

# The IRM Quarterly

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that grip was beginning to weaken. Price (1958) writes: "We should remember, throughout any reading of this book, that Gilbert was writing within the matrix of Aristotelian thought and, though he escapes from it miraculously from time to time, much of the book, in both language and content, is embedded in Aristotelian terminology and ideas. If Gilbert's basic theories of magnetism and electricity seem almost theological, it is for this reason, and we must therefore view with even greater respect the firm foundations on which he placed so many phenomena. It was no light matter, and the year of publication of this book was also that in which Giordano Bruno was burned at the stake for perhaps lesser scientific heresies."

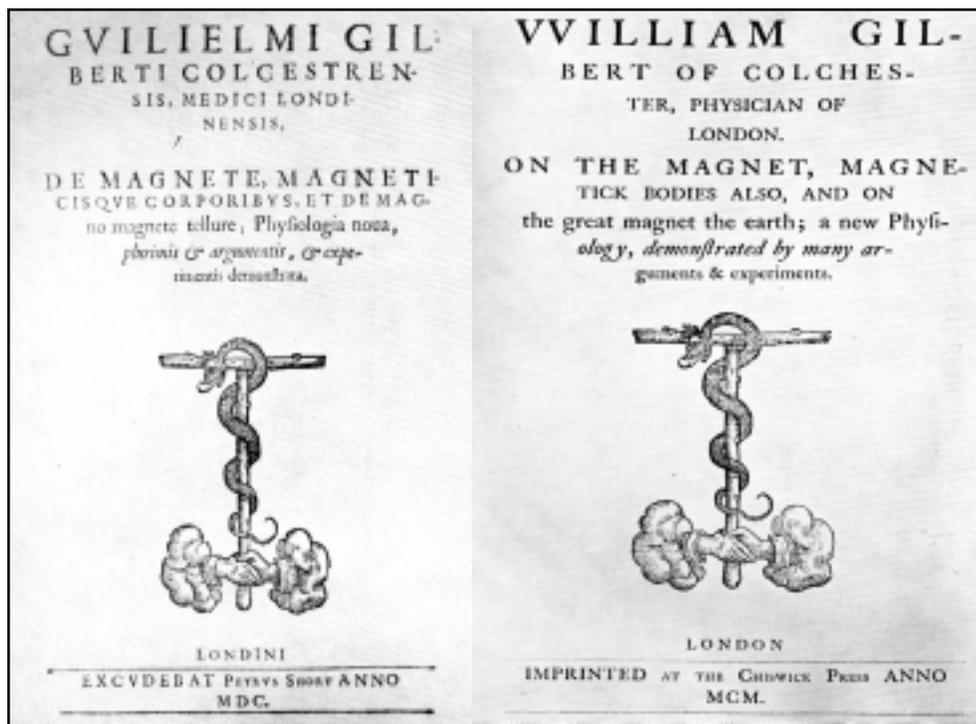
Gilbert, along with Galileo and Bruno, heretically rejected (at least in part) the Aristotelian geocentric/geostatic view of the cosmos. In Book 6 of *De Magnete*, Gilbert argues for diurnal rotation of the earth on its axis, and proposes magnetic causes for this. He is noncommittal, however, about the more radical Copernican assertion that the earth orbits the sun. In Gilbert's other book, *De Mundo nostra Sublunari Philosophia nova*, he credits mutual magnetic attraction for holding the moon in orbit around the earth, and for the lunar influence on terrestrial tides. He also argues against the elemental nature of Fire, Water, and Air, accepting only Earth from the Aristotelian periodic table. It is clear from his defiant prefatory remarks that he recognized the revolutionary nature of *De Magnete*. Despite his heresies, Gilbert escaped the fates of Galileo and Bruno; however, three years after publication of *De Magnete*, he succumbed to the plague in the great London outbreak.

Price (1958) compares Gilbert to Edison: "he methodically and exhaustively tried all possibilities within range, sometimes repeating experiments to the point of tedium." However, "Gilbert, like the other fathers of modern science, was not content simply to note and formulate the results of his experiments; he sought ultimate explanations of the phenomena. How can a loadstone attract a piece of iron that is separated from it in space? His answer in essence was one which had been current in ancient times; magnetism is interpreted animistically. Magnetic force is something 'animate,' it

**Gilbert**

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Reproduced from The De magnete of William Gilbert by D.H. Rollet, Menno Hertzberger, Amsterdam, 1959



Left: First Edition, 1600; Right: the "Gilbert Club" translation, 1900.

## Gilbert On the Magnet, MDC

**Mike Jackson**  
IRM

**Wm Gilbert**  
MD

*"why should I, in so vast an Ocean of Books by which the minds of studious men are troubled and fatigued, through which very foolish productions the world and unreasoning men are intoxicated and puffed up, rave and create literary broils, and while professing to be philosophers, physicians, mathematicians and astrologers, neglect and despise men of learning: why should I, I say, add aught further to this so-perturbed republic of letters, and expose this noble philosophy, which seems new and incredible by reason of so many things hitherto unrevealed, to be damned and torn to pieces by the maledictions of those who are already sworn to the opinions of other men, or are foolish corruptors of good arts, learned idiots, grammatists, sophists, wranglers, and perverse little folk? But to you alone, true philosophizers, honest men, who seek knowledge not from books only but from things themselves, have I addressed these magneetical principles in this new sort of Philosophizing."*

The year 1600 conveniently marks the transition from the Renaissance to the Baroque period in European music and art. The first opera, Jacopo Peri's *Euridice* was performed in 1600. This was the year in which Shakespeare's *Hamlet* was written and first performed. In mathematics and the sciences, 57 years had passed since the publication of Copernicus' *De Revolutionibus*. Kepler began working in 1600 as Tycho's assistant in Prague; John Napier had invented but not yet published on logarithms; Fermat would be born the following year; and eight years would pass before Galileo made his first telescope. In this auspicious setting four centuries ago, William Gilbert of Colchester published the results of seventeen years of investigation in *De Magnete (On the Magnet)*.

Scientific thought in 1600 was still ruled by the firm grip of the ancients, but

# Visiting Fellows' Reports

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### Evidence Of Domestic Fires In Antiquity: A Mineral Magnetic Approach Based On Recent Experimental Samples

Identifying burnt sediments and soils provides significant archaeological evidence and may help elaborate the interpretation of specific features, such as a hearth or burnt post-hole. The presence of a distinctive colour change, usually reddening, or the inclusion of charcoal and ash in the deposit may often reveal such features. However, if the material is redeposited from adjacent settlement activity or associated with a truncated occupation surface there may be little visual evidence to confirm whether the sediment was burnt or not. In addition, the thermal history of a sediment, in terms of the maximum temperature attained and length of exposure to this heat, may further identify the function of associated features separating deliberate, high temperature processes from more ephemeral burning episodes due to natural fires. This may be of particular importance on sites where the underlying sediments produce distinctive colour changes at comparatively low temperatures (Canti and Linford, 2000).

The aim of this project was to utilise magnetic measurements to identify burnt sediments by exploiting the sensitivity of iron minerals to thermal alteration. Samples were obtained from a number of actualistic fire experiments conducted over a range of substrates (clay soil, gravelly sand and a sandy loam) together with a series of samples prepared in a laboratory furnace over a range of temperatures from 50 - 600°C. In addition, samples of burnt archaeological deposits were also recovered from sites over the same geology to investigate the longevity of any thermal alterations identified from the experimental analogues.

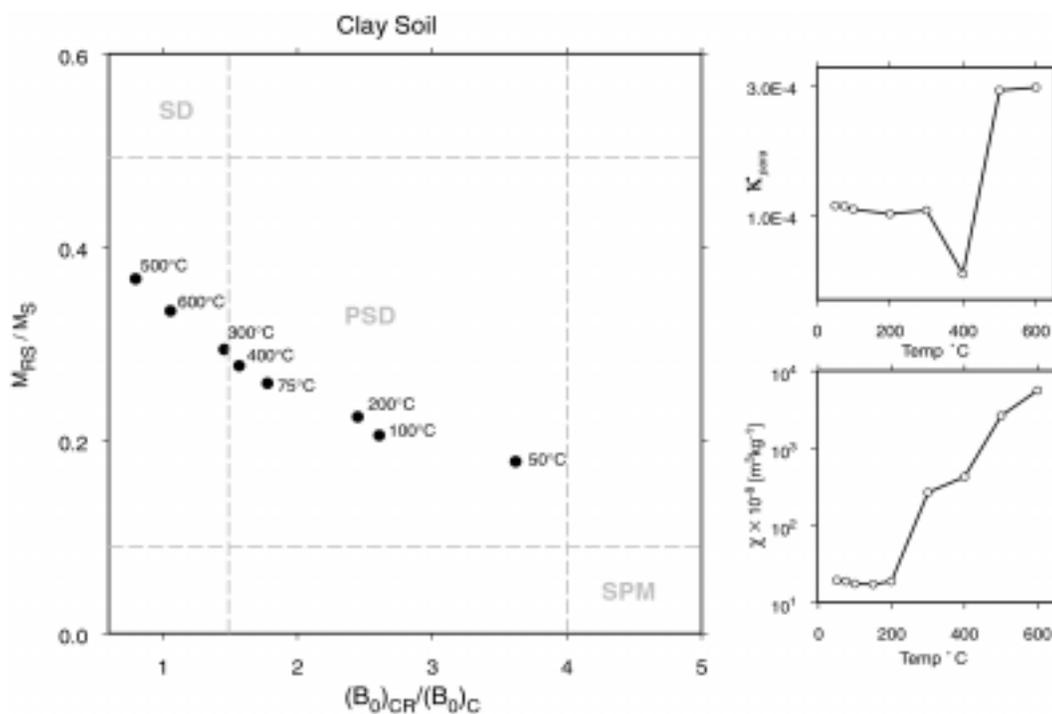
Previous work had concentrated on the geophysical (magnetometer) response produced by fire experiments of varying duration over the chosen substrates. This revealed that initially even a short duration camp fire forms an intense magnetic anomaly. However, much of the enhanced magnetic material is associated with the surface ash layer that will be rapidly dispersed by weathering. Of greater interest was the enhancement of soil immediately below the fires that correlated well with the subsoil temperature data obtained from a series of buried thermocouples and confirmed that significant thermal alteration occurs at relatively low temperatures <250°C.

Initial measurements of  $\chi$ ,  $\chi_{FD}$ , ARM and various IRM back-field ratios suggested an increased concentration of very fine grained / superparamagnetic material within the enhanced post-burn samples but failed to fully identify the minerals present or their magnetic domain states. I therefore hoped to investigate the samples further through use of the following equipment:

- Determine full hysteresis and forward IRM acquisition parameters using the MicroMag VSM and with the furnace in place measure hysteresis loops at a series of temperatures to a maximum of 700°C
- Investigate the frequency dependence of the samples at room temperature over a range of frequencies with the Lakeshore susceptometer to detect the presence of superparamagnetic material
- Analyse the variation of a laboratory induced remanent magnetisation from 300K → 20K → 300K with the MPMS and further investigate the magnetic viscosity of SP rich samples
- Attempt to determine the precise magnetic mineralogy of selected samples through Mössbauer spectroscopy

Not surprisingly, the results show a massive enhancement of the magnetic properties of the burnt sediments which is largely a function of the maximum temperature attained and the length of exposure to this temperature. Perhaps of greater interest was the comparatively low maximum temperature required (<200°C) to produce a detectable change in the hysteresis parameters. Figure 1 shows data for the Clay soil laboratory samples that demonstrate an apparent increase in single domain type behaviour of the high-field slope corrected hysteresis parameters when compared to the experimental results of Day *et al.*, (1977). The magnetic properties of the low temperature samples are dominated by a paramagnetic phase that gradually decreases with the susceptibility until 200°C when a major thermal alteration occurs. Frequency dependence of susceptibility also increases for the clay soil from <3% to >11% at the same temperature, suggesting an increase in the concentration of SP material with temperature.

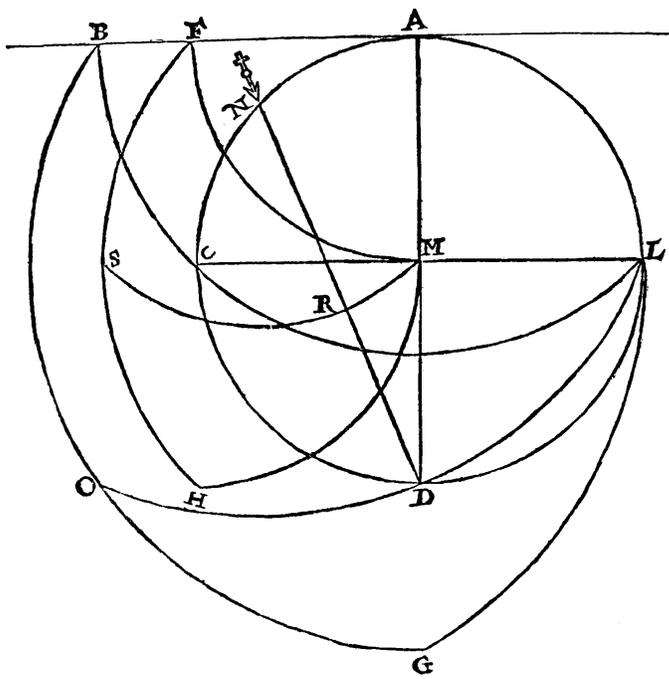
Results from the other substrates were similar with the exception of the sandy loam soil collected from a site where archaeological activity had been proved through both geophysical survey and subsequent excavation. This substrate demon-



**Figure 1;** Variation of high field slope corrected hysteresis parameters for samples of the clay soil heated overnight in a laboratory furnace from 50 to 600°C. The two inset graphs show the variation of paramagnetic susceptibility  $\kappa_{para}$  (calculated from the high field slope of the hysteresis loop) and total susceptibility  $\chi$  for the same samples with temperature.

## Visiting Fellows

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Gilbert's construction for determining magnetic "declination" (which we now call "inclination"). Circle ACDL represents the earth or a terrella; AD is the equator and CL the axis. Arcs FH and BG are concentric with the earth. To construct the "declination" at point N, at 45° latitude, construct arc OL around N, from arc BG to the south pole L. Divide arc OL into 90 equal parts, and count from O towards L one part for each degree of latitude, to determine the point D. The line from N to D shows the orientation of the magnetic needle at N. From *On the Magnet*, by William Gilbert. *The Collector's Series in Science*, D. J. Price, ed., Basic books, New York, 1958.

## 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 5000 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the IRM Quarterly are always welcome.

## Alteration & Remagnetization

Katz, B., Elmore, R. D., Cogoini, M., Engel, M. H., and Ferry, S., 1999, **Associations between burial diagenesis of smectite, chemical remagnetization, and magnetite authigenesis in the Vocontian trough, SE France**: *Journal of Geophysical Research*, v. 105, no. B1, p. 851-68.

Paleomagnetic, rock magnetic, geochemical, and petrographic results from these carbonates support a connection between smectite alteration and magnetite authigenesis. A prefolding, secondary magnetization is found where smectite has altered to other clay minerals, and a primary magnetization where the clays show no evidence for burial alteration. IRM, ARM and NRM intensities increase where smectite has altered, as does superparamagnetic content. Sr, C and O isotopes show no sign of alteration by orogenic fluids.

Yongxin, P., Rixiang, Z., Banerjee, S. K., Gill, J., and Williams, Q., 1999, **Rock magnetic properties related to thermal treatment of siderite: Behavior and interpretation**: *Journal of Geophysical Research*, v. 105, no. B1, p. 783-94.

When high-purity natural crystalline siderite was heated in air, susceptibilities increased sharply between 400° and 530° C due to generation of a new ferrimagnetic mineral phase. Rock magnetic experimental results show that magnetite, maghemite, and hematite are the transformation products. Maghemite was not completely inverted to hematite even at temperature as high as 690° C. The mineral transformation processes were confirmed by conventional optical microscopic observation, X-ray diffractometry and Mössbauer spectroscopic analyses. It is concluded that these temperature-dependent variations of magnetic properties can be used as criteria for identification of siderite in rocks and sediments.

## Environmental Magnetism and Paleoclimate

Evans, M. E., 1999, **Magnetoclimatology: a test of the wind-vigour model using the 1980 Mount St. Helens ash**: *Earth and Planetary Science Letters*, v. 172, no. 3, p. 255-9.

For ash produced by the 1980 eruption of Mount St. Helens, there is a clear exponential decrease of magnetic susceptibility with increasing distance from the vent. This supports the wind-vigour concept (in which glacial intervals are associated with stronger, more frequent winds which are more efficient at entraining and transporting dense iron oxide particles) as a viable alternative (at least in some environments) to the pedogenetic model of magnetoclimatology.

Sartori, M., Heller, F., Forster, T., Borkovec, M., Hammann, J., and Vincent, E., 1999, **Magnetic properties of loess grain size fractions from the section at Paks (Hungary)**: *Physics of the Earth and Planetary Interiors*, v. 116, no. 1, p. 53-64. This 50-m thick loess/palaeosol sequence was deposited largely during the Brunhes normal

polarity chron and its magnetic properties resemble those of similar sections in Europe, Central Asia and China. Two loess and two palaeosol samples were separated into ten grain size fractions, ranging from 50 µm down to 10 nm. Susceptibility, hysteresis parameters, and TRM show a strong grain size dependence for the ferromagnetic minerals. Strong relationships between weathering processes, destruction of paramagnetic minerals and possibly iron-hydroxides, and enhancement of the ferromagnetic signal are observed.

Stockhausen, H., and Thouveny, N., 1999, **Rock-magnetic properties of Eemian maar lake sediments from Massif Central, France: a climatic signature?**: *Earth and Planetary Science Letters*, v. 173, no. 3, p. 299-313.

The rock-magnetic stratigraphies of three lakes (Lac du Bouchet, Lac St. Front and Ribains maar lake) show poor correlation, suggesting that local effects may have altered the original detrital (climatic) signal. Lac du Bouchet susceptibility variations are at least partly affected by postdepositional magnetite dissolution, Lac St. Front sediments show a complex behaviour resulting in partly contradicting interpretations of rock-magnetic parameters. Ribains maar lake sediments show a homogeneous magnetic mineralogy without major variations in most of the rock-magnetic parameters. The purely detrital origin of the Lac du Bouchet Eemian susceptibility variations must be questioned but it nevertheless appears to be the only lake whose susceptibility variations can tentatively be correlated with the GRIP Eemian oxygen isotope record.

## Geomagnetic Field Records and Paleointensity Methods

Brachfeld, S. A., and Banerjee, S. K., 1999, **A new high-resolution geomagnetic relative paleointensity record for the North American Holocene: a comparison of sedimentary and absolute intensity data**: *Journal of Geophysical Research*, v. 105, no. B1, p. 821-34.

Lake Pepin sediments yield the same Holocene paleosecular variation curve as nearby Lake St. Croix and satisfy all of the criteria recommended for paleointensity studies. Relative intensity (NRM/ARM) records from both lakes correlate well with absolute paleointensities from volcanic and archeomagnetic samples, for features with wavelengths of 1000 years. Normalizations using SIRM and  $\chi$  were less successful at isolating the paleointensity signal; both NRM/SIRM and NRM/ $\chi$  were strongly coherent with grain-size proxies such as MDF(NRM) and  $H_{CR}$ . However an empirical correction function successfully removed the grain size dependence from these normalized records.

Channell, J. E. T., 1999, **Geomagnetic paleointensity and directional secular variation at Ocean Drilling Program (ODP) Site 984 (Bjorn Drift) since 500 ka: comparisons with ODP Site 983 (Gardar Drift)**: *Journal of Geophysical Research*, v. 104, no. B10, p. 22937-51. Relative paleointensity records can be matched between these two Iceland Basin

sites and correlated with other high-resolution records. Directional secular variation is, however, not easily correlated. Both sites record the Iceland Basin event at 186-189 ka, with a rotation through 180° and back, coincident with a paleointensity low that lasted about 3 kyr. Other geomagnetic excursions appear as intervals of higher-amplitude secular variation during lows in paleointensity. There is a tendency for paleointensity lows to correlate with peak interglacials in the oxygen isotope records; however, this does not translate into a correlation between paleointensity and %CO<sub>2</sub> or between paleointensity and magnetic concentration or grain size parameters.

Guyodo, Y., Richter, C., and Valet, J. P., 1999, **Paleointensity record from Pleistocene sediments (1.4-0 Ma) off the California Margin:** *Journal of Geophysical Research*, v. 104, no. B10, p. 22953-64.

High resolution magnetic measurements of 45 m of sediment from ODP Site 1021 isolated a very stable NRM which showed the succession of the Cobb and Jaramillo subchrons and directional changes associated with the Punaruu event (1.105 Ma). A significant climatic component remained present in the NRM/ARM record. In contrast, since NRM and susceptibility ( $k_{if}$ ) are both driven by orbital forcing, NRM/ $k_{if}$  is not contaminated by climate changes and is taken as the best estimate of relative paleointensity.

Kok, Y. S., and Tauxe, L., 1999, **A relative geomagnetic paleointensity stack from Ontong-Java plateau sediments for the Matuyama:** *Journal of Geophysical Research*, v. 104, no. B11, p. 25401-13.

A new paleointensity stack for the Matuyama Chron is based on sedimentary magnetizations from 4 ODP cores analyzed with Thellier-Thellier techniques. A coherent feature with two other data sets spanning the Matuyama Chron is the occurrence of a 150-kyr cyclicity. However, the time control of the OJP stack is not accurate, except for the 10 tie points at the reversals. This could, at least in part, explain why the three Matuyama paleointensity records show no other coherent frequencies.

Leonhardt, R., Heider, F., and Hayashida, A., 1999, **Relative geomagnetic field intensity across the Jaramillo subchron in sediments from the California margin: Ocean Drilling Program Leg 167:** *Journal of Geophysical Research*, v. 104, no. B12, p. 29133-46.

Uniformity criteria are fulfilled for the Site 1010, and relative paleointensities obtained with various normalizers were consistently show several fine-scale intensity features. A comparison of this relative paleointensity record with several published records of cross the Jaramillo subchron with different sedimentation rates and sediment composition shows reasonable agreement between the paleointensity patterns but differences in amplitudes. This suggests an influence of postdepositional magnetization processes which were not removed during normalization.

Riisager, J., Perrin, M., Riisager, P., and Ruffet, G., 1999, **Paleomagnetism, paleointensity and geochronology of Miocene basalts and baked sediments from**

**Velay Oriental, French Massif Central:**

*Journal of Geophysical Research*, v. 105, no. B1, p. 883-96.

These baked sediments are ideal for Thellier experiments, with 11 out of 13 samples giving reliable paleointensity estimates. Rock magnetic experiments show that the main ferromagnetic minerals are fine-grained magnetite and hematite with a large proportion of superparamagnetic grains. In addition to the standard pTRM checks to detect alteration, a new "pTRM tail" check was used to test the equality of blocking and unblocking temperatures, which are here found to be identical, indicating SD remanence carriers.

## Magnetic Microscopy and Spectroscopy

Fellows, R. A., Lennis, A. R., Raza, H., Pang, C. L., Thornton, G., and Vaughan, D. J., 2000, **Fe<sub>3</sub>O<sub>4</sub>(111) formation on a reduced  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub>(1123) substrate: a low-energy electron diffraction and scanning tunnelling microscopy study:** *Surface Science*, v. 445, no. 1, p. 11-17.

A (1123) surface of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> was prepared by Ar<sup>+</sup>-ion sputtering and annealing in ultrahigh vacuum at 1123 K. Examination of this surface by low-energy electron diffraction (LEED) reveals two distinct reciprocal unit cells. The first is identical to that observed for a (111) bulk termination of Fe<sub>3</sub>O<sub>4</sub>; the second corresponds to a bulk termination of the (1123) plane. We propose that Fe<sub>3</sub>O<sub>4</sub> (111) nucleates on the reduced  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> (1123) substrate, with the [100] direction of  $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> parallel to the [110] direction of Fe<sub>3</sub>O<sub>4</sub>. This epitaxial relationship is favoured by substrate oxygen planes parallel to  $\alpha$ -Fe<sub>3</sub>O<sub>4</sub> (1123), and by close-packed oxygen planes parallel to Fe<sub>3</sub>O<sub>4</sub> (111).

Inglot, Z., Lieb, K. P., Uhrmacher, M., Wiarda, D., and Ziegeler, L., 1999, **PAC measurements of the Verwey transition in magnetite:** *Hyperfine Interactions*, v. 120-121, no. 1, p. 237-41.

Perturbed angular correlation experiments with <sup>111</sup>In tracers have recently been used to investigate magnetic phase transitions in metal oxides. Here we report on PAC measurements for <sup>111</sup>Cd in polycrystalline Fe<sub>3</sub>O<sub>4</sub> in the neighborhood of the Verwey phase transition ( $T_v \approx 120$  K). PAC spectra were taken for implanted <sup>111</sup>In probes at temperatures between 9 and 850 K. The two observed Larmor frequencies are attributed to the two cation sites in the cubic inverse spinel lattice. At the Verwey temperature we find a rapid change of both Larmor frequencies. The Verwey transition also affects the widths of the frequency distributions, which double below  $T_v$ . This possibly indicates the presence of several components with Larmor frequencies similar to those found in the previous Mössbauer data, or for electronic after-effects correlated with the semiconductivity of magnetite below  $T_v$ .

Soszka, W., and Kim-Ngan, N. T. H., 1999, **Low energy ion scattering from the single crystal magnetite and from magnetite covered by condensed xenon at the Verwey transition:** *Surface Science*, v. 441, no. 2, p.

311-19.

Energy spectra of He<sup>+</sup>, Ne<sup>+</sup>, Ar<sup>+</sup> and Kr<sup>+</sup> ions, scattered from a cleavage surface of a single crystal of magnetite, have been measured in small-angle geometry and in the temperature range of 85-300 K. Large energy losses of scattered ions and a very deep minimum around 120 K in the temperature dependence curve of ion yield ( $R^+(T)$ ) have been observed for all bombarding ions. The minimum in the  $R^+(T)$  curve corresponding to the Verwey phase transition of magnetite can be explained by a change of the neutralization probability of incoming and outgoing ions, by a change of the target material transparency and by a change in the number of the trajectories containing ionizing collisions.

## Modeling and Theory

Ahdjoudj, J., Martinsky, C., Minot, C., Van Hove, M. A., and Somorjai, G. A., 1999, **Theoretical study of the termination of the Fe<sub>3</sub>O<sub>4</sub> (111) surface:** *Surface Science*, v. 443, no. 1, p. 133-53.

Calculations for the structure of the (111) surface of magnetite show that the stability of the surface layers depends on the overall composition, specifically on the deviation from stoichiometry, and on the dipole moment perpendicular to the surface. The symmetrical oxygen-deficient slab with the layer sequence Fe<sub>2</sub>O<sub>2</sub>Fe<sub>3</sub>O<sub>2</sub>Fe<sub>2</sub> terminated on each side by iron bilayers, is the best compromise since symmetry insures the neutrality of the dipole moment. The energetically preferred structure relaxes so that one of the two outermost iron layers moves toward the slab center plane, exchanging sequence with the oxygen layer. The symmetric slab with the layer sequence FeO<sub>4</sub>Fe<sub>3</sub>O<sub>4</sub>Fe, terminated by iron single monolayers, would represent an excessive oxidation of the iron atoms. This slab may be reduced by hydrogenation; it is then strongly stabilized and the vertical displacement of the oxygen atoms agrees with the structure determined by LEED.

Kloor, H., and Honig, J. M., 1999, **Quantum state model of the Verwey transition in magnetite:** *Journal of Solid State Chemistry*, v. 148, no. 1, p. 135-42.

The Verwey transition in magnetite has been modeled in terms of the statistical properties of an array of quantum states associated with ferrous or ferric ions in octahedrally coordinated interstices of the spinel lattice. This collection is represented by an assembly of bonds and sites. Individual sites can be empty (as in the Fe<sup>3+</sup> state), trapped, or polaronic (if in the Fe<sup>2+</sup> state). Neglecting high-energy states involving electron occupation of neighboring lattice sites, one arrives at an analytic equation of state for the order parameter in its dependence on temperature, which can be solved numerically. This equation is sufficiently flexible to handle both the first- and second-order transitions by appropriate changes in parameters. The present theory rationalizes the experimentally observed changes in the order of the Verwey transition that result from alterations in the sample stoichiometry.

Muxworthy, A. R., and McClelland, E., 2000, **Review of the low-temperature magnetic properties of magnetite from a rock**

**magnetic perspective:** *Geophysical Journal International*, v. 140, no. 1, p. 101-14. The low-temperature behaviour of the magnetic energies that control domain structure is reviewed in detail. For the first time in rock magnetic literature, the low-temperature anomaly in spontaneous magnetization ( $M_s$ ) is documented and the differences between the saturation magnetization and  $M_s$  near the Verwey transition are discussed. The low-temperature behaviour of the magnetocrystalline anisotropy, and in particular the anomaly at  $T_v$ , is most likely to affect multidomain remanence during low-temperature cycling. For multidomain crystals the large increase in magnetocrystalline anisotropy intensity and reduction in symmetry on cooling through  $T_v$  is likely to reduce the stability of closure domains.

Muxworthy, A. R., and Williams, W., 1999, **Micromagnetic models of pseudo-single domain grains of magnetite near the Verwey transition:** *Journal of Geophysical Research*, v. 104, no. B12, p. 29203-17. Domain structures of small pseudo-single domain (PSD) magnetite near the Verwey transition ( $T_v$ ) at  $\approx 120$  K were modeled using an unconstrained three-dimensional micromagnetic algorithm. The single-domain (SD) threshold ( $d_0$ ) for the monoclinic phase below  $T_v$  was calculated to be  $\approx 0.14$   $\mu\text{m}$  at 110 K. However, as a result of the very high energy barriers in the monoclinic phase, grains near  $d_0$  in size and in vortex states are unlikely to denucleate domain walls to become SD. In simulated low-temperature cycling of SIRM, TRM, and pTRM through  $T_v$ , domain structures aligned along the monoclinic "easy" magnetocrystalline anisotropy axis, i.e. the c axis, below  $T_v$ . This process destroyed SIRM structures; however, for TRM and pTRM structures only "closure" domains were removed, increasing magnetostatic leakage and giving rise to a reversible anomaly in rough agreement with experimental studies. SIRM displayed a smaller anomaly at  $T_v$ , in agreement with experimental studies.

## Remanence & Magnetization Processes

Muxworthy, A. R., and McClelland, E., 2000, **The causes of low-temperature demagnetization of remanence in multidomain magnetite:** *Geophysical Journal International*, v. 140, no. 1, p. 115-31. New experimental observations of the behaviour of SIRM, TRM and pTRM at low temperatures show two main contributions to low-temperature demagnetization. The first (type-1 demagnetization) is due to 'kinematic' domain state reorganization and occurs throughout cooling from room temperature to the Verwey transition, at 120-124 K. The second arises from the change in anisotropy from cubic to monoclinic at  $T_v$ , which changes the overall domain structure of the grain. On warming in zero field, some domain walls will not return to their original positions but will take up a position that leads to a lower net remanence (type-2 demagnetization). In stoichiometric magnetite, demagnetization does not occur at 130 K at the isotropic point,  $T_k$ , contrary to some previous predictions. In non-stoichiometric magnetite,

the influence of the Verwey transition is greatly reduced, and anomalous behaviour is observed at  $T_k$ .

Shcherbakova, V. V., Shcherbakov, V. P., and Heider, F., 1999, **Properties of partial thermoremanent magnetization in pseudosingle domain and multidomain magnetite grains:** *Journal of Geophysical Research*, v. 105, no. B1, p. 767-81. Fifteen different igneous rocks and five synthetic specimens containing crushed and hydrothermally grown magnetite have domain structures (DS) over the range from single domain (SD) to multidomain (MD) grains. Two different kinds of pTRM were considered: (1) pTRM<sub>a</sub>( $T_1, T_2$ ) acquired when the upper temperature  $T_1$  of acquisition of pTRM is reached by cooling from  $T_c$  and (2) pTRM<sub>b</sub>( $T_1, T_2$ ) acquired by heating to  $T_1$  from room temperature. Thellier's laws of independence and additivity of pTRM( $T_1, T_2$ ) are violated in MD grains, as follows: (1) There is a decrease of pTRM( $T_1, T_2$ ) on cooling below  $T_2$ ; (2) the intensity of pTRM( $T_1, T_2$ ) depends on the thermal prehistory of the sample, e.g., pTRM<sub>b</sub>( $T_1, T_2$ )  $\neq$  pTRM<sub>a</sub>( $T_1, T_2$ ); and (3) a pTRM( $T_1, T_2$ ) has a tail that is not removed by thermal demagnetization at  $T_1 < T \leq T_c$ . Half of the natural samples have MD or PSD properties for low-temperature pTRMs, and typical SD-PSD behavior for high-temperature pTRMs. A linear relation was found for MD samples, such that pTRM<sub>a</sub>( $T_1, T_2$ )-pTRM<sub>b</sub>( $T_1, T_2$ ) is equal to intensity of a tail of pTRM<sub>a</sub>( $T_1, T_2$ ) after thermal demagnetization at  $T_1$ . This relationship implies that the remanence carriers, which constitute the tail of pTRM<sub>a</sub>, do not participate in the acquisition of pTRM<sub>b</sub>.

Worm, H. U., and Jackson, M., 1999, **The superparamagnetism of Yucca Mountain Tuff:** *Journal of Geophysical Research*, v. 104, no. B11, p. 25415-25. Yucca Mountain Tuff contains small titanomagnetite grains with narrow size distributions in the superparamagnetic range. Grain volume distributions calculated from thermal demagnetization results have been used in turn to calculate the frequency and temperature dependence of susceptibility, which agree well with experimental results. The frequency dependence of susceptibility reaches 30% at room temperature (RT) for one sample with a blocking temperatures just below RT, while  $\chi_{rd}=0$  at RT for a superparamagnetic sample with smaller grains. Thus  $\chi_{rd}$  is not limited to 15%, as a number of studies suggest, and  $\chi_{rd}=0$  must not be taken to imply the absence of superparamagnetic grains.

## Synthesis and Properties of Magnetite Minerals

Brown, A. P., and O'Reilly, W., 1999, **The magnetism and microstructure of pulverized titanomagnetite,  $\text{Fe}_{2.4}\text{Ti}_{0.6}\text{O}_4$ : the effect of annealing, maghemitization and inversion:** *Physics of the Earth and Planetary Interiors*, v. 116, no. 1, p. 19-30. TM pulverized in a ball-mill readily maghemitizes on the laboratory time scale. Ball-milling reduces particle size and also produces an internal nanocrystalline structure.

This structure is removed by annealing at 600°-800° C, but not by maghemitization. Magnetization parameters are consistent with an increasing importance of thermal fluctuations as maghemitization proceeds. In the transformations produced by annealing, maghemitization and inversion, the spinel component immediately post-transformation has non-equilibrium composition and/or concentration inherited from the pre-transformation spinel. Later re-equilibration of the coexisting phases, accelerated in the laboratory by elevated temperature, leads to diminution of the spinel component in favour of more stable phases. Unlike the inversion of maghemite to haematite, the inversion product of titanomaghemite is not a unique assemblage of phases.

Kurtz, R. L., Karunamuni, J., and Stockbauer, R. L., 1999, **Synthesis of epitaxial  $\text{Fe}_3\text{O}_4$  films on Cu(001):** *Physical Review B*, v. 60, no. 24, p. R16342-5. Fe films, oxidized on a Cu(001) substrate, have been found to form large, uniformly thick patches of oxide that dominate the mesoscopic surface structure producing large, atomically flat terraces. The oxide is found to grow in highly oriented chains, many microns in length, with well-defined preferred orientations relative to the substrate crystalline axes. Under the oxidation conditions used here,  $\text{Fe}_3\text{O}_4$  is the dominant oxide formed in thick films, a material with potential as a spin-polarized contact for magnetic tunneling devices.

Mornet, S., Vekris, A., Bonnet, J., Duguet, E., Grasset, F., Choy, J. H., and Portier, J., 2000, **DNA-magnetite nanocomposite materials:** *Materials Letters*, v. 42, no. 3, p. 183-8. It is shown that magnetite nanoparticles can be associated with double-stranded DNA. In a first step, a complex of DNA with  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$  ions is formed. Then, in a second step, magnetite nanoparticles are formed by increasing the pH. As shown by electrophoresis, the nanoparticles are strongly attached to the nucleic acid. From TEM imaging and Mössbauer measurement, a tentative model for the textural organization of DNA and magnetite is proposed.

Suber, L., Fiorani, D., Imperatori, P., Foglia, S., Montone, A., and Zysler, R., 1999, **Effects of thermal treatments on structural and magnetic properties of acicular  $\alpha\text{-Fe}_2\text{O}_3$  nanoparticles:** *Nanostructured Materials*, v. 11, no. 6, p. 797-803. The effect of transformations induced by annealing at different temperatures ( $450 < T_a < 1000^\circ\text{C}$ ) on the structure and magnetic properties of acicular  $\alpha\text{-Fe}_2\text{O}_3$  particles have been investigated by X-ray diffraction, TEM, SEM and magnetization measurements. The particles were prepared by hydrolysis and polymerization in an aqueous solution of  $\text{FeCl}_3$ . In the as-prepared sample, particles are constituted by small units (3-5 nm) separated by a less dense interlayer, while keeping the same crystallographic orientation. With increasing  $T_a$ , the sample microstructure evolves towards a collapse of the small units and then to a coalescence of particles. Coherently, the spin reorientation Morin temperature  $T_M$ , increases with  $T_a$ , the highest value ( $T_M=259$  K) being comparable to that of the bulk sample.

strated high initial values of  $\chi$  and  $\chi_{FD}\%$  with a less pronounced thermal alteration at 200°C and a marked decrease in  $\chi_{FD}\%$  above 400°C.

Whilst the detection of low temperature thermal alteration may well be of significance, of greater use would be a means to separate deliberate anthropogenic use of high temperature fires (eg permanent camp fires, semi industrial activity, funeral pyres etc.) from naturally occurring, rapid, low temperature events such as natural forest fires. This would be of particular use on sites where partial archaeological enhancement has occurred (such as the sandy loam site discussed above) and routine room temperature magnetic measurements may not be able to distinguish significant high temperature thermal alterations.

One potential answer to this problem was revealed during the low temperature study of the laboratory samples made on the MPMS. Figure 2 shows the low temperature results from the clay soil with the

cooling curves (2.5T field applied at 273K followed by cooling in zero field to 20K) plotted separately from the warming curves (2.5T applied at 20K followed by warming in zero field back to 273K). The more usual practise of plotting both curves together on the same graph axes often compresses the cooling curve (due to much greater magnitude of the remanent magnetisation obtained at 20K) suppressing the visual analysis of this data.

In this case, the separate curves demonstrate the anomalous behaviour of the samples heated above 300°C. The more usual positive slope of the cooling curves, due to the increase of  $M_s(T)$  as  $T \rightarrow 0K$ , is reversed for these samples and would appear to be diagnostic of heating to 300°C for at least 30 minutes for all three sediment types including the sandy soil. The origin of this anomalous behaviour is unclear, although it would appear to be related to the concentration or grain size of superparamagnetic material present.

Further time dependent measurements made on the MPMS demonstrate that the normalised magnetic viscosity shows only a marginal increase for samples heated above 300°C. However, the absolute magnitude of the viscosity increases significantly above this temperature. As the viscosity measurements were made over a similar period of time to the cooling curves it is possible that the anomalous cooling curve behaviour is explained by the gradual decay of the viscous remanence. It would appear that for the samples heated above 300°C the absolute magnitude of the initial viscous remanence is great enough to mask the expected increase of  $M_s$  as  $T \rightarrow 0K$ .

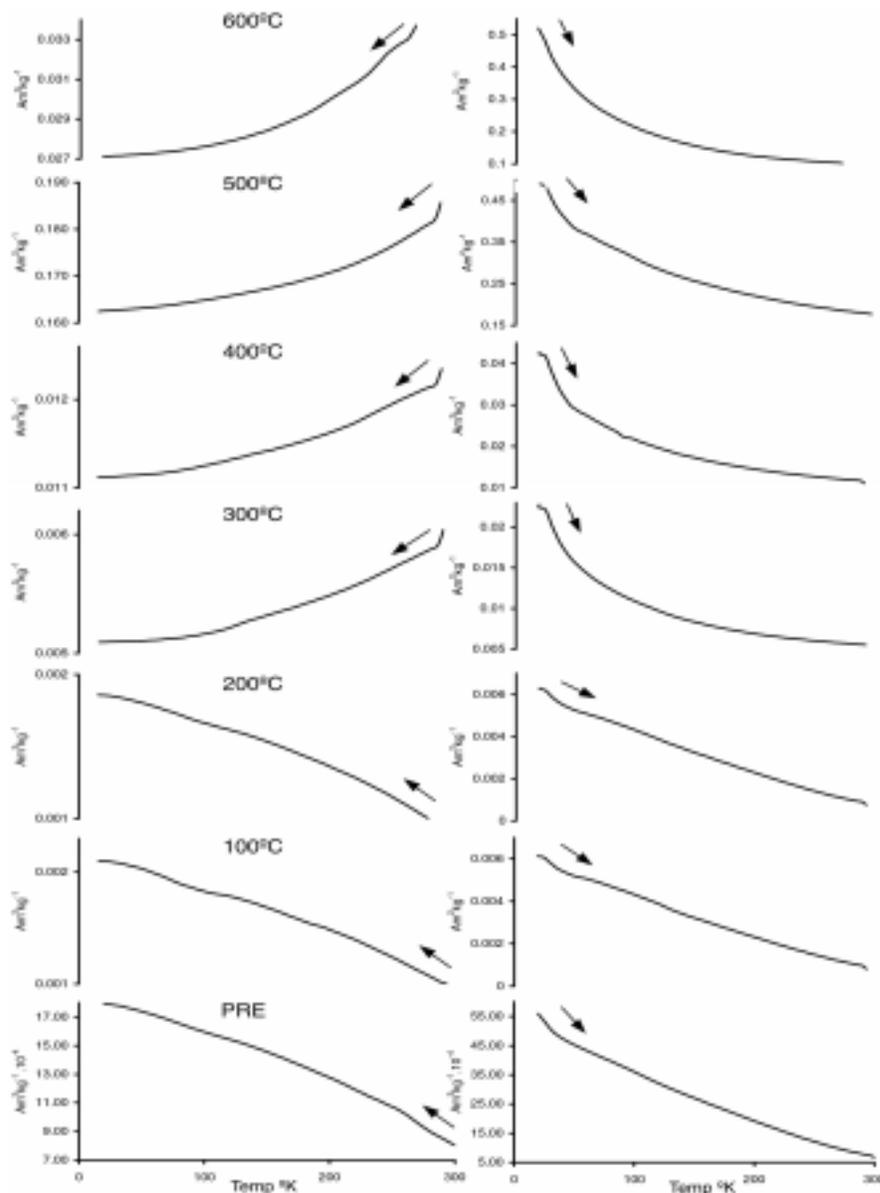
Whilst this latter explanation could account for the clay data shown in Figure 2 a number of deviations occur from the other substrates which are not, apparently, related to a simple decay of viscous remanence. This suggests the influence of a more complex mechanism due, perhaps, to increased grain-grain interactions between SP particles in the heated samples. Hopefully, further experiments can be devised to investigate this phenomenon further.

Similar anomalous cooling curves were demonstrated by both the burnt field samples recovered from the experimental camp fires and more importantly from a number of burnt archaeological deposits. This confirms that the phenomenon is stable over significant periods of time and may well provide a means for the identification of burnt deposits in absence of other visual evidence.

Finally, I would like to extend my thanks to all at the IRM who made visit such a highly enjoyable scientific and social experience. My project has certainly been greatly improved both through access to such a unique collection of instrumentation and the stimulating discussions on magnetism and many other matters that always seems to accompany IRM coffee, Friday afternoon tea and the occasional curry!

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**Figure 2;** Low temperature cooling (left hand side) and warming (right hand side) curves for the clay soil samples shown in Figure 1. Note the anomalous behaviour of the cooling curves for samples heated to greater than 300°C.

## Grain size dependent magnetic susceptibility of hematite

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My visit to the Institute for Rock Magnetism provided me the opportunity to measure some of the intriguing properties of pure hematite. I was interested in characterizing the fundamental magnetic properties of multidomain hematite. Many magnetic aspects of hematite are contrary to conventional wisdom. The coercivity of MD hematite is much less than that of SD hematite, yet mass-specific TRM and CRM are larger. My measurements were aimed at determining the grain size dependent properties.

Hematite is antiferromagnetic. Above the Morin transition temperature ( $T \sim 263$  K) the antiferromagnetically-coupled sublattice magnetizations lie in the basal plane, orthogonal to the c-axis. A slight canting of the spin axis out of exact antiparallelism, however, results in a net ferromagnetic moment within the basal plane, perpendicular to the spin sublattices. In addition to this 'spin-canted moment', hematite may have a slightly variable magnetization referred to as the 'defect moment'. Observed variation in SIRM is ascribed to this variable 'defect moment', which is thought to arise from lattice defects or from substituted non-magnetic cations. In perfect crystal this 'defect moment' ought to be negligible, but it could be large in strained and otherwise imperfect grains. Single domain grains of hematite have very large coercive force. The origin of this force is thought due to stress-induced anisotropy which is larger in smaller hematite grains.

Multidomain hematite grains acquire a TRM equal to more than 50% of their saturation magnetization when cooling

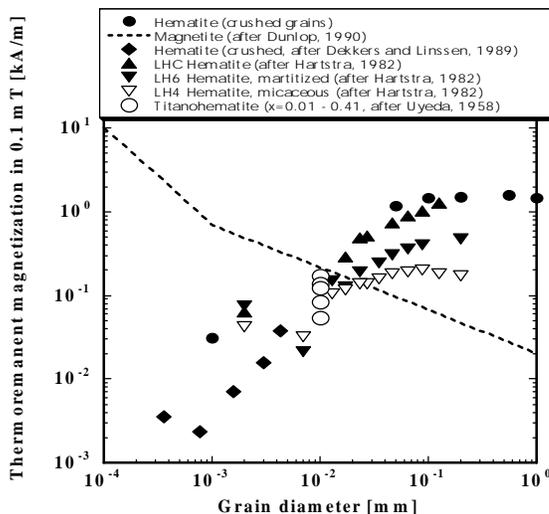


Figure 1: Grainsize dependence of weak-field TRM intensity in hematite and in magnetite (Kletetschka et al., 2000b).

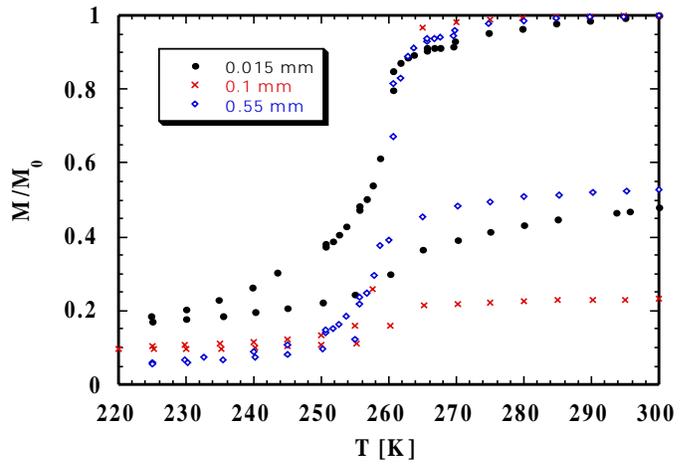


Figure 2: Morin transition for various grain sizes of hematite. Samples were saturated in a 5 Tesla magnetic field at room temperature. Then they were cooled to 220 K and rewarmed in zero field.

through the Curie point in the geomagnetic field (Kletetschka et al. 2000a). Besides hematite and titanohematite, all common magnetic minerals have TRM values much more than order of magnitude less than their SIRM values.

Hematite exhibits an inverse TRM grain-size dependence (Figure 1) across the SD-PSD transition, in contrast to all other magnetic minerals found in the crust (Kletetschka et al. 2000b). This is likely to be due to the weaker influence of demagnetizing energy with respect to wall pinning energy in the case of hematite, at temperatures almost up to the Curie temperature. Another factor is the greater importance of the magneto-static energy in the applied field, which for hematite dominates the total energy at high temperatures. Thermal blocking only occurs just below the Curie temperature in MD hematite, because of the large volume associated with Barkhausen moments in such grains.

### Hematite granulometry

Kletetschka et al. (2000b) suggested, based on their measurements, that at a grain size between 0.1 mm and 0.05 mm there is a significant magnetic transition in hematite behavior. At this transition TRM stops increasing with grain size and the resistance against AF demagnetization reaches a minimum. I wanted to know if this grain size of 0.1 mm can be detected by other magnetic experiments, and hoped to determine why this particular grain size is significant.

I wanted to establish if there is a similar grain size dependence for measurement of Morin transition (discontinuity in magnetic and other properties around 285 K). Iron - ore hematite sample L2, from Central Labrador (Kletetschka, 1998) was

crushed and sieved to obtain average grain sizes of 0.55, 0.2, 0.1, 0.05, 0.038, 0.025, and 0.015 mm. The individual grain size fractions were placed in gelatin capsule sample holders for low temperature magnetic measurements. Figure 2 shows characteristic curves for low-temperature cycling of a room-temperature remanence for three-grain sizes. All fractions showed a sharp Morin transition, however the detailed character of the transition changed with grain size. The variation with grain size is best seen in the fraction of memory recovered after the cooling experiment (Figure 3). The minimum remanence recovery is for the grain size range between 0.1 and 0.05 mm, confirming the observation by Kletetschka et al (2000b). This minimum suggests that this particular grain size fraction has a unique metastable saturated state balanced with the demagnetizing field and thus the demagnetization by cooling is the most effective. In grains larger than this threshold size, domain walls are strongly pinned in positions highly displaced with respect to zero magnetization state, raising the energy barrier for cooling demagnetization.

This observation inspired me to perform additional experiments to monitor the grain-size dependence of susceptibility as a function of the amplitude of external alternating magnetic field (at a constant frequency of 3 Hz). These experiments are shown in Figure 4. Remarkably, the grain size of 0.1 mm is a threshold for an onset of amplitude dependency of magnetic susceptibility. The phenomenon of amplitude dependency of magnetic susceptibility has been observed previously in titanomagnetite and pyrrhotite. The phenomenon is absent in pure magnetite, though. The grain size of

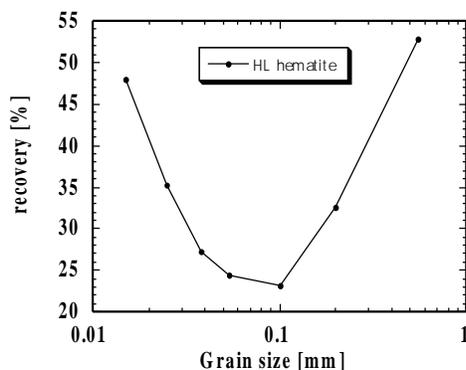


Figure 3: Magnetic memory recovery for different grain sizes of pure hematite during the Morin transition measurements (Figure 2)

0.1 mm forms a sharp boundary between distinct susceptibility behavior for smaller and larger grain sizes. Below 0.1 mm, susceptibility increases with increasing grain size, with negligible dependence on amplitude of the alternating magnetic field. However above the critical grain size of 0.1 mm, further size increases result in a significant susceptibility increase for higher amplitudes, but a negligible increase for the low amplitudes (Figure 4).

These results indicate that the characteristic high coercivity of fine hematite grains is lowered when the grain size increases in the region < 0.1 mm. I attribute this behavior to the increase in metastability of the hematite single domain state. As the volume increases (< 0.1mm) a grain continues to behave like a single domain particle, and

has its entire volume magnetized in one direction within the basal plane. The increase in magnetizing volume increases the value of demagnetizing field, forcing the grain to demagnetize by nucleation of new domain walls. The delicate balance between the single domain state and demagnetizing energy is reached for the grain size 0.1 mm. As soon as the 0.1 mm threshold is reached, grains start to increase their magnetic stability by nucleation of domain walls. But below this threshold the magnetic response to an alternating magnetic field is rotation of the entire volume of magnetization and thus the susceptibility is determined by the viscosity of the magnetic moment to rotate within the basal plane. According to Figure 4, the susceptibility of this process seems to be independent of the magnetic field amplitude. With onset of domain wall nucleation for grain sizes >0.1 mm the magnetic response to the applied field is different. This is because the mechanism of the response of the domain wall to the demagnetizing field relates to the magnetic interaction of the domain wall inside the hematite grain and not to the rotation of the entire magnetic moment within the plane perpendicular to the c-axis. Thus I think that the amplitude dependence of susceptibility relates to the fact that low amplitudes affect the entire volume like in the SD case for small grain sizes. However, with the introduction of the large amplitudes of magnetic field the domain walls add additional susceptibility component that increases with the grain size due to increase of the domain wall population.

**Conclusions:**

Grain-size-dependent magnetic behavior of hematite reveals a fairly large threshold size for the SD-MD transition. This change can be monitored through the observation of the minimum of the remanence recovery when cycling through the Morin transition. An even more apparent magnetic signature of this transition is observed in the variation of susceptibility with grain size. The magnetic susceptibility of SD grains has negligible dependence on the amplitude of the applied alternating magnetic field. With introduction of the domain walls, for grains above 0.1 mm, another amplitude-dependent susceptibility component is introduced allowing a clear distinction between the domain state of different grain sizes.

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 Kletetschka, G., P. J. Wasilewski and P. T. Taylor, Hematite vs. magnetite as the signature for planetary magnetic anomalies? *Physics of the Earth and Planetary Interiors*, In Press, 2000a.  
 Kletetschka, G., P. J. Wasilewski and P. T. Taylor, Unique thermoremanent magnetization of multidomain sized hematite: Implications for magnetic anomalies. *Earth and Planetary Science Letters*, 176, 469-479, 2000b.

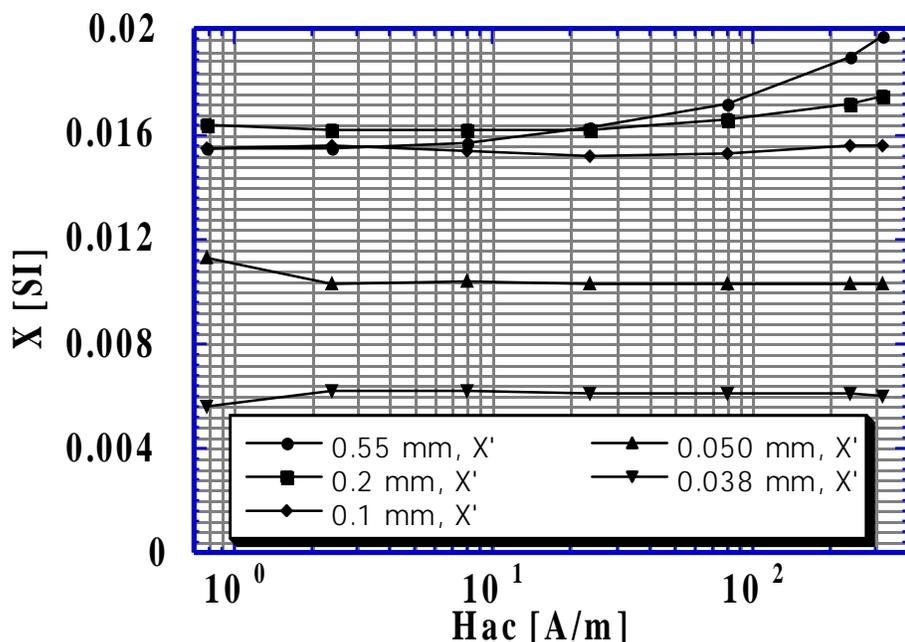


Figure 4: Susceptibility variation as a function of amplitude and grain size of hematite

# New Visiting Fellows

*Next application deadline: June 15. Check our Web site for new application forms.*

**Gary Acton**, *Texas A&M University*, Characterization of the rock-magnetic signature across glacial/interglacial transitions and geomagnetic excursions and reversals

**Cecilia Caballero**, *Universidad Nacional Autonoma de México*, Late Quaternary paleoclimate and paleoenvironments in Mexico and their inter-hemispheric connections: The Zacapu Basin, Michoacan

**Ellen Cowan**, *Appalachian State University*, Characterization of the

magnetic signature of glaci-marine sediment from coastal Alaska

**Özden Özdemir and David Dunlop**, *University of Toronto–Erindale Campus*, Low- and high-temperature experiments on iron oxides and sulphides

**Jürgen Matzka**, *Universität München*, Natural titanomaghemite: low-temperature/high-field hysteresis loops

**Lena Rubensdotter**, *University of Stockholm*, Transportation process and depositional environment derived from lacustrine sediments

**Daming Wang and Weiming Zhou**, *University of Michigan*, Correlation between low-temperature alteration and magnetic changes in MORB

**Xixi Zhao**, *University of California–Santa Cruz*, Rock magnetic study of basalt cores from Kerguelen Plateau in the southern Indian Ocean

## Domains to Terranes: The Fifth Santa Fe Conference on Rock Magnetism

The Fifth Santa Fe Conference on Rock Magnetism will be held at St John's College (Santa Fe, NM), July 20-23, 2000. The format, as usual, is designed to promote in-depth discussion of particular aspects and applications of rock magnetism; this year's themes will be 1) fundamental mineral magnetism and 2) problems and opportunities in tectonic applications of rock magnetism. **Sue Halgedahl** (U. of Utah) and **John Geissman** (U. of New Mexico) will chair the respective sessions.

Overview presentations by **Glenn Waychunas** (LBNL, Berkeley), **Sue**

**Brantley** (Penn State), and **Rob Van der Voo** (U. of Michigan) will introduce the themes and place them in a broad context. A small number of speakers (invited by the session chairs) will begin each session with critiques of particular relevant issues, to serve as starting points for discussion. All participants are encouraged to come armed with a few overhead transparencies to contribute to the discussion.

There is no conference registration fee. \$200 will cover housing in the St John's dorms (double occupancy) and meals in the cafeteria. A small number

of single rooms will be available for an additional \$40. Thanks to the sponsorship of the National Science Foundation, we will be able to offer partial reimbursement (approximately \$200 - \$250) of travel costs to and from Santa Fe.

Contact Mike Jackson at IRM to register and reserve a room; participation will be limited to about 45.

*Note:* Historic Santa Fe was founded in 1610, just a decade after publication of Gilbert's *De Magnete*.

...Gilbert  
*continued from page 1*

*'imitates a soul,' nay, it 'surpasses the human soul while united to an organic body.'*" (Burt, 1954)

Although Gilbert never had to answer to the Inquisition for his views, he did receive some harsh criticism from his scientific contemporaries, especially Francis Bacon (1561-1620). Sarton (1957) writes that Bacon's "severe judgment of Gilbert's achievement was largely due to the fact that he was so shocked by Gilbert's metaphysical fancies that he overlooked his first-class experiments. Gilbert was one of the first to vindicate the Baconian method of induction, but Bacon did not recognize this; he himself would have been unable to apply his own method as brilliantly as Gilbert did."

*De Magnete* consists of six books. The first is encyclopedic, containing "Ancient and modern matters of mention only, various opinions, & vanities" as well as ideas about the nature and origin of iron ores. Books 2-5 contain Gilbert's

experiments on iron and loadstones, mostly involving spherical stones that he called "terrellas" (little earths). Based on his observations, he makes a clear distinction between the magnetic phenomena of attraction (which he terms "coition," Book 2) and orientation ("verticity," or "disponent faculty"), both of which operate within an "orbe of virtue" around a loadstone or around the earth. Book 3 treats the general horizontal orientation of a compass ("versorium") along the meridian; Book 4 deals with departures from the meridian ("variation," which we now call declination). The vertical dip angle of a magnetized needle (Gilbert's "declination," our inclination) and its dependence on latitude are the subjects of Book 5. The final book deals with Gilbert's cautiously heretical cosmological views.

In about 1889 the "Gilbert Club" was formed, with Sir William Thompson (Lord Kelvin) as its president, to celebrate the tercentennial of the original publication and the dawn of the 20<sup>th</sup>

Century, with an English translation of *De Magnete*. (They were beaten to the punch by the "American translation" of P. Fleury Mottelay in 1893.) The Gilbert Club translation was primarily the work of Sylvanus P. Thompson, and the excerpts here come from this masterpiece. The flamboyant Elizabethan exposition contrasts sharply with the blandness of modern scientific prose. However, a careful 21st Century reader will recognize many familiar ideas, colorfully phrased, as well as a few surprises.

### Book 1

*"The earth emits various humours, not begotten of water nor of dry earth, nor of mixtures of these, but from the substance of the earth itself... The humours proceed from vapours sublimated from great depths... the vapours are condensed in places which are less hot than the spot whence they issued, and by help of the nature of the soils and mountains, as in a womb, they are at fitting seasons congealed and changed into metals... But in so*

far as that it becomes gold, or silver, or copper, or any other of the existing metals, this does not happen from the quantity or proportion of material, as the Chemists fondly imagine; but when the beds and region concur fitly with the material, the metals assume forms from the universal nature by which they are perfected...”

“Chemists say that if a bed of earthy sulphur be combined with fixed earthy quicksilver, ...iron is formed. These stern masters ...decide that this metal... is more truly a son of the earth than any other...; for that reason it is not smelted except in the hottest furnaces, with bellows... It is the strongest of metals, subduing and breaking all things, by reason of the strong concretion of earthy matter.”

“... it is not iron alone (the smelted metal) that points to the poles, nor is it the loadstone alone that is attracted by another and made to revolve magnetically: but all iron ores, and other stones, as Rhenish slates and the black ones from Avignon.... and many more of other colours and substances, provided they have been prepared; as well as all clay, grit, and some sorts of rocks, and, to speak more clearly, all the more solid earth that is everywhere apparent; given that the earth be not fouled with fatty and fluid corruptions; as mud, as mire, as accumulations of putrid matter; nor deformate by the imperfections of sundry admixtures; nor dripping with ooze, as marls: all are attracted by the loadstone, when simply prepared by the fire, and freed from their refuse humour...”

“Nor do I consider that there is any such thing as the Theamedes, or that it has a power opposite to that of the loadstone. Although Pliny...has copied from others the fable now made familiar by repetition: That in India there are two mountains near the river Indus; the nature of one being to hold fast all that is iron, for it consists of loadstone; the other's nature being to repel it for it consists of the Theamedes. Thus if one had iron nails in one's boots, one could not tear away one's foot on the one mountain, nor stand still on the other.”

#### Book Second

“Aristotle admits only two simple motions of his elements, from the centre and toward the centre, of light ones upward and heavy ones downward... But now our inquiry must be into the causes of other motions... which we have plainly seen in our magnetick bodies; and these we have seen to be present in the earth and in all its homogenic parts also... Five motions or difference of motions are then observed by us: Coition (commonly called attraction), the incitement to magnetic union; Direction towards the poles of the earth, and the verticity and continuance of the earth toward the determinate poles of the world; Variation, a deflection from the meridian, which we call a perverted movement; Declination, a descent of the magnetic pole below the horizon; and circular motion, or Revolution.”

“...we shall now show the reason of ... coition and the translatory nature of that motion. Since there are really two kinds of bodies, which seem to allure bodies with motions

manifest to our senses, Electricks and Magneticks; the Electricks produce the tendency by natural effluvia from humour; the Magneticks by agencies due to form, or rather by the prime forces.... A body which is attracted by an Electrick is not changed by it, but remains unshaken and unchanged, as it was before, nor does it excel any the more in virtue. A loadstone draws magnetical substances, which eagerly acquire power from its strength, not in their extremities only, but in their inward parts and their very marrow.”

“Lucretius, the poet of the Epicurean sect, sang his opinion of it thus:

‘First, then know,  
Ceaseless effluvia from the magnet flow –

“At an early period, while philosophy lay as yet rude and uncultivated in the mists of error and ignorance, few were the virtues and properties of things that were known and clearly perceived: there was a bristling forest of plants and herbs, things metallick were hidden, and the knowledge of stones was unheeded.”

Effluvia, whose superior powers expel  
The air that lies between the stone and steel.  
A vacuum formed, the steely atoms fly  
In a linked train, and all the void supply,  
While the whole ring to which the train is join'd  
The influence owns, and follows close behind.’

“But this cannot be the case in the least; since solid and very dense substances interposed, even squared blocks of marble, do not obstruct this power, though they can separate atoms from atoms.... Electrick effluvia are not only impeded by any dense matter, but also in like manner by flames... But as iron is not hindered by any obstacle from receiving force or motion from a loadstone, so it will pass through the midst of flames to the body of the loadstone and adhere to the stone... But if the iron itself became heated by a great heat, it is demonstrable that it would not be attracted.”

“Even a loadstone itself through a longish stay in the fire, loses the power of attracting implanted and innate in it, and any other powers. And although certain veins of loadstone exhale when burnt a dark vapour of a black colour, or of a sulphurous foul odour, yet that vapour was not the soul, or the cause of its attraction of iron (as Porta thinks), nor do all loadstones whilst they are being baked or burnt smell of or exhale sulphur. It is acquired as a sort of inborn defect from a rather impure mine or matrix.”

“... a slightly longer stone attracts more than a spherical one... even if the stones are both from the same mine and of the same weight and size. The way from pole to pole is longer in a longer stone, and the forces brought together from other parts are not so scattered as

in a round magnet and terrella, and in a narrow one they agree more and are better united, and a united stronger force excels and is pre-eminent. A much weaker office, however, does a plane or oblong stone perform, when ... the pole stops neither on the apex nor in the circle and orbe, but is spread over the flat. Wherefore also it invites a friend wretchedly, and feebly retains him, so that it is esteemed as one of an abject and contemptible class, according to its less apt and less suitable figure.”

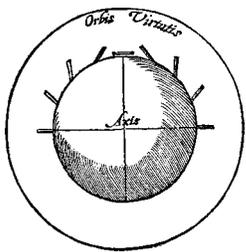
“Quite similar in potency are those stones which are of the same mine, and not corrupted by adjacent ores or veins. Nevertheless that which excels in size shows greater powers, since it seizes greater weights and has a wider orbe of virtue... But, it may be asked, if a stone of the same species and goodness weighing a drachm would seize upon a drachm of iron, would a stone of an ounce weight seize on an ounce, a pound on a pound, and so on? And this is indeed true; for it both strains and remits its strength proportionately, so that if a loadstone... were in equal proportion applied either to a suitably large obelisk or to an immense pyramid of iron, it would lift it directly... with no greater effort of its nature or trouble than a loadstone of a drachm weight embraces a drachm.

“Whatever things, whether animals or plants, are endowed with life need some sort of nourishment, by which their strength not only persists but grows firmer and more vigorous. But iron is not, as it seemed to Cardan and to Alexander Aphrodisius, attracted by the loadstone in order that it may feed on shreds of it, nor does the loadstone take up vigor from iron filings as if by a repast on victuals. Since Porta had doubts on this and resolved to test it, he took a loadstone of ascertained weight, and buried it in iron filings of not unknown weight; and when he had left it there for many months, he found the stone of greater weight, the filings of less. But the difference was so slender that he was even then doubtful as to the truth. What was done by him does not convict the stone of voracity, nor does it show any nutrition; for minute portions of the filings are easily scattered in handling.”

#### Book Third

“Directive force, which is also called by us verticity, is a virtue which spreads by an innate vigour from the equator toward the poles. That power, inclining in both directions towards the termini, causes the motion of direction, and produces a constant and permanent position in Nature, not only in the Earth itself but also in all magneticks.... All the interior parts of the earth mutually conspire together in combination and produce direction toward north and south.”

“The true austral pole of a loadstone, not the boreal (as all before us used to think), if the loadstone is placed in its boat on the surface of water, turns to the North.... But it must be understood on the threshold of this argument ... that these pointings of the loadstone or of iron are not perpetually made toward the true poles of the world, do not always seek those fixed and definite points, or remain on the line of the true



“A terrella sends out in an orbe its powers in proportion to its vigour and quality. ... when iron or any other magnetick of convenient magnitude comes within its orbe of virtue, it is allured... The nearer the parts are to the equinoctial, the more obliquely are the magneticals allured; but the parts nearer the poles appeal more directly, at the poles quite straight.”

## Gilbert, William

b. May 24, 1544, Colchester;  
d. Nov 30, 1603, London

Physician to Queen Elizabeth, Gilbert was “the first man to raise himself from the Aristotelian morass and work scientifically through an entire field of inquiry” (Price, 1958). The first prominent English Copernican, Gilbert is also credited with originating in *De Magnete* the term and concept of “mass.” In *De Mundo*, Gilbert wrote about comets, meteorological phenomena, and the nature of the sea. But his masterwork was his methodical investigation of magnetism, which began about 1581. Like Giambattista della Porta in Italy (whom he criticizes sharply and frequently in *De Magnete*), Gilbert formed one of the first informal scientific societies or academies, a forerunner of the Royal Society.

*meridian, but usually diverge some distance to the East or to the West. This discrepancy is called the Variation... and is merely a certain disturbance and perversion of the true direction...*

*“Let the blacksmith beat out upon his anvil a glowing mass of iron of two or three ounces weight into an iron spike of the length of a span or nine inches. Let the smith be standing with his face to the north, his back to the south, so that the hot iron on being struck has a motion of extension to the north. ... it is demonstrable that all those which are thus beaten out toward the north, and so placed whilst they are cooling, turn about on their centres; and floating pieces of iron (being transfixed, of course, through suitable corks) make a motion in the water, the determined end being toward the north... Those, however, which are pointed or drawn out rather toward the eastern or western point, conceive hardly any verticity or a very undecided one.”*

*“Let the same rod be heated again in the contrary position, and let it be placed so at a red heat until it is cool; for it is from its position in cooling (by the operation of the verticity of the earth) that verticity is put into the iron, and it turns round to parts contrary to its former verticity. So the end which formerly looked toward the north now turns to the south.”*

*“Let us see also what position alone and a direction toward the poles of the earth can affect by itself without fire and heat. Iron rods which have been placed and fixed for a long time, twenty or more years (as they not infrequently are fixed in buildings and across windows), those rods, I say, by that long lapse of time acquire verticity and turn round, whether hanging in the air, or floating (being placed on a cork), to the pole toward which they were pointing... for the long continued position of the body toward the poles is of much avail.”*

### Book Fourth

*“Since... in fact, the earth’s magnetic direction, owing to some fault and slip, deviates*

*from its right course and from the meridian, we must extract and demonstrate the obscure and hidden cause of that variance which has troubled and sore racked in vain the minds of many... And here we must at the outset reject that common opinion of recent writers concerning magnetick mountains, or any magnetick rock, or any phantasmal pole distant from the pole of the earth, by which the motion of the compass or versorium is controlled. This opinion... is entirely at variance with experience.”*

*“Since the surface of the globe is divided into high lands and deep seas, ... and since the force of all magnetical motions is derived from the constant and magnetick terrestrial nature which is more prevalent on the greater continent and not in the aqueous or fluid or unstable part; it follows that in certain parts there would be a magnetick inclination from the true pole east or west away from any meridian (whether passing through seas or islands) toward a great land or continent rising higher, that is, obviously toward a stronger and more elevated magnetick part of the terrestrial globe.”*

*“... along the coasts of Spain, France, England, Belgium, Germany, Denmark, and Norway, there lie on the right hand and toward the east a continent and extensive connected regions, and on the left extensive seas and a vast ocean lie open far and wide, it is consonant with the*

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*“We may see how far from unproductive magnetick philosophy is, how agreeable, how helpful, how divine!”*

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*theory (as has been carefully observed by many) that magnetical bodies should turn slightly to the East from the true pole toward the stronger and more remarkable elevations of the earth. But it is far otherwise on the eastern shores of northern America; for from Florida by Virginia and Norumbega to Cape Race and away to the north the versorium is turned toward the west.”*

*“Unless there should be a great dissolution of a continent and a subsidence of the land such as there was of the region Atlantis of which Plato and the ancients tell, the variation will continue perpetually immutable.”*

*“Let there be a round vessel filled with water: in the middle of the surface of the water place a slender iron wire on a perfectly round cork, so that it may just float in equilibrium on the water; let the wire be previously touched by a magnet, so that it may more readily show the point of variation, the point D as it were: and let it remain on the surface for some time. It is demonstrable that the wire together with the cork is not moved to the side D of the vessel: which it would do if an attraction came to the iron wire by D: and the cork would be moved out of its place. ... it is moved about its own centre without any transference to the edge of the vessel. Direction does not arise from attraction, but from the turning and disposing power which exists in the whole earth, not in the pole or some other attracting part of the stone...”*

### Book Fifth

*“The declination of a magnetick needle above a terrella is shown by means of several iron wires, of the length of a barleycorn, arranged along a meridian. The wires on the equator are directed by virtue of the stone toward the poles, and lie down upon its body along the plane of its horizon. The nearer they are brought to the poles, the more they are raised up by their versatory nature. At the poles themselves they point perpendicularly toward the very centre.”*

*“We may see how far from unproductive magnetick philosophy is, how agreeable, how helpful, how divine! Sailors when tossed about on the waves with continuous cloudy weather, and unable by means of the celestial luminaries to learn anything about the place or the region in which they are, with a very slight effort and with a small instrument are comforted, and learn the latitude of the place.”*

*“We ... consider that the whole universe is animated, and that all the globes, all the stars, and also the noble earth have been governed since the beginning by their own appointed souls and have the motives of self-conservation. Nor are there wanting, either implanted in their homogenic nature or scattered through their homogenic substance, organs suitable for organick activity, although these are not composed of flesh and blood as animals... Miserable were the condition of the stars, abject the lot of the earth, if that wonderful dignity of life be denied to them, which is conceded to worms, ants, moths, plants, and toadstools...”*

### Book Sixth

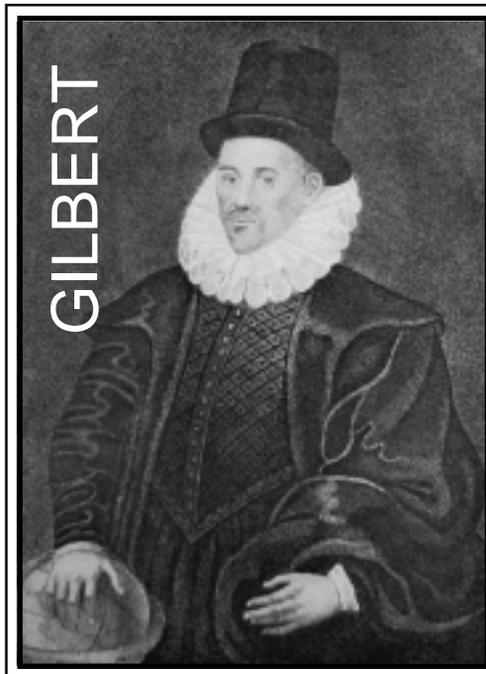
*“...not only probable, but manifest, does the diurnal rotation of the earth seem, since nature always acts through a few rather than through many; and it is more agreeable to reason that the Earth’s one small body should make a diurnal rotation, than that the whole universe should be whirled around.”*

*“And if the Earth were not made to spin with a diurnal revolution, the Sun would ever hang over some determinate part with constant beams, and by long tarriance would scorch it, and pulverize it, and dissipate it, and the Earth would sustain the deepest wounds; and nothing good would issue forth; it would not vegetate, it would not allow life to animals, and mankind would perish. In other parts, all things would verily be frightful and stark with extreme cold; whence all high places would be very rough, unfruitful, inaccessible, covered with a pall of perpetual shades and eternal night. Since the Earth herself would not choose to endure this so miserable and horrid appearance on both her faces, she, by her magnetick astral genius, revolves in an orbit, that by a perpetual change of light, there may be a perpetual alternation of things, heat and cold, risings and settings, day and night...”*

Gilbert

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The Gilbert portrait from the Bodleian Library, Oxford, from *The De Magnete of William Gilbert*, by Duane H Roller, 1959, Menno Hertzberger.



press), or if you have any suggestions to improve the newsletter, please notify the editor:

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