interdisciplinary research. **Rob Van der Voo** (*University of Michigan*) illustrated an integrated approach to studying alteration, using both magnetic techniques and analytical microscopy. Drawing examples from an extensive body of research carried out in collaboration with mineralogist **Donald Peacor** (*University of Michigan*), Van der Voo showed how scanning and transmission electron microscopy have illuminated the diagenetic and authigenic magnetic phases in remagnetized carbonates, and how new techniques such as higher-order Laue Zone (HOLZ) diffraction are providing insights into the processes of oxidation and alteration of seafloor basalts. **Glenn Waychunas** (LBNL, Berkeley) showcased the latest mineral physics tools using synchrotron radiation sources for microscopy and spectroscopy, and their potential for studying the target minerals of rock magnetists. The tremendous radiation fluxes available with such sources allow not only high sensitivity and speed, but also optimization for a variety of targets, through wavelength filtering, beam collimation, etc. The rapidly-evolving field of biogeochemistry was brought into the discussion by **Susan Brantley** (*Penn State University*), who described experimental and empirical investigations of biogeochemical weathering of Fe-bearing minerals, a topic of burgeoning importance for both paleomagnetists and rock magnetists. Bacteria have been found to accelerate silicate dissolution by a factor of ten in laboratory experiments, in part through the action of extracellular organic molecules called siderophores, which scavenge $Fe^{3+}$ for the cells.

The keynote sessions were each followed and complemented by working/technical sessions, which were introduced in 15-minute talks on current "burning" questions by invited lead speakers. After these lead-off talks, a panel of three or four served both for commentary and as a moderating influence on questions, comments and volunteered contributions from the floor, lasting two hours.

The session on basic rock magnetism was coordinated and chaired by **Susan Halgedahl** (*University of Utah*). The opening presentations explored the roles of detrital input, diagenetic alteration, and biomineralization in sedimentary magnetism. **Alexei Smirnov** (*University of Rochester*) documented rockmagnetic evidence for a progressive alteration sequence, in which bacterial magnetosomes are first oxidized in the suboxic zone, then de-maghemitized at the iron-redox boundary, and ultimately consumed by reduction diagenesis. **Ken Kodama** (*Lehigh University*) presented a thoughtful and thought-provoking large-scale view of the many interwoven processes that impact sedimentary magnetic records. These were followed by a set of talks on the magnetic behavior of mineralogical and grain-size mixtures, based on controlled experiments and theory, and implications for the interpretation of data from natural samples. **Özden Özdemir** (*University of Toronto*) described the behavior of magnetite on passing through the Verwey transition, and dehydration of goethite on heating. **David Dunlop** (*University of Toronto*) brought up a variety of interesting points, including the "10-nm mystery:" why do all published hysteresis data for natural SP-SSD mixtures follow the theoretical trend for SP particles of 10-nm size? Halgedahl and **David Handwerger** (*University of Utah*) showed how numerical "mixing" of hysteresis data for glass-ceramic magnetite samples produces different trends in $H_C$ and $H_{CR}$ than those found for discrete sizes. Finally, **Benjamin Weiss** (*Caltech*) highlighted developments in micrometer-scale SQUID magnetic mapping, which currently attains a spatial resolution of 250 $\mu$m and an astounding sensitivity of $10^{-16}$ $Am^2$ for room-temperature samples.

**John Geissman** (*University of New Mexico*) organized and ran the session dealing with applied rock magnetism. The mechanisms and timing of remanence acquisition, critical issues in all paleomagnetic studies, were discussed for redbeds and for remagnetized carbonate rocks by Geissman and by **Arlo Weil** (*University*

**Santa Fe**
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# Visiting Fellows' Reports

**Suzanne A. McEnroe**
Geol. Survey of Norway
*Suzanne.McEnroe@ngu.no*
**and Laurie Brown**
UMass-Amherst
*lbrown@eclogite.geo.umass.edu*

## Rock-Magnetic Studies in Support of Aeromagnetic Anomaly Interpretation

Aeromagnetic surveys have become an important tool for exploration of mineral resources as well as for regional geologic and planetary mapping programs. With the use of new and more sensitive magnetometers, and satellite navigation to make more precise magnetic maps, still greater understanding of rock-magnetic properties is needed. Conventional interpretation of the magnetic signature of crustal rocks has been to attribute magnetic anomalies solely to magnetite. Fundamental to this assumption was that induced magnetization would dominate over remanent magnetization, unless the magnetite is in the SD- state. Nevertheless, examples are encountered, where magnetic susceptibility was lower than would be expected for coarse-grained magnetite, and where the rock body could be shown to contain a large NRM. More importantly, in cases of negative anomalies where remanence contributes or dominates the magnetic response of the rock, detailed information about concentrations, compositions, and microstructures of magnetic minerals is needed. At the IRM we worked on two projects based on continental rocks thought to have been adjacent in the Middle Proterozoic, from the Rogaland Igneous Province of Southern Norway, and from the Adirondack Mts, in upstate New York.

The Rogaland rocks are from the anorthosite-norite suite, which contains historic, and presently mined hemoilmenite ore deposits that currently produce 15% of the world's titanium. A high-resolution aeromagnetic map over the area shows local negative anomalies of up to 16,000nT. The aim of this research was to increase our fundamental understanding of the magnetic properties of hemoilmenite. We attempted to quantify the contribution of hemoilmenite to the magnetic response of the rocks. These samples have high NRMs, Q values and moderate to strong susceptibilities. Mineral chemistry and petrography of the hemoilmenite samples (McEnroe et al., 2000) indicated that magnetite was absent, or in some norite samples, present in minor quantities. Detailed microprobe analyses and imaging of hemoilmenite ore samples did not indicate any fine-scale magnetite intergrowths with hemoilmenite. Low-temperature remanence measurements on "pure" hemoilmenite rocks commonly show low temperature Néel transitions for ilmenite, a Morin transition for hematite, but very rarely Verwey transitions for magnetite. In the ore bodies the very large remanence values controlling the magnetic response of the rocks are attributed to the hemoilmenite. Our best estimate of the composition of the hematite lamellae is from thermal demagnetization and Curie temperature determinations that suggest a composition of hematite$_{88}$. It is difficult to explain the high NRM measurements with only a hemoilmenite phase, because the estimated compositions of the hematite lamellae are in the disordered AF region of the hematite-ilmenite phase diagram. We are further exploring the role of microstructures in the lamellae that could enhance the NRM and coercivity of the samples.

A second group of samples we worked on were hematite-bearing sillimanite microcline granitic gneisses of Grenville age (ca. 1.0 b.y.) from the Russell Belt in the western Adirondack Mountains. These rocks were previously studied by Balsley and Buddington in the 1950s, who related the large negative anomalies over them to remanent magnetization. The samples have steep negative inclinations, strong remanence (up to 5 A/m) and low susceptibilities, resulting in large Q values. Rock-magnetic studies were designed to investigate the titanohematite seen in polished sections and to probe for any possible magnetite present. Hysteresis loops on numerous samples showed a wide range of shapes, from "wasp-waisted" to "pot-bellied" to "hummingbird" (Figure 1), but all indicated the presence of a hematite-rich phase, with only small, if any, amounts of magnetite. Several temperature-dependent hysteresis runs were done at 25ºC intervals up to 675ºC. Samples with hummingbird shapes kept this shape with increasing temperature, only decreasing in magnitude. Wasp-waisted loops became less restricted at 500ºC and reverted to the hummingbird shape by 600ºC, clearly indicating the presence of a small amount of magnetite. From these and other data we collected it is evident that the large negative anomalies in the Russell area are produced by strong negative remanence directions held in metamorphic titanohematite. These results are already published in McEnroe and Brown, JGR, July 2000 where more details are shown.

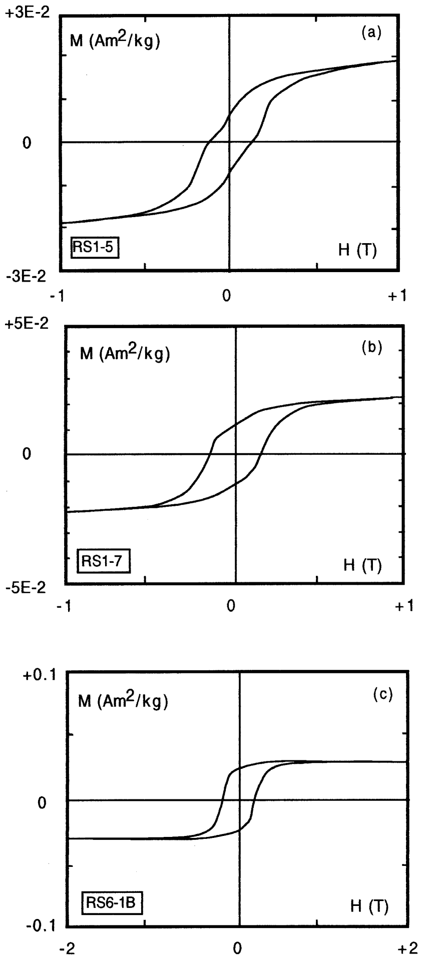

***Figure 1**. Three representative hysteresis loops from the Russell Belt rocks. (a) Wasp-waisted samples with both titanohematite and magnetite, (b) Pot-bellied and (c) Hummingbird shapes where titanohematite is the only oxide present.*

*References*:

McEnroe, S. A. and Brown, L.L., (2000) A closer look at remanence dominated aeromagnetic anomalies: Rock-magnetic properties and magnetic mineralogy of the Russell Belt microcline-sillmanite gneiss, northwest Adirondack Mountains, New York, *JGR, v.105,* 16,437-16,456.

McEnroe, S. A., Robinson, Peter and Panish, P. T., (2000) Chemical and petrographic characterization of ilmenite and magnetite oxide-rich cumulates of the Sokndal region, Rogaland, Norway. *Norwegian Geological Survey Bulletin, 435*, p. 37-44.

**VF Reports**
*continued on page 6...*

**Paul Langevin**, par Picasso (vers 1945).

*From* Langevin 1872-1946: Science et Vigilence, *by Bernadette Bensaude-Vincent, Editions Belin, 1987.*

# 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 5200 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the* IRM Quarterly *are always welcome.*

## Anisotropy

Owens, W. H., 2000, **Error estimates in the measurement of anisotropic magnetic susceptibility**: *Geophysical Journal International, v. 142*, no. 2, p. 516-26.
Hext's (1963) first-order analysis for error estimation in measurements of second-rank tensors is applied to the class of instruments that measures differences in magnetic susceptibility. Error estimates are derived for a set of anisotropy parameters, $K_{mean}$, H and μ. The applicability of a first-order analysis is discussed and illustrated by simulation studies.

Owens, W. H., 2000, **Statistical applications to second-rank tensors in magnetic fabric analysis**: *Geophysical Journal International, v. 142*, no. 2, p. 527-38.
Hext's theory allows the rotatability of the measuring scheme to be assessed (rotatability describes the degree of independence of error variance on the orientation of the fabric axes relative to the measurement reference frame). An alternative, more nearly rotatable, design is suggested. Normalized descriptions are used almost universally, but may not always be appropriate: the distinction is formalized here for a simple case. The directional covariance, a 3D projection of the 6D (or 5D, if normalized) covariance matrix, which has an analogue in the assessment of the rotatability of measurement schemes, is suggested as a possible means for describing and visualizing populations of magnetic fabrics.

Rosenbaum, J., Reynolds, R., Smoot, J., and Meyer, R., 2000, **Anisotropy of magnetic susceptibility as a tool for recognizing core deformation: reevaluation of the paleomagnetic record of Pleistocene sediments from drill hole OL-92, Owens Lake, California**: *Earth and Planetary Science Letters, v. 178*, no. 3, p. 415-24.
Intervals of high directional dispersion in this core were previously interpreted to record geomagnetic excursions. New AMS data and analyses of sedimentary structures carried out for the upper 120 m demonstrate that most of the paleomagnetic features previously interpreted as excursions are more likely the result of core deformation.

## Anomaly Sources

Airo, M. L., 1999, **Magnetic and compositional variations in Proterozoic mafic dykes in Finland, northern Fennoscandian shield**: *Canadian Journal of Earth Sciences, v. 36*, no. 6, p. 891-903.
The more magnesian dykes are highly magnetic and associated with distinctive aeromagnetic anomalies; the tholeiitic dykes are weakly magnetic. Those iron-bearing silicates which participate in the reactions where titanomagnetites are formed or destroyed contain ferric iron in their crystal structures. The early crystallization of hydrous mafic silicates, biotite and amphibole, versus the anhydrous mafic silicate, clinopyroxene (augite), seems to be of key importance to formation of titanomagnetites.

Kletetschka, G., Wasilewski, P. J., and Taylor, P. T., 2000, **Hematite vs. magnetite as the signature for planetary magnetic anomalies?**: *Physics of the Earth and Planetary Interiors, v. 119*, no. 3, p. 259-67.
TRM acquisition curves of magnetite and hematite show that multidomain hematite approaches TRM saturation (0.3-0.4 $Am^2/kg$) in fields as low as 0.1 mT. However, multidomain magnetite reaches only a few percent of its TRM saturation in a field of 0.1 mT (0.02-0.05 $Am^2/kg$). These results suggest that multidomain hematite may play an important role in remanence-dominated magnetic anomalies on Mars and Earth.

McEnroe, S. A., and Brown, L. L., 2000, **A closer look at remanence-dominated aeromagnetic anomalies: rock magnetic properties and magnetic mineralogy of the Russell Belt microcline-sillimanite gneiss, northwest Adirondack Mountains, New York**: *Journal of Geophysical Research, v. 105*, no. B7, p. 16437-56.
These gneisses contain up to 3% oxide, predominantly metamorphic titanohematite, with multiple generations of ilmenite, pyrophanite, rutile, and spinel exsolution lamellae. Microprobe analyses confirm titanohematite compositions ranging from 72 to 97% $Fe_2O_3$, with $hematite_{83}$ being most typical. The ubiquitous presence of titanohematite, and the rare occurrence of magnetite, is supported by thermal and alternating field demagnetization studies, high-temperature hysteresis studies, and low-temperature remanence measurements. Numerous crustal granulites have titanohematite as part of the oxide assemblage, and this may contribute a strong remanent component to what have previously been considered to be solely induced anomalies.

## Data Analysis

Symons, D. T. A., and Cioppa, M. T., 2000, **Crossover plots: a useful method for plotting SIRM data in paleomagnetism**: *Geophysical Research Letters, v. 27*, no. 12, p. 1779-82.
The effective grain-size of magnetic minerals, and therefore domain type, controls the SIRM acquisition and subsequent demagnetization response. This paper presents templates of "crossover" plots for magnetite, pyrrhotite, hematite and goethite, onto which sample data can be plotted for conventional paleomagnetic specimens to characterize their magnetic mineralogy and effective grain-size.

## Diagenesis and Magnetic Mineral Alteration

Smirnov, A. V., and Tarduno, J. A., 2000, **Low-temperature magnetic properties of pelagic sediments (Ocean Drilling Program Site 805C): tracers of maghemitization and magnetic mineral reduction**: *Journal of Geophysical Research, v. 105*, no. B7, p. 16457-71.
No Verwey transition was observed in samples shallower than the iron redox boundary, but below the boundary the transition is visible for all samples studied. We interpret this in terms of low-temperature oxidation of primary

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magnetite and the subsequent dissolution of maghemite coatings below the iron redox boundary. Field-cooled and zero-field-cooled thermal demagnetization curves of all samples diverge for the entire temperature range measured; this may be caused by the low-temperature stabilization of spontaneous magnetization vectors along with exchange interaction in the magnetite-maghemite system.

## Environmental Magnetism and Paleoclimate

Houyuan, L., Tungsheng, L., Zhaoyan, G., Liu, B., Liping, Z., Jiamao, H., and Naiqin, W., 2000, **Effect of burning C3 and C4 plants on the magnetic susceptibility signal in soils**: *Geophysical Research Letters, v. 27*, no. 13, p. 2013-16.
Burning of C3 and especially C4 plants can enhance susceptibility ($\chi$) of modern soils. The average $\chi$ of C4 plant ashes collected from natural fires is $532*10^{-8}$ $m^3$ $kg^{-1}$, much higher than the average $\chi$ of $120*10^{-8}$ $m^3$ $kg^{-1}$ of C3 plant ashes. The $Fe_2O_3$ concentration in C4 plants is two to four times higher than that in C3 plants. One burning of a grassland mainly consisting of C4 plants can enhance $\chi$ of the surface soil up to 30-40%.

Vidic, N. J., TenPas, J. D., Verosub, K. L., and Singer, M. J., 2000, **Separation of pedogenic and lithogenic components of magnetic susceptibility in the Chinese loess/palaeosol sequence as determined by the CBD procedure and a mixing analysis**: *Geophysical Journal International, v. 142*, no. 2, p. 551-62.
The CBD procedure underestimates the lithogenic component, moderately in loess layers but almost negligibly in palaeosols. The mixing analysis overestimates the lithogenic component. Both methods can be adjusted to yield better estimates of both components. A single estimate of the average lithogenic susceptibility is not an accurate basis for adjusting the total susceptibility. A long-term decline in lithogenic susceptibility with depth in the section suggests more intense or prolonged periods of weathering associated with the formation of the older palaeosols.

Zhengtang, G., Biscaye, P., Lanying, W., Xihui, C., Shuzhen, P., and Tungsheng, L., 2000, **Summer monsoon variations over the last 1.2 Ma from the weathering of loess-soil sequences in China**: *Geophysical Research Letters, v. 27*, no. 12, p. 1751-4.
The ratio of CBD-extractable free $Fe_2O_3$ (a measure of iron liberated by chemical weathering), to total $Fe_2O_3$ available provides a quantitative measurement of the degree of pedogenesis in the Loess Plateau. The new proxy has been used to document a series of summer monsoon changes of global significance, which are not necessarily recorded by magnetic susceptibility.

## Extraterrestrial Magnetism

Torrent, J., and Barron, V., 2000, **Key role of phosphorus in the formation of the iron oxides in Mars soils?**: *Icarus, v. 145*, no. 2, p. 645-7.
Abundance of phosphorus (P) in martian rocks might be crucial in the formation of iron oxides, hematite ($\alpha$-$Fe_2O3$) and maghemite ($\gamma$-$Fe_2O3$) in martian soils. This hypothesis is supported by laboratory experiments showing that the thermal transformation of P-doped lepidocrocites and magnetites results in hematite and maghemite with magnetic and spectral properties consistent with those of martian soils.

## Magnetic Microscopy and Spectroscopy

Mizoguchi, M., 2000, **Nuclear magnetic resonance study of $Fe^{3+}$ ions on A-sites of $Fe_3O_4$ in the low-temperature phase**: *Journal of the Physical Society of Japan, v. 69*, no. 5, p. 1298-301.
The hyperfine field spectra of $Fe^{3+}$ ions on A-sites have been investigated at 4.2 K by nuclear magnetic resonance. From the spectra of a single-domain specimen in an external magnetic field, it has been confirmed that at least eight inequivalent A-sites exist. The directions of the principal and subprincipal axes of the anisotropic hyperfine field were determined for five sites, and one of the sites has mirror symmetry with reference to the ac-plane. This cannot be explained by the symmetry groups Cc and c-glide which have been proposed by diffraction studies. For the sites with a lower hyperfine magnetic field (≤508.5 kOe), the anisotropic part of the field is appreciably larger than the dipole field from the nearest-neighbour Fe ions on the B-sites. This result suggests a delocalization of the electron cloud of neighboring B-sites.

Rudee, M. L., Margulies, D. T., and Berkowitz, A. E., 1997, **Antiphase domain boundaries in thin films of magnetite**: *Microscopy and Microanalysis, v. 3*, no. 2, p. 126-9.
50-nm-thick films of $Fe_3O_4$ were prepared by sputter deposition onto MgO substrates of both <100> and <110> orientations. X-ray diffraction and Mössbauer spectroscopy showed that the films were stoichiometric single crystals, and electron microscopy showed that they were essentially dislocation free, yet the magnetic properties of the films were inconsistent with bulk single crystal properties. For example, the magnetization of the films did not saturate in fields as large as 7 Tesla. The films were removed from the substrates in a reactive bath and examined by TEM, showing a high density of antiphase domain boundaries (APBs), spaced several tens of nanometers apart, and tending to lie in the {110} planes. The electron diffraction patterns repeatedly showed unusually prominent diffraction spots that are not allowed by the standard kinematical structure factor.

## Magnetization Processes

Hansen, M. F., Bender Koch, C., and Mørup, S., 2000, **Magnetic dynamics of weakly and strongly interacting hematite nanoparticles**: *Physical Review B, v. 62*, no. 2, p. 1124-35.
The magnetic dynamics of two differently treated samples of hematite nanoparticles from the same batch with a particle size of about 20 nm have been studied by Mössbauer spectroscopy. The dynamics of the first sample, in which the particles are coated and dispersed in water, is in accordance with the Néel expression for the superparamagnetic relaxation time of noninteracting particles. The dynamics of the second, dry sample, in which the particles are uncoated and thus allowed to aggregate, is slowed down by interparticle interactions and a magnetically split spectrum is retained at room temperature. The temperature variation of the magnetic hyperfine field can be consistently described by a mean field model for "super-ferromagnetism" in which the magnetic anisotropy is included. The coupling between the particles is due to exchange interactions and the interaction strength can be accounted for by just a few exchange bridges between surface atoms in neighboring crystallites.

## Modeling and Theory

Fabian, K., 2000, **Acquisition of thermoremanent magnetization in weak magnetic fields**: *Geophysical Journal International, v. 142*, no. 2, p. 478-86.
A phenomenological model of TRM depicts a sample as a collection of statistically independent magnetization elements, each of which possesses definite blocking and unblocking temperatures, and assumes, for weak fields, linear dependence of remanence on applied field. These assumptions are sufficient to derive to first order the experimentally found relations between the different types of pTRMs. Using magnetic phase theory, the coefficients that occur in the kinematic equation derived from the phenomenological model can be physically interpreted for an isotropic ensemble of uniaxial MD particles. A rigorous micromagnetic analysis of the thermal equilibrium state proves the linearity of equilibrium remanence as a function of a weak applied field. A statistical argument extends this linearity to weak-field TRM, which may be carried by non-equilibrium states.

Kachkachi, H., Ezzir, A., Nogues, M., and Tronc, E., 2000, **Surface effects in nanoparticles: application to maghemite $\gamma$-$Fe_2O_3$**: *European Physical Journal B, v. 14*, no. 4, p. 681-9.
We present a microscopic model for nanoparticles of maghemite, composed of a core and a surface shell of constant thickness, and perform classical Monte Carlo simulations of their magnetic properties. The magnetic state in the particle is described by the anisotropic classical Dirac-Heisenberg model including exchange and dipolar interactions and bulk and surface anisotropy. We consider the case of ellipsoidal particles with free boundaries at the surface. Using a surface shell of constant thickness (0.35 nm) we vary the particle size and study the effect of surface magnetic disorder on the thermal and spatial behaviors of the net magnetisation of the particle. It is shown that the profile of the local magnetisation exhibits strong temperature dependence, and that surface anisotropy is responsible for the non saturation of the magnetisation at low temperatures.

Teanby, N., and Gubbins, D., 2000, **The effects of aliasing and lock-in processes on palaeosecular variation records from sediments**: *Geophysical Journal International, v. 142*, no. 2, p. 563-70.
The authors examine possible effects of aliasing by creating a 100-kyr-long synthetic sequence of palaeointensity variation with a similar spectrum to that of archaeomagnetic data from the last 12 kyr and resampling at longer intervals. With no lock-in smoothing, aliasing produces spurious energy in the spectra at long periods. When smoothing by the sedimentation process is applied, the amplitudes of the aliased peaks are reduced but still cause significant, spurious, long-period energy in the spectra for some sedimentation rates. The authors restrict their analysis to palaeointensity data but similar problems may also exist for coarsely sampled directional data. To avoid aliasing they recommend a maximum sampling interval of 2 kyr.

Ye, J., and Halgedahl, S. L., 2000, **Theoretical effects of mechanical grain-size reduction on GEM domain states in pyrrhotite**: *Earth and Planetary Science Letters, v. 178*, no. 1, p. 73-85.
Domain widths in pyrrhotite change very little, or not at all, as a grain is mechanically thinned along one or two directions. Global energy minimum (GEM) domain widths in pyrrhotite have been calculated as grains are thinned to one-fourth or less of their original size. Nine models assume one-dimensional (1D) thinning, which greatly changes both particle size and shape. Two other models address the effects of three-dimensional (3D) thinning, in which particles retain a cubic shape as their sizes are reduced. If a particle can maintain a GEM state while it is thinned, seven of the nine 1D models and both 3D models predict that domain widths will adjust by amounts that are readily detected experimentally. Thus, results of these calculations support the interpretation that local energy minimum (LEM) states in pyrrhotite can be stable over a broad range of grain sizes and shapes.

## Rock Magnetism

Rauen, A., Soffel, H. C., and Winter, H., 2000, **Statistical analysis and origin of the magnetic susceptibility of drill cuttings from the 9.1-km-deep KTB drill hole**: *Geophysical Journal International, v. 142*, no. 1, p. 83-94.
Magnetic susceptibility $\chi$ was measured at 2 m depth intervals on drill cuttings from the main drill hole of the German Deep Drilling Project KTB. Metamorphic rocks (metabasites and gneisses) were the rock types most frequently found down to 9101 m. The higher metabasite susceptibility is caused by higher contents of paramagnetic silicates such as hornblende. A theoretical paramagnetic susceptibility $\chi_{Pt}$ was calculated from the Fe and Mn contents derived from XRF measurements. The ferrimagnetic susceptibility $\chi_F$ was determined by subtracting $\chi_{Pt}$ from the measured $\chi$. Cross-plots of $\chi_F$ versus density are used to discriminate between samples with predominantly magnetite or pyrrhotite as the main ferrimagnetic mineral. A factor analysis was applied to investigate the background factors representing the data variabilities.

Wasilewski, P., Kletetschka, G., and Dickinson, T., 2000, **Magnetic characterization of reduction in Mount Fuji basaltic tree-mold**: *Geophysical Research Letters, v. 27*, no. 10, p. 1543-6.
A Mount Fuji basaltic tree-mold presents the mineralogical record associated with a large oxygen fugacity gradient during the cooling of the basalt. Magnetic exchange anisotropy is postulated to be characteristic of cation excess in some spinel titanomagnetites. The exchange anisotropy is characterized by loop shifting along the field and magnetization axes when cooled in a magnetic field, large coercivity increase, and magnetic viscosity which has discrete activation fields and logarithmic to linear decay characteristics. The cryogenic loop characteristics attributable to exchange anisotropy are not found in the tree-mold where iron and ilmenite are the main phases, nor in cation-deficient spinels. These features are thus characteristic of cation-excess spinels that have equilibrated in the low oxygen fugacity range of the spinel stability field.

## Synthesis and Properties of Magnetic Minerals

Berry, F. J., Greaves, C., Helgason, O., McManus, J., Palmer, H. M., and Williams, R. T., 2000, **Structural and magnetic properties of Sn-, Ti-, and Mg-substituted $\alpha$-$Fe_2O_3$ : a study by neutron diffraction and Mössbauer spectroscopy**: *Journal of Solid State Chemistry, v. 151*, no. 2, p. 157-62.
Hydrothermal techniques have been used to synthesize samples of $\alpha$-$Fe_2O_3$ in which ca. 10% of the Fe cations have been replaced by $Sn^{4+}$, $Ti^{4+}$, and $Mg^{2+}$. Neutron powder diffraction data show the dopant ions to occupy both interstitial and substitutional sites in the corundum-related $\alpha$-$Fe_2O_3$, structure. The details of the defect cluster depend on the charge on the dopant ion. The magnetic structures are related to that of $\alpha$-$Fe_2O_3$ with ambient temperature $Fe^{3+}$ moments of 4.01(5), 3.89(4), and 3.92(4) BM for Sn-, Ti-, and Mg-doped samples, respectively. The $^{57}Fe$ Mössbauer spectra recorded in situ at elevated temperatures show the Néel temperatures of Sn- and Mg-doped $\alpha$-$Fe_2O_3$ to be between 890 and 910 K and 910 and 930 K, respectively, as compared to 950-960 K for pure $\alpha$-$Fe_2O_3$.

Kendelewicz, T., Liu, P., Doyle, C. S., Brown, G. E., Jr., Nelson, E. J., and Chambers, S. A., 2000, **Reaction of water with the (100) and (111) surfaces of $Fe_3O_4$**: *Surface Science, v. 453*, no. 1, p. 32-46.
We have examined changes in the electronic structure of magnetite (100) and (111) surfaces after reaction with water vapor and liquid water at 298 K using chemical shifts in the photoelectron spectra obtained with a synchrotron radiation source. $P(H_2O)$ for the onset of an extensive hydroxylation reaction is $\approx 10^{-3}$ Torr (3 min dose). Magnetite (100) and (111) surfaces exposed to higher $P(H_2O)$ react more extensively, with hydroxylation extending several layers ($\approx$8 Å) deep. Spectra clearly show that the reaction product on the magnetite surfaces is not goethite, limonite or hematite, and that the oxidation state of iron is unchanged. Surprisingly, liquid immersion experiments resulted in smaller chemical shifts and lower intensities of hydroxyl features than exposure to the highest water vapor pressures (10 Torr for 3 min) in our dosing experiments.

King, J. G., and Williams, W., 2000, **Low-temperature magnetic properties of magnetite**: *Journal of Geophysical Research, v. 105*, no. B7, p. 16427-36.
Lithographically-produced arrays of both interacting and noninteracting cubic magnetite particles, as well as magnetite powders, show a gradual increase in the amount of SIRM lost at the Verwey transition $T_V$ with increasing particle size in the PSD size range. This behavior is consistent with the vortex state domain structure. The grain size dependence of the amount of SIRM lost at $T_V$ is most probably what previous researchers reported as a magnetic memory particle-size-dependent trend. Magnetic memory measured during the cooling and warming process is shown to be a stress-related phenomenon. Such measurements could be useful in assessing the nature of stress in a magnetite sample.

Okudera, H., 2000, **Change in anisotropic temperature factors in magnetite with temperature and cation deficit**: *Journal of the Crystallographic Society of Japan, v. 42*, no. 2, p. 160-4.
Anomalous change of the mean square displacements (m.s.d.'s) of the octahedral (B) site cation in magnetite was investigated by means of single crystal X-ray diffraction and discussed with respect to an electron-phonon interaction. At lower temperatures the B site cation prefers to vibrate along [111], but this preference is reduced with temperature rise up to 630 K, above which the mean square displacement normal to [111] becomes dominant. This preference at lower temperature is also reduced with increasing cation deficit, in other words decreasing carrier population in the B-sublattice. In the MPMS measurements weakening of the electron-phonon interaction in the cation deficit is apparently shown. The coordinate of oxygen remains nearly constant at x=0.2549 below approximately 600 K, but increases above this temperature, indicating cation disordering over the tetrahedral (A) and octahedral (B) sites above 600 K.

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**Yong Jae Yu**
University of Toronto
*yjyu@*
*physics.utoronto.ca*

## Rock Magnetic and Paleomagnetic Experiments on Some Self-reversing Pumices from Japan

*(1) Kurokami pumices, Mt. Sakurajima, Japan*

Preliminary paleomagnetic studies on Kurokami pumices revealed several interesting magnetic properties (Yu et al., 1998). Thermal demagnetization results show two different magnetic phases; phase A with higher unblocking temperatures (~500°C) and phase B with lower unblocking temperatures (240-260°C). A partially self-reversed component was also detected in the heating range between 500°C and 580°C. The magnetization directions of phase A, phase B, and the partially self-reversed phase are almost constant during thermal demagnetization.

In order to investigate the magnetic carriers in the Kurokami pumices, I visited the IRM in late August 1999. I measured low- and high- temperature hysteresis properties and temperature dependence of saturation remanence (20-900 K). Crushed powders and 12 rock chips were used. The results clearly show that phase A is titanomagnetite with composition x<0.1. However, it is difficult to explain all magnetic properties measured on phase B in terms of either titanomagnetite or hemoilmenite. Subsequent microprobe analysis in Toronto revealed the surprising result that phase B is actually a chromite ($FeFe_{(2-x)}Cr_xO_4$, $0 \le x \le 2$).

Unfortunately, all the measurements on the chromites are bulk properties because the chromite grains were too small to separate (the diameter of the largest grain under the SEM was 0.3 micron). Coercive forces from the rock chips vary from 30 to 80 mT. No significant low-temperature transition was found. This study shows that chromites can contribute to NRM with reasonably high unblocking temperatures (up to 260°C).

*(2) Haruna dacite pumices, Mt. Haruna, Japan*

I carried out similar experiments on powders of self-reversing Haruna dacite pumices. Most results are almost the same as those reported by Nagata et al. (1951). One interesting thing that I observed was a wider range of Néel temperatures than commonly reported (as high as 350°C). This result implies that the composition range of self-reversing hemoilmenites may extend down to y~0.45.

My stay at the IRM was very fruitful. I am grateful to Mike Jackson, Jim Marvin, Peat Solheid, Christoph Geiss, and Stefanie Brachfeld for their help with my measurements.

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Nagata, T., S. Uyeda, and S. Akimoto, Self-reversal of thermoremanent magnetization of igneous rocks, *J. Geomagn. Geoelectr., 4*, 22-38, 1951.

Yu, Y. J., D. J. Dunlop, and Ö. Özdemir, Rock magnetic and paleomagnetic experiments on hemoilmenites and titanomagnetites in some self-reversing pumices from Japan, *EOS, 79*, 45, F237, 1998.

**Özden Özdemir**
University of Toronto-Erindale
*ozdemir@*
*physics.utoronto.ca*

## TRM and Low-Temperature SIRM in Submicron Hematites

Low-temperature saturation remanent (SIRM) and thermoremanent magnetizations (TRM) have been studied on synthetic hematites having grain sizes between 0.04 and 0.25 µm and a natural rhombohedral single crystal of hematite (11×6×1 mm). The hematites were given an SIRM in a field of 2.5 T at room temperature then cooled to 20 K and back to 300 K in zero field. In cooling through the Morin transition $T_m$, hematite undergoes a magnetic phase transition from weakly ferromagnetic to antiferromagnetic and the spins rotate 90 from the basal plane to the [111] trigonal c-axis. The submicron size hematites showed a well-defined Morin transition around 230 K, where magnetization decreased sharply with the onset of antiferromagnetism. The Morin transition of the natural single crystal was also sharp and took place at 250 K. The lower $T_m$ for the submicron size hematites is probably due to the fine particle size. The SIRM memory after low-temperature cycling was about 30% of the original SIRM for the submicron hematites. In the 11mm single crystal, the SIRM memory was 40% of the initial SIRM, higher than that of fine-grained hematites.

The thermoremanent magnetizations were produced in a water-cooled non-inductive furnace by cooling in a field of 1 mT from 700 C and were later thermally demagnetized in zero field in the same furnace. Before TRM experiments the samples were heated to 700 C and cooled in zero field to erase any prior remanence and to establish a standard initial state. Low-temperature demagnetization experiments were carried out by cooling the samples to 77 K in a liquid $N_2$ dewar, allowing the temperature to equilibrate for 30 min, and warming back to room temperature, all in the zero-field environment of a six layer mu-metal shield.

In the fine grained hematites, as in the 11 mm natural crystal, the TRM was very stable against stepwise thermal demagnetization. The thermoremanence has no unblocking temperatures below 600 C and very little change until 670 C, only 5 C below the Néel temperature. The TRM memory after the low-temperature demagnetization was about 40% of the original TRM for the submicron size hematites. In the single crystal, the TRM memory was only about 15% of the virgin TRM. The memory fraction of TRM has mainly unblocking temperatures $T_{ub}$>600 C, very similar to those of the total TRM.

**David Dunlop**
University of Toronto-Erindale
*dunlop@*
*physics.utoronto.ca*

## Are Meteorite NRM's and Paleointensity Estimates Contaminated by Terrestrial Inverse TRM?

The question I set out to answer was whether inverse TRM (ITRM), discovered in 1963 by Nagata, Ozima & Yama-ai (*Nature 197*, 444-5), is likely to be an important contributor to spurious NRM in certain types of meteorites. Meteorites are our main source of knowledge about paleomagnetic fields in the Solar System. We need to be able to recognize and reject any NRM component of terrestrial rather than extra-terrestrial origin. ITRM is one such potential spurious remanence. It results from heating (rather than cooling: thus inverse) through a magnetic phase transition in a magnetic field. Part of the NRM of carbonaceous chrondrites and some Martian meteorites could be an ITRM acquired on Earth as the impacting meteorite's cold interior warms in the geomagnetic field through phase transitions like those of pyrrhotite (35 K), magnetite (120 K) and hematite (250 K). Pyrrhotite ITRM is unlikely because a meteorite parked in near-Earth orbit would not have a sufficiently cold interior, but magnetite ITRM is plausible. Magnetite and pyrrhotite are known to occur in carbonaceous chrondrites and in Martian meteorite ALH84001.

The experiments I carried out at the

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## Langevin, Paul

*b. Jan. 23, 1872, Paris;*
*d. Dec. 19, 1946, Paris*

Einstein wrote that if he had not developed the theory of special relativity, Langevin would have been the one to do so. Langevin studied statistical mechanics and magnetism with Poincaré, Brillouin and Pierre Curie in Paris, and then worked for a year at Cambridge with J.J. Thomson. After returning to Paris, Langevin succeeded Curie at l'Ecole de Physique et de Chemie, and developed the thermodynamical theories of paramagnetism and diamagnetism to account for the observations of Curie. Langevin is also remembered as a pioneer in the development of ultrasonic ('sonar') techniques for underwater imaging. In addition to his scientific legacy, Langevin attained a large stature as a social activist, pacifist, and educational reformer.

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*of Michigan*). For the redbeds, Geissman showed several interesting examples of highly stable secondary magnetizations that had survived later major tectonic events, and he related their stability to the nature and origin of the remanence carriers. Weil's case study of multiply-remagnetized Devonian carbonates used analytical electron microscopy in combination with hysteresis and low-temperature magnetic measurements on whole-rock samples, extracts and residue, to pinpoint the carriers of the remanences and shed light on their origins. In the following pair of talks, **Lisa Tauxe** (*Scripps Inst. of Oceanography*) and **Kaushik Katari** (*Harvard*) presented a revolutionary view of the process of magnetic field recording by marine sediments, which generated a most spirited discussion. Based on theoretical and experimental work, they rejected the standard views of both depositional remanence (arguing that isolated grains of magnetite do not exist in the water column; they are all bound up in clay flocs and fecal pellets) and post-depositional remanence (arguing that even extensive bioturbation is not sufficient to remobilize the tightly-bound magnetic grains below the sediment-water interface). Although others have previously stressed the importance of interactions with nonmagnetic particles, Katari and Tauxe emphasized that such interactions are the nearly-universal rule rather than the exception. **Jeff Gee** (*Scripps*) finished the applied session with a discussion on magnetic anisotropy and the use of low-temperature, high-field, and remanence-based techniques for isolating different mineral fabrics in intrusive and extrusive rocks and sediments.

A morning session on the last day was led by another guest speaker, **James Tyburczy** (*Arizona State University*), who gave a one-hour talk on the history of research planning, research activities, and outreach efforts to the relevant sections of AGU that has led to the resurgence and high visibility of the mineral physics committee (of AGU), established in 1985. Discussion ensued on how the mineral physics "model" can or cannot be followed by rock magnetists, and on how the exciting results of our research should be communicated to the entire AGU membership and to the relevant program managers at NSF and NASA.

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IRM used both the MPMS SQUID magnetometer, to continuously monitor induced or remanent magnetization during heating and cooling runs between 10 K and 300 K, and the SRM to measure stepwise AF and thermal demagnetization of ITRM in selected samples. The development of ITRM was studied in magnetites of 9 different grain sizes, from submicron to 150 microns, in coarse and fine pyrrhotites, and in hematite crystals from several sources. Demagnetized samples were first warmed from 10 K to 300 K in a low field (2 mT, the smallest stable field available with the MPMS), their induced magnetization being measured at 1 K to 5 K intervals. (In retrospect, it would have been just as quick to use high resolution, i.e. 1 K increments, for the whole experiment because the MPMS takes a long time to stabilize after any change in the program.) At 300 K, the field was reset to zero, ITRM was measured, and the remanence was then cooled in zero field to 10 K, again with continuous monitoring.

In the magnetites, the magnetization doubled or tripled in warming through the Verwey transition, and 5-40% of this induced magnetization was retained as ITRM when the field was removed at 300 K. In the pyrrhotites and hematites, the magnetization increased by much larger amounts in warming through the phase transition, and the retention as ITRM at 300 K was also larger (up to 85% in the case of Elba hematite). In most magnetites and hematites, all but a few percent of the ITRM was erased during zero-field cooling through the same phase transition. The pyrrhotite samples, however, retained 40-60% of their ITRM after zero-field cooling to 10 K. Thus low-temperature demagnetization (LTD) would be an effective pre-treatment for removing unwanted ITRM in magnetite (or hematite) before beginning conventional thermal or AF demagnetization of a meteorite, but would be less effective for ITRM carried by pyrrhotite.

ITRM's of the 1, 6, 20 and 135 micron magnetite samples had unusual thermal demagnetization curves. Unblocking temperatures were distributed almost linearly from room temperature to the Curie point, with a median $T_{UB}$ around 300 C. The lower-$T_{UB}$ ITRM could mimic extra-terrestrial NRM of low $T_{UB}$, cited as evidence for negligible heating of meteorites such as ALH84001 during their transfer to Earth (Kirschvink et al., *Science 275*, 1629-1633, 1997). The higher-$T_{UB}$ ITRM could contaminate paleointensity determinations up to the highest temperature steps. The best cure for ITRM contamination, as noted above, would be to low-temperature demagnetize the meteorite before beginning above-room-temperature thermal experiments.

ITRM is only one example of a remanence acquired by crossing a magnetic phase transition in the presence of a field. ITRM is a transition warming remanence; I also investigated the properties of the corresponding transition cooling remanence in magnetite, hematite and pyrrhotite below room temperature. Initially demagnetized samples were cooled in a 2 mT field from 300 K to 10 K. Their induced magnetizations were measured at 1 K to 5 K intervals, the highest resolution data being taken between 140 K and 90 K for the magnetite samples. At 10 K, the field was zeroed, and the remanence was then monitored during zero-field warming back to 300 K. The properties of transition cooling remanence were generally similar to those of transition warming remanence (i.e., ITRM), but the increase in induced magnetization for the magnetites and pyrrhotites in cooling through their phase transitions was relatively small. The reason for this is probably the very high coercivity of the low-temperature phase of both minerals. In the case of hematite, where the low-temperature phase is almost non-ferromagnetic, the induced magnetization actually decreased across the transition. On the other hand, 70-90% of the induced magnetization was retained as remanence when the field was zeroed at 10 K, and up to 20% of this remanence survived zero-field warming through the transition. For hematite, this room-temperature memory was much larger than the remanence below the Morin transition!

Although transition cooling remanence, unlike ITRM, does not have an obvious practical application, both types of remanence give interesting insights into magnetization acquisition during field-cooling through a transition. They may even be relevant to the TRM acquisition process. Some of this work will be presented at the fall AGU meeting. Special thanks go to Jim Marvin for much help with the design of the MPMS experiments.

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 and Facility Manager, and **Peat Solheid**, Scientist.

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**Mike Jackson**
Institute for Rock Magnetism
University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: irm@geolab.geo.umn.edu
www.geo.umn.edu/orgs/irm/irm.html

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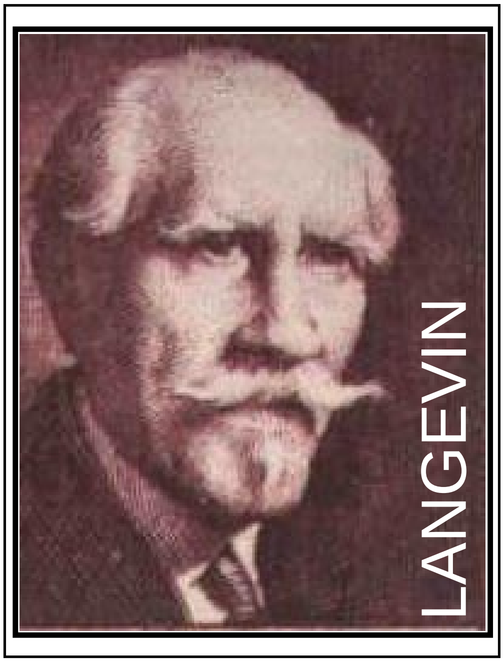

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