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Institute for Rock Magnetism

von Humboldt's Equinoxial Journey

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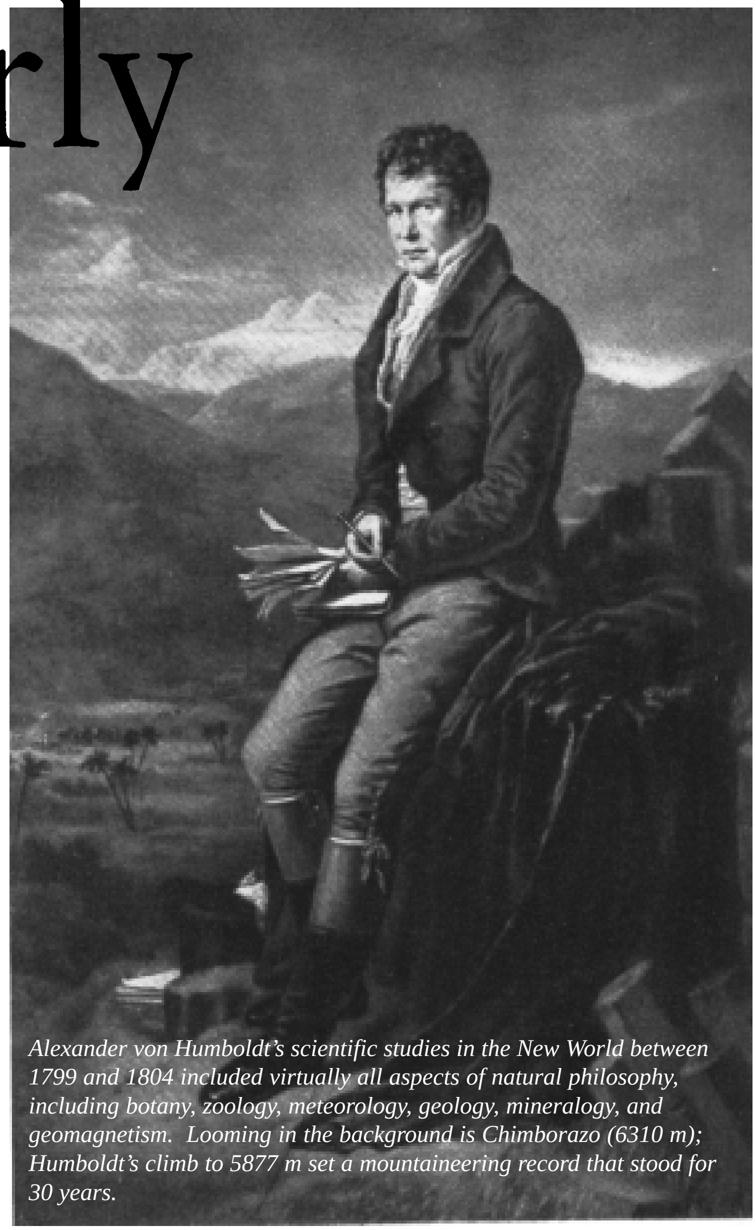
IRM

Century Series, part 3.
1600: Gilbert (v9, n4)
1700: Halley (v7, n4)
1800: Humboldt

"I regard the discovery of the law of [decreasing] magnetic force from the pole to the equator as the most important result of my American voyage" - Humboldt, *Relation Historique du Voyage aux Régions Équinoxiales du Nouveau Continent.*

In June 1799, Alexander von Humboldt set sail from Madrid with the French botanist Aimé Bonpland, bound for the Spanish territories in the New World for a five-year voyage of scientific investigation. The specimens and data they collected provided Humboldt with sufficient material for a lifetime of research and popular writings, which were so well received that within a few years, he is said to have been the second-most famous man in Europe (after Napoleon).

Humboldt had studied at Göttingen and then at the Freiburg Mining Academy (run by Abraham Werner, father of the Neptunist school of thought). His broad interests in the natural sciences were combined with a zeal for travel that had been excited by the writings of Bougainville (the first Frenchman to circumnavigate the globe) and the German naturalist Johan Forster (who had, with his son Georg, accompanied Cook on his second voyage around the world in 1775). Humboldt became acquainted with the younger Forster in Göttingen, and after he left Freiburg they travelled together through northern Europe, further whetting his appetite for field studies. When his mother passed away in 1796 (his father having preceded her in 1779), Humboldt's inheritance allowed him to leave his position with the Prussian Department of Mines and move to Paris.



Alexander von Humboldt's scientific studies in the New World between 1799 and 1804 included virtually all aspects of natural philosophy, including botany, zoology, meteorology, geology, mineralogy, and geomagnetism. Looming in the background is Chimborazo (6310 m); Humboldt's climb to 5877 m set a mountaineering record that stood for 30 years.

Gemälde von Karl Baron von Steuben, Paris 1812: Schloß Tegel. From Alexander von Humboldt: Sein Leben in Selbstzeugnissen, Briefen und Berichten, *by Rudolph Borch, Verlag des Druckhauses Tempelhof, Berlin, 1948.*

There he was immersed in the scientific culture of the First Republic, becoming acquainted with Cuvier, Laplace and Lamarck. A new round-the world expedition was being planned, and Humboldt and Bonpland eagerly enlisted, but they were disappointed by repeated postponements, and eventually decided to mount an expedition of their own to northern Africa. En route through Spain, however, their plans were abruptly changed by an invitation from the Castilian court to survey the Spanish territories in the New World and report on exploitable mineral assets.

It was the astronomer/mathematician Jean-Charles de Borda who drew Humboldt's attention to the study of geomagnetism, especially with regard to the intensity of the field. The spatial variations in the direction of the field were by then fairly well documented, the first declination map having been produced by Halley nearly a century earlier. The first known study of possible intensity variations at different points on the Earth's surface was that of Mallet in 1769, which, due to faulty apparatus, yielded no apparent difference between the intensities at St Petersburg and at a point 17° farther north. Borda himself had measured the oscillation period of a magnetic needle at various points on a 1776 expedition to the Canary Islands, and again failed to detect any changes in field strength. Despite these negative results, Borda was convinced that intensity does change with latitude, and he encouraged Humboldt to try again with an improved oscillation apparatus.

Humboldt *continued on page 9...*

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Separation of paramagnetic and ferrimagnetic susceptibility anisotropy using high field and low field methods: Or, adventures at 1 am with a VSM

Magnetic methods have long been used as a method to characterize the preferred orientation of minerals within rock samples. The anisotropy of magnetic susceptibility (AMS) is a common magnetic method used to examine rock fabric, and has been used to investigate sedimentary, igneous, metamorphic, and deformation processes. AMS is typically measured with a low field (<0.1mT), alternating current, magnetic induction bridge. The AMS signal is a result of a combination of grain shape, grain distribution, crystallographic orientation.

The interpretation of magnetic fabrics, however, is generally limited to rocks in which the susceptibility is dominated by a single phase which dominates the magnetic fabric. The interpretation of samples with contributions from multiple phases often requires the implicit assumption that different minerals have similarly oriented AMS ellipsoids. Alternatively, a method can be devised to separate the magnetic components. One method for doing this relies on the differing response of ferrimagnetic and paramagnetic minerals to high applied fields. With an increase in applied field (H), the magnetization (M) for paramagnetic and diamagnetic minerals increases and decreases, respectively, in a linear manner. In contrast, ferrimagnetic minerals tend to saturate at some applied field, such that there is no longer an increase in magnetization. So, if you can go to the Institute of Rock Magnetism and crank the field of the Vibrating Sample Magnetometer (VSM) so high that anyone with a pacemaker within 10m is going to be in serious trouble*, one has a chance of separating these components.

During the Fall of 2000, we designed and built some hardware, wrote some software, and generally made nuisances of ourselves in order to separate the high field paramagnetic component of AMS from the ferrimagnetic AMS component. Because we wanted to be able to determine whether we had succeeded, we made natural/synthetic samples. The methodology was to start with known, but separate, paramagnetic and ferrimagnetic components and then combine them to determine if we can accurately separate them. We used standard paleomagnetic cores of the Thomson Formation that were known to have only a paramagnetic signal. We then sawed these samples in half, inserted a nylon spacer the thickness of the saw blade and measured the AMS in low field conditions in the KLY-2 Kappa Bridge. At the same time, we created a thin nylon disk and inserted grains of magnetite into a hole in the center. We put nylon "ends" around this disk to make a standard size core and measured its AMS in low field conditions. Finally, we put the magnetite-laden disk in the middle of the pre-cut Thomson Formation and subjected the whole mess to low-field and then high-field conditions. It turns out, at least for these rocks, we could separate the ferrimagnetic and the paramagnetic components.

Our technique was to apply high magnetic fields, which saturate the ferromagnetic minerals, and use the high field slope (the change in induced magnetization for changes in applied field at high field values) to calculate the paramagnetic directional susceptibilities. We were able to successfully saturate the ferromagnetic component and to correct for significant shape effects in these high field measurements. Using the high field slope, one can eliminate the ferromagnetic component and determine the magnetic fabric resulting solely from the paramagnetic component. Using this information, in combination with low field AMS measurements which is the result of the paramagnetic plus ferromagnetic susceptibility, it is also possible to calculate the magnetic fabric resulting solely from the ferromagnetic component through tensor subtraction. This new method promises to be useful in the interpretation of AMS from rocks with a significant susceptibility from both paramagnetic and ferromagnetic minerals.

Here are the nitty-gritty details: Hysteresis loops were measured in multiple orientations as the sample holder was rotated around its X, Y and Z axis. The hysteresis loop configuration on the VSM was set such that: 1) The maximum field was ~500mT (400 kA/m); 2) The field increment between measurements was10kA/m; 3) There was a 0.5 s averaging time for each measurement; and 4) The rotation increment was 45º between loops. Since the sample rotated around 3 axes at 45° intervals, 24 hysteresis loops were measured on each sample. Consequently, each orientation measured at least twice (i.e., in the positive and negative direction), and thus there were four independent measurements taken for each of the three rotation axes. Individual hysteresis loops required about two minutes each and a complete suite of measurements for an individual sample took 50-60 minutes. A series of three computer programs were used to analyze the data from each sample. The purpose of the first program was to calculate the high-field slope from the VSM data, in order to determine the paramagnetic signal. The purposes of the second program are to: 1) Average the same orientations for consistency; 2) Normalize by measured values for a standard isotropic sample, to remove shape effects; 3) Normalize the X,Y, and Z axis rotations with respect to each other, using the common orientations where the measurement planes intersect; and 4) Output the data in a format acceptable for calculation of the eigenvalues and eigenvectors using the same software used for the low field values. The magnitude and direction of the AMS ellipsoid is then calculated by substituting the values into the program that operates the KLY-2 Kappa bridge at the *IRM* at the University of Minnesota.

Although the science was challenging, a major problem was designing equipment that could do the analysis accurately enough to determine the high field AMS. Many thanks are due to John, Jon, and Mike at the engineering shop at the University of Minnesota for building us multiple versions of the equipment in the pursuit for a design that worked. They did the work quickly and put up with some very strange prototypes. Thanks also to everyone at the *IRM* for their hospitality and baked goods during our stay.

Post Script Note: We have left all of the equipment for taking high-field measurements on 1 inch cores at the IRM, in the hope that other workers may find it useful. Basil is marginally responsible for the marginal computer programs, and copies of the programs are available at the *IRM*.

* editor's note: the lowest field known to affect a pacemaker is 1.7 mT (17 G), and persons with pacemakers are usually advised to avoid fields exceeding 0.5 mT (5 G). Measured values of the field near the VSM (and in fact near all the *IRM* instruments) never exceed 0.5 mT at a distance of 1 m from the magnet.

VF Reports
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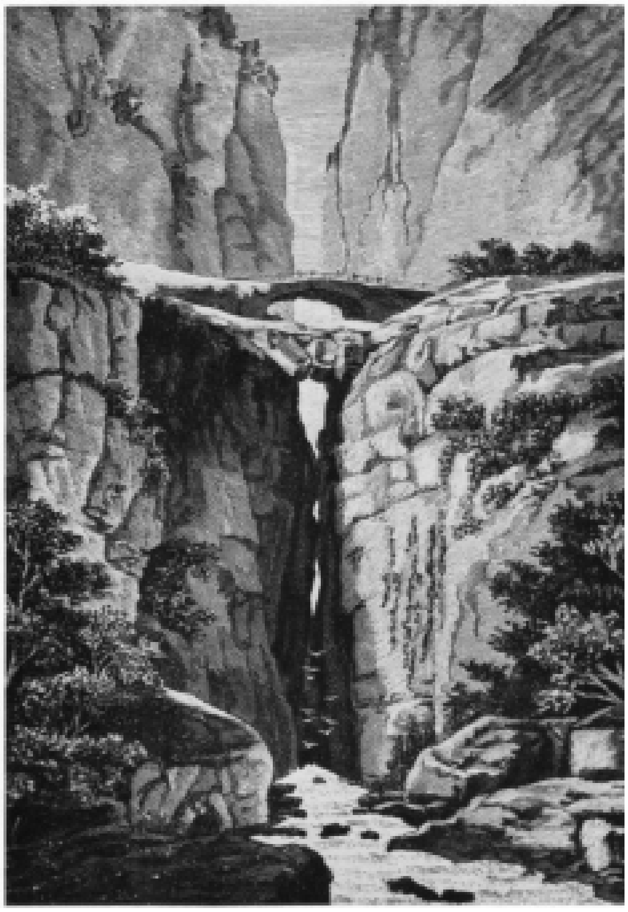

Source: Alexander von Humboldt, *by L. Kellner, 1963, Oxford University Press, London.*

The natural bridge of Icononzo, over the Rio de la Suma Paz (Colombia), from Humboldt's ***Vues des Cordillères et monuments des peuples indigènes de l'Amérique*** *(Paris, 1810).*

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.*

Alteration, Diagenesis and Remagnetization

Passier, H. F., de Lange, G. J., and Dekkers, M. J., 2001, **Magnetic properties and geochemistry of the active oxidation front and the youngest sapropel in the eastern Mediterranean Sea**: *Geophysical Journal International, v. 145*, no. 3, p. 604-14.
Original aeolian and volcanic magnetic grains were altered during deposition of sapropel S1 by reductive diagenesis, causing lower magnetic intensities and coarser grain sizes. Since the end of sapropel deposition a downward-moving oxidation front has oxidized the upper half, which is enriched in diagenetic Fe oxides with relatively high coercivity and ARM. The maximum coercivity is found in a distinct layer at the top of the unoxidized sapropel, containing a mixture of freshly precipitated SP grains and SD magnetite.

Anisotropy

Hounslow, M. W., 2001, **The crystallographic fabric and texture of siderite in concretions: implications for siderite nucleation and growth processes**: *Sedimentology, v. 48*, p. 533-557.
Anisotropy of magnetic susceptibility is controlled by paramagnetic siderite in Westphalian non-marine concretions (which show a preferred orientation of siderite c-axes in the bedding plane), and in Pliensbachian marine concretions (c-axes perpendicular to bedding). Both fabrics are apparently controlled by the substrate at the site of nucleation, which was probably clay mineral surfaces. Fabric changes across the concretions partially mimic the progressive compaction-induced alignment of the clay substrates, while the concretions grew during burial.

Trindade, R. I. F., Mintsa Mi Nguema, T., and Bouchez, J. L., 2001, **Thermally enhanced mimetic fabric of magnetite in a biotite granite**: *Geophysical Research Letters, v. 28*, no. 14, p. 2687-90.
Thermally induced growth of mimetic magnetite after biotite is demonstrated by the equivalence of AMS and anisotropy of ARM, after heating of biotite single crystals and whole rock specimens from a magnetite-free granite (Elba Island, Italy). Between 500° and 725° C magnetite nucleates and grows within and parallel to the biotite cleavages. At higher temperatures magnetite undergoes partial haematization. In granites having composite (tourmaline+biotite) paramagnetic fabrics, the fabric of biotite can be selectively thermally enhanced.

Data Processing and Analytical Methods

Kruiver, P. P., Dekkers, M. J., and Heslop, D., 2001, **Quantification of magnetic coercivity components by the analysis of acquisition curves of isothermal remanent magnetisation**: *Earth and Planetary Science Letters, v. 189*, no. 3, p. 269-76.
A refined method of analysing IRM acquisition curves in terms of log Gaussian distributions is based on fitting the IRM acquisition curve (log applied field) with: (i) the IRM on a linear scale, (ii) the acquisition curve expressed as a gradient, and (iii) the IRM on a probability scale. Even when a sample is not saturated, its magnetic properties can be defined, although with less certainty. The number of magnetic components required for an optimal fit to a measured IRM acquisition curve is evaluated statistically.

Pike, C. R., Roberts, A. P., and Verosub, K. L., 2001, **First-order reversal curve diagrams and thermal relaxation effects in magnetic particles**: *Geophysical Journal International, v. 145*, no. 3, p. 721-30.
There are four distinct manifestations of thermal relaxation on FORC diagrams: 1) it shifts the FORC distribution to lower coercivities; 2) at intermediate temperatures, it can generate a secondary peak about the origin of a FORC diagram (superparamagnetic); 3) it can produce a small, but systematic, upward shift of a FORC distribution; 4) it produces contours that lie near and parallel to the vertical axis in the lower quadrant of a FORC diagram. These make FORC diagrams a powerful tool for studying the effects of thermal relaxation in bulk natural samples.

Smirnov, A. V., and Tarduno, J. A., 2001, **Estimating superparamagnetism in marine sediments with the time dependency of coercivity of remanence**: *Journal of Geophysical Research, v. 106*, no. B8, p. 16135-43.
A model describing the dependence of H_{cr} on measurement time and SP content is supported by experimental data. Measurements on pelagic sediments (ODP Site 805C) reveal a 25-30% SP increase starting just above the modern iron redox boundary. Thermal demagnetization of an SIRM acquired at 20 K fails to show the same SP changes, because the low-temperature data are sensitive to small differences in magnetic mineralogy that accompany diagenesis. Specifically, differential maghemitization causes varying suppression of the remanence changes associated with the Verwey transition.

van Oorschot, I. H. M., and Dekkers, M. J., 2001, **Selective dissolution of magnetic iron oxides in the acid-ammonium oxalate/ ferrous iron extraction method. I. Synthetic samples**: *Geophysical Journal International, v. 145*, no. 3, p. 740-8.
In an adapted version of the acid-ammonium oxalate (AAO) method, Fe^{2+} is added to the extraction solution prior to the experiment [the AAO-Fe(II) method]. Synthetic samples contained a quartz matrix with 0.1 wt per cent of iron oxides (either magnetite or maghemite with grain sizes of <0.5 µm (fine grained or SD/PSD) and <5 µm (coarse grained or MD/ PSD), or a 1:1 mixture of both minerals). The AAO-Fe(II) method preferentially dissolved the smaller iron oxides from the samples. For samples containing iron oxides with coarse grain size there is a preference for dissolving maghemite rather than magnetite.

Environmental Magnetism

Lanci, L., Hirt, A. M., Lotter, A. F., and Sturm, M., 2001, **A record of Holocene**

abstracts *continued on page 4...*

climate in the mineral magnetic record of Alpine lakes: Sagistalsee and Hinterburgsee: *Earth and Planetary Science Letters, v. 188*, no. 1, p. 29-44.
Although relatively similar in water volume and general environment, Sagistalsee and Hinterburgsee have different catchment vegetation and lithology. The mineral magnetic records from the two lakes compare well on a common time scale and show that the influence of local conditions is rather small. A climatic influence on both records is a consequence of the production of an authigenic mineral with particularly uniform magnetic properties during warmer stages and the influx of heterogeneous detrital magnetic minerals during colder stages.

Lanci, L., Kent, D. V., Biscaye, P. E., and Bory, A., 2001, **Isothermal remanent magnetization of Greenland ice: preliminary results**: *Geophysical Research Letters, v. 28*, no. 8, p. 1639-42.
IRM was measured on a small suite of ice samples of Holocene and Last Glacial Maximum (LGM) age. All samples contained an easily measurable concentration of magnetic minerals that can be estimated using IRM intensity. Experiments at 77 K indicate ice magnetic properties which are consistent with varying concentrations of magnetite or maghemite. Interestingly, the Holocene ice samples tend to have higher magnetic concentrations, despite having much lower total polar dust contents, than the few LGM ice samples tested thus far.

Stage, M., 2001, **Magnetic susceptibility as carrier of a climatic signal in chalk**: *Earth and Planetary Science Letters, v. 188*, no. 1, p. 17-27.
The insoluble residue of the Maastrichtian North Sea chalk contains quartz, dolomite, pyrite, organic material, ferrimagnetic minerals and clay minerals (smectite-illites). The concentration and in particular the type of clay minerals determine the magnetic susceptibility of the residue and of the bulk chalk. The existence of a detrital component in the insoluble residue suggests that the cyclic variations in the bulk magnetic susceptibility are controlled by changes in the runoff from land into the basin.

Torii, M., Lee, T. Q., Fukuma, K., Mishima, T., Yamazaki, T., Oda, H., and Ishikawa, N., 2001, **Mineral magnetic study of the Taklimakan desert sands and its relevance to the Chinese loess**: *Geophysical Journal International, v. 146*, no. 2, p. 416-24.
Modern sands in the central and western Taklimakan desert contain nearly stoichiometric magnetite as the dominant magnetic mineral. The presence of titanomagnetite is unlikely, and contributions from a high-coercivity mineral(s) are minor. Mean magnetic grain size is PSD or larger. Comparison of hysteresis data for these and samples from the Chinese Loess Plateau shows an apparent decreasing grain size trend that suggests the Taklimakan desert is one of the potential dust source areas, even though it is located more than 2000 km west of the central Loess Plateau.

Extraterrestrial Magnetism

Morris, R. V., Golden, D. C., Ming, D. W., Shelfer, T. D., Jorgensen, L. C., Bell, J. F., III, Graff, T. G., and Mertzman, S. A., 2001, **Phyllosilicate-poor palagonitic dust from Mauna Kea Volcano (Hawaii): a mineralogical analogue for magnetic Martian dust?**: *Journal of Geophysical Research, v. 106*, no. E3, p. 5057-83.
These samples are spectral analogues of Martian bright regions at visible and near-IR wavelengths. The crystalline phases are plagioclase feldspar, Ti-magnetite, minor pyroxene, and trace hematite. Mössbauer spectroscopy showed nanophase ferric oxide, magnetite/titanomagnetite, hematite, and minor glass and ferrous silicates. Direct observation by TEM showed that the crystalline and X-ray amorphous phases are normally present together in composite particles. Ti-bearing magnetite occurs predominantly as 5-150 nm particles embedded in noncrystalline matrix material and most likely formed by crystallization from silicate liquids under conditions of rapid cooling prior to palagonitization of glass.

Thomas-Keprta, K. L., Bazylinski, D. A., Kirschvink, J. L., Clemett, S. J., McKay, D. S., Wentworth, S. J., Vali, H., Gibson, E. K., Jr., and Romanek, C. S., 2000, **Elongated prismatic magnetite crystals in ALH 84001 carbonate globules: potential Martian magnetofossils**: *Geochimica et Cosmochimica Acta, v. 64*, no. 23, p. 4049-81.
TEM analysis of 594 magnetite (Fe_3O_4) crystals acid-extracted from carbonate globules in ALH 84001 indicates three morphological populations: irregularly shaped (389), elongated prisms (164), and whisker-like (41). As a possible terrestrial analog, the authors examined 206 magnetites recovered from strain MV-1 cells, and identified six distinguishing properties that, collectively, are not observed in any known population of inorganic magnetites. Of the ALH 84001 magnetites, the elongated prismatic particles (27% of the total) are indistinguishable from the MV-1 magnetites in five of these six characteristics observed for biogenically controlled mineralization of magnetite crystals.

Magnetic Field Records and Paleointensity Methods

Cronin, M., Tauxe, L., Constable, C., Selkin, P., and Pick, T., 2001, **Noise in the quiet zone [paleomagnetism]**: *Earth and Planetary Science Letters, v. 190*, no. 1, p. 13-30.
Two overlapping sections from the Scaglia Bianca Formation (85-89.5 Ma) show the expected normal field orientation, but a number of specimens are directionally anomalous. Most of these deviant specimens have distinct rock magnetic characteristics. After elimination of this rock magnetic 'noise' there is a high degree of agreement in direction and to a lesser extent relative intensity between the two sections. The clean data set is a robust record of geomagnetic field behavior during this interval. The normalized variability in paleointensity (std. dev. ~28% of the mean value) is significantly lower than seen during the Oligocene over intervals in which reversals or tiny wiggles occur (typically ~50%). The VGP dispersion is compatible with that in volcanic rocks from the same latitude and 80-110 Ma in age.

Fabian, K., 2001, **A theoretical treatment of paleointensity determination experiments on rocks containing pseudo-single or multi domain magnetic particles**: *Earth and Planetary Science Letters, v. 188*, no. 1, p. 45-58.
A phenomenological theory of TRM is applied to model Thellier paleointensity experiments. Intrinsic curvature of the Arai plot for samples containing PSD or MD particles can be attributed exclusively to remanences which are unblocked below their blocking temperature. Thus the demagnetization tail of pTRM is not a direct measure for a sample's tendency to yield a curved Arai plot. Here it is proposed to use the decay of a pTRM(T_1, T_2) which occurs below the lower temperature T_1 as a more reliable pre-selection criterion. An extended Thellier method which compares the thermal demagnetization of NRM with that of an artificial TRM according to the applied TRM theory should result in a perfectly linear modified Arai plot even for PSD or MD samples if no alteration or viscous effects occur.

Ravilly, M., Horen, H., Perrin, M., Dyment, J., Gente, P., and Guillou, H., 2001, **NRM intensity of altered oceanic basalts across the MAR (21° N, 0-1.5 Ma): A record of geomagnetic palaeointensity variations?**: *Geophysical Journal International, v. 145*, no. 2, p. 401-22.
In samples collected along two long cross-sections, NRM intensities range from 1.3 to 25.4 A m^{-1} but do not display the expected exponential decay with age. Despite the scatter, they seem to present short-wavelength variations consistent on both flanks. Because of the relative uniformity in grain size, ulvospinel content and amount of magnetic minerals, the observed intensity variations may be due either to oxidation degree variations or to geomagnetic field intensity changes. Curie temperatures display no increase towards the flanks nor a clear relationship with NRM intensities, suggesting that oxidation degree is not the major control on NRM variations. Half of the collected samples, either fresh or highly altered, provide good-quality palaeointensity determinations.

Shcherbakov, V. P., and Shcherbakova, V. V., 2001, **On the suitability of the Thellier method of palaeointensity determinations on pseudo-single-domain and multidomain grains**: *Geophysical Journal International, v. 146*, no. 1, p. 20-30.
The concavity of the Arai-Nagata diagrams is not related to the two most noticeable violations of the Thellier laws documented for non-SD particles: the tail of pTRM and the dependence of pTRM intensity on the thermal history of the sample. The non-linear Arai-Nagata plots occur because samples lose too much remanence at relatively low temperatures and recover too little of it. The excessive loss of the TRM is due at least partly to some partial demagnetization of high-temperature TRM components and to progressive stabilization of domain structure during repetitive heatings to moderate temperatures. For natural MD samples a linear fit to the low-temperature data yields palaeointensities overestimated by as much as 60 per cent.

Hydrothermally grown or crushed and sieved MD magnetites give apparent palaeointensities two to three times larger than the correct value. For small PSD samples the overestimate is less than 10-20 per cent and, in general, PSD samples can be used for the palaeointensity determinations.

Magnetic Microscopy and Spectroscopy

Baruchel, J., Boller, E., Espeso, J. I., Klein, H., Medrano, C., Nogues, J., Pernot, E., and Schlenker, M., 2001, **Bragg-diffraction imaging of magnetic crystals with third-generation synchrotron radiation**: *Journal of Magnetism and Magnetic Materials, v. 233*, no. 1, p. 38-47.
X-ray diffraction imaging based on Thomson scattering provides information on the magnetic moments if their arrangement entails a variation in distortion. Recent results obtained on high-quality magnetic single crystals include: (1) the observation of the domains in the low-temperature phase of magnetite, showing that the actual symmetry is triclinic; (2) new results on the unusual magnetization process in hematite (3) the observation of the helimagnetic-ferromagnetic-fan phase coexistence (triple point) in manganese phosphide (4) the visualization of magneto-acoustic modes in iron borate and (5) the imaging, through the inverse piezomagnetic effect, of the 180° antiferromagnetic domains in cobalt fluoride and of memory effects.

Koltun, R., Herrmann, M., Guntherodt, G., and Brabers, V. A. M., 2001, **Enhanced atomic-scale contrast on Fe_3O_4(100) observed with an Fe STM tip**: *Applied Physics A, v. A73*, no. 1, p. 49-53.
Clean (100) surfaces of a synthetic single crystal of magnetite (Fe_3O_4) have been prepared in situ using current pulses in a scanning tunneling microscope without subsequent annealing. We have observed atomically resolved terraces with rows of Fe^{2+} and Fe^{3+} ions of the B-sublattice (octahedrally coordinated lattice sites). Along these rows a long-distance corrugation (12 Å) has been observed at 300 K using in situ prepared Fe tunneling tips. This corrugation is interpreted as a Wigner localization associated with a Verwey transition above 300 K in the top surface layer.

Magnetization Processes

Crouzet, C., Rochette, P., and Menard, G., 2001, **Experimental evaluation of thermal recording of successive polarities during uplift of metasediments**: *Geophysical Journal International, v. 145*, no. 3, p. 771-85.
A post-tectonic NRM carried by pyrrhotite in the Dauphinoise Zone has recorded a sequence of magnetic polarities during slow cooling. Laboratory experiments show that the pyrrhotite grains are SD-sized and that they are able to record successive independent pTRMs. The NRM contains several anti-parallel components, and the authors attempt to retrieve the temperature at which each reversal occurs during the post-metamorphic cooling.

Stephenson, A., and Snowball, I. F., 2001, **A large gyromagnetic effect in greigite**: *Geophysical Journal International, v. 145*, no. 2, p. 570-5.
RRM and ARM acquisition curves of two samples containing greigite have been measured up to 80 mT, between 5 and 95 revolutions per second (rps). At 95 rps the ARM increased almost linearly with peak field but the RRM increased approximately exponentially. The effective field (B_g), defined as 70*RRM/ARM, is approximately 10 times higher than previously observed for magnetite of size 1 μm. At present it is not clear why gyromagnetic remanences are so strong in greigite. Unlike magnetite, both greigite samples had a negative RRM below 50 rps. In addition, unlike magnetite, the ARM was not constant but approximately halved as the RRM became strong and positive above 50 rps (ARM antiparallel to RRM). Thus there appeared to be an interaction between the ARM and the RRM.

Synthesis and Properties of Magnetic Minerals

Cannas, C., Concas, G., Falqui, A., Musinu, A., Spano, G., and Piccaluga, G., 2001, **Investigation of the precursors of γ–Fe_2O_3 in Fe_2O_3/SiO_2 nanocomposites obtained through sol-gel**: *Journal of Non-Crystalline Solids, v. 286*, no. 1, p. 64-73.
The structure and the magnetic properties of a series of Fe_2O_3–SiO_2 nanocomposites (16.9 and 28.5 wt% of Fe_2O_3 /(Fe_2O_3 +SiO_2)), prepared by a sol-gel method and submitted to thermal treatments in a temperature range 300-700° C, were investigated through XRD, TEM, Mössbauer spectroscopy and magnetometry. Poorly crystallized particles, belonging to the 2-line ferrihydrite phase, were found in all the samples and recognized as precursors of the γ– Fe_2O_3 that form in $Fe_2O_3SiO_2$ nanocomposites at T>700° C.

De Boer, C. B., Mullender, T. A. T., and Dekkers, M. J., 2001, **Low-temperature behaviour of haematite: susceptibility and magnetization increase on cycling through the Morin transition**: *Geophysical Journal International*, *v. 146*, no. 1, p. 201-16.
The low-field susceptibility of large (>1.5 μm) haematite particles can be increased by cycling through their Morin transition (T_M). We suggest that transdomain changes are responsible: nucleation of additional domain walls in formerly 'metastable' SD and PSD grains is triggered on rewarming through the isotropic point, when the crystalline anisotropy is relatively low. A 'true' critical SD threshold size of 1.5 μm is obtained for a well-crystalline platy haematite. Below this grain size walls cannot be nucleated, even in the more favourable conditions at the transition. By the same mechanism, a new remanence component can be induced in large SD and PSD haematite grains on cycling through T_M in fields as low as 5 mT.

Guigue-Millot, N., Keller, N., and Perriat, P., 2001, **Evidence for the Verwey transition in highly nonstoichiometric nanometric Fe-based ferrites**: *Physical Review B, v. 64*, no. 1, p. 012402.
The impact of varying degree of oxidation of Fe cations on the Verwey transition was studied by means of zero-field-cooled SQUID measurements in nanometric highly nonstoichiometric particles of pure and Ti-substituted magnetite synthesized using soft chemistry route. It is clearly shown that (i) there is a shift of the transition towards higher temperatures for nanometer scaled compounds and (ii) the amplitude, the temperature, and the order of the transition depend only on the number of Fe^{2+}/Fe^{3+} pairs in octahedral coordination.

Kumar, R. V., Koltypin, Y., Xu, X. N., Yeshurun, Y., Gedanken, A., and Felner, I., 2001, **Fabrication of magnetite nanorods by ultrasound irradiation**: *Journal of Applied Physics, v. 89*, no. 11, pt.1, p. 6324-8.
Magnetite nanorods have been prepared by the sonication of aqueous iron(II)acetate in the presence of beta–cyclodextrin. The properties of the magnetite nanorods were characterized by X-ray diffraction, Mössbauer spectroscopy, transmission electron microscopy, thermogravimetric analysis, and magnetization measurements. The as-prepared magnetite nanorods are ferromagnetic and their magnetization at room temperature is 78 emu/g. The particle sizes measured from transmission electron micrographs are about 48/14 nm (L/W). A mechanism for the sonochemical formation of magnetite nanorods is discussed.

Rabelo, D., Lima, E. C. D., Reis, A. C., Nunes, W. C., Novak, M. A., Garg, V. K., Oliveira, A. C., and Morais, P. C., 2001, **Preparation of magnetite nanoparticles in mesoporous copolymer template**: *Nano Letters, v. 1*, no. 2, p. 105-8.
Preparation of size-controllable magnetite (Fe_3O_4) nanoparticles by alkaline oxidation of ferrous ion adsorbed in sulfonated mesoporous styrene-divinylbenzene copolymer is described. It was observed that the magnetite nanoparticle size increases by ion-charging the sulfonated polymeric template with ferrous aqueous solution at increasing iron concentration. The magnetite–based composite was investigated by atomic absorption, transmission electron microscopy, Mössbauer spectroscopy, X-ray diffraction, and magnetization data.

Roh, Y., Lauf, R. J., McMillan, A. D., Zhang, C., Rawn, C. J., Bai, J., and Phelps, T. J., 2001, **Microbial synthesis and the characterization of metal-substituted magnetites**: *Solid State Communications, v. 118*, no. 10, p. 529-34.
We describe a bacterially mediated electrochemical process in which metal (Co, Cr, or Ni)-substituted magnetite powders were synthesized by iron(III)-reducing bacteria under anaerobic conditions. Amorphous Fe(III) oxyhydroxides plus soluble metal species (Co, Cr, Ni) comprise the electron acceptor and hydrogen or simple organics comprise the electron donor. The microbial processes produced copious amount of nm-sized, metal-substituted magnetite crystals. Chemical analysis and X-ray powder diffraction analysis showed that metals such as Co, Cr, and Ni were substituted into biologically facilitated magnetites.

...VF Reports
continued from page 2

Partial Transition Warming Remanence ("Inverse TRM")

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Last year at the IRM, I investigated some basic properties of remanences acquired when minerals are warmed or cooled in the presence of a field through a magnetic phase transition, e.g. the Verwey transition of magnetite at T_V = 120 K. I found that magnetite, pyrrhotite and hematite in various grain sizes all acquired both transition warming and transition cooling remanences on passing through their low-temperature transitions.

Of greatest potential importance is remanence acquisition in warming magnetite through T_V, which was discovered by Nagata, Ozima and Yama-ai (*Nature* **197**, 444-5, 1963) and called by them "inverse TRM" ("inverse" because acquired in warming rather than cooling). They speculated that the NRM of magnetite-bearing meteorites could be in part ITRM acquired by warming in the Earth's magnetic field after impact rather than a record of extra-terrestrial fields.

My experiments this year concentrated on ITRM and on partial ITRMs acquired when a field is applied over only a narrow temperature interval during warming. The main experiments were:

(1) low-temperature demagnetization (LTD) of ITRM in magnetite as a function of grain size, in comparison to LTD of TRM;
(2) thermal demagnetization of ITRM as a function of grain size, in comparison with thermal demagnetization of TRM and pTRM;
(3) thermal demagnetization of partial ITRM for various grain sizes, compared to that of total ITRM;
(4) tests of partial ITRM additivity and reciprocity (i.e., is pITRM demagnetized by zero-field cooling over exactly the same range it was acquired during in-field warming?)

The latter experiments were intended to establish analogs to the Thellier laws of additivity and reciprocity of pTRMs and to lay the groundwork for a Thellier-analog cooling method of paleointensity determination using ITRM. Since one would expect terrestrial fields to be much stronger than the field(s) of meteorite parent planet(s), this could be an important test for the extra-terrestrial origin of paleofields recorded by meteorites.

Experiments 1, 2 and 3 used ITRM and partial ITRM produced by the field of a solenoid that fit snugly inside a 7-layer Schonstedt shield. The solenoid enclosed a liquid N_2 mini-Dewar inside which the samples were taped in known orientations, either vertical or horizontal, in a plastic sample basket. LTD was performed using the same setup. Thermal demagnetization used a mini-furnace consisting of a non-inductive resistance winding on a quartz tube with an outer quartz water jacket. All remanence measurements were made with the SRM magnetometer.

The memory ratios R for ITRM after zero-field cooling to 77 K and warming to 300 K ranged from 0.254 for the 0.6 μm magnetite to 0.092 for the 20 μm sample, decreasing monotonically with increasing grain size for the seven samples in this set. R values were slightly higher for 110 μm and 135 μm magnetites (e.g., 0.105 for 135 μm). In every case, ITRM was much less resistant to LTD than TRM, ARM or SIRM. The R values for ITRM were roughly one-third of R_T, R_A or R_I. Thus ITRM can be erased efficiently by LTD, leaving a room-temperature ITRM memory that is similar to that remaining after 15 mT AF demagnetization. However, the ITRM memory is much more stable against AF and especially thermal demagnetization than the original ITRM and would remain a significant contaminant of NRM up to the highest steps of AF or thermal cleaning or Thellier paleointensity determination.

In experiments 2 and 3, total ITRM and a partial ITRM produced by switching off the field partway through warming from 77 K to 300 K were stepwise thermally demagnetized for all nine particle sizes of magnetite. The temperature at which H → 0 was unknown but it must have been in the lower part of the Verwey transition region because the pITRM was 25-30% of total ITRM. The lower remanence levels of pITRM posed a problem even with a SQUID detector, and thermal demagnetization curves of pITRM for three of the samples (0.6, 110 and 135 μm) are much noisier than the total ITRM curves. The problem is not so much with absolute level of magnetization, but with the background of irreducible remanence in certain samples, which determines the measurement threshold. In these samples, thermal and AF demagnetization, separately or in combination, failed to reduce the sample moment below a level that was very reproducible from day to day (or for that matter, from year to year, based on previous years' experience). F.D. Stacey speculated 30 years ago about the nature of irreducible moments after demagnetization, which he believed were linked to PSD moments, but we are no closer to understanding their origin today.

Thermal demagnetization curves of total ITRMs are quite unusual. For the 1 μm to 14 μm magnetites, 75-85% of the ITRM decays in almost linear fashion over the range 25-550°C, then plummets to zero by 570°C. Beginning with the 20 μm sample, an inflection point develops at intermediate temperatures. In the 110 and 135 μm samples, this is more pronounced and the thermal demagnetization is seen to proceed in two stages: an ≈50% loss of remanence by 200-250°C, a leveling out until 500-550°C, and a final plunge to zero above 550°C. This type of behavior has been noted previously for TRM and SIRM of 100 μm to mm-size magnetites (e.g., Özdemir and Dunlop, *JGR* **103**, 2549-62, 1998), but the meaning of the two stages of decay is not established with certainty.

Partial ITRMs of 0.6 μm to 20 μm magnetites are significantly more resistant to thermal demagnetization than total ITRMs. The decay is still quasi-linear, but almost twice as much remanence survives at 500-550°C. The inflected two-stage decay is still present for the 110 and 135 μm magnetites, but again much more remanence survives at 500-550°C. This unanticipated result is quite exciting. It means that the most stable part of ITRM is acquired in the earliest stages of the Verwey transition, well below 120 K. Nagata et al. (1963) showed that in AF demagnetization, higher-temperature (well above T_V) pITRMs had lower stability, akin to that of room-temperature weak-field IRM, while lower-temperature (closer to but still above T_V) pITRMs had stability more like that of TRM. However, they did not attempt to probe within the Verwey transition region itself.

A number of different experiments were carried out using the MPMS with temperature increments of 1 K. The most successful were sets of 12 neighbouring partial ITRMs, using intervals of 20-50 K, 50-70 K, 70-80 K, 80-90 K, 90-100 K, 100-110 K, 110-120 K, 120-130 K, 130-150 K, 150-200 K, 200-250 K and 250-300 K. Finer intervals between 80 K and 130 K permitted me to zoom in on the detailed acquisition of ITRM in and adjacent to the Verwey transition region. A basic program was written with Mike Jackson's help, starting with the 250-300 K interval and using a 0.2 mT field produced by copper coils instead of the much larger minimum superconducting solenoid field of ≈2 mT used in last year's experiments. The lower field is a big help in achieving paleomagnetic relevance. For the other 11 partial ITRMs, some operator presence was needed initially, to modify the temperature limits in the program. Each experiment followed the same pattern: field on at the lower temperature T_1, heat in H to the upper temperature T_2, set H → 0, cool in H = 0 from T_2 to T_1 and 10-50 K beyond. The extra cooling has two purposes: to ensure complete demagnetization of the pITRM and to reach the starting temperature for the next pITRM.

The results were quite straightforward. Time permitted only three samples to be run: 3 μm (annealed), 20 μm (unannealed) and 135 μm (annealed). They all had the same basic behaviour. First, the law of reciprocity was obeyed. Each pITRM(T_1, T_2)

was completely erased by cooling in zero field from T_2 to T_1. This is the main requirement for a successful paleointensity method. Second, the largest pITRMs were acquired in the 90-100 K and 100-110 K intervals, and not in the 110-120 K interval. This is surprising because most of the demagnetization of total ITRM (and other remanences) occurs in zero-field cooling from 120 to 110 K. These lower-T pITRMs are also more stable to thermal demagnetization than total ITRM, as described above.

Although this year's experiments were both intricate and time-consuming, they were mostly very successful, thanks to lots of help from IRM staff and my measuring partner Özden Özdemir.

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Stable Thermoremanence And Memory In Hematite

In previous years, at the IRM, I measured thermal demagnetization of thermoremanent magnetization (TRM) for synthetic submicron hematites (0.04-0.4 µm) with and without prior low-temperature demagnetization (LTD, zero-field cycling through the Morin transition T_M). The TRM before and after LTD has the following properties:

1. The TRM is very stable against stepwise thermal demagnetization. There is no unblocking below 600°C.
2. TRM memory after LTD is about 40% of original TRM and is very stable against thermal demagnetization. There is no decrease, in fact a very slight increase, in memory up to 600°C.

This year I investigated further the TRM and LTD behaviour of hematite, this time using an oriented single crystal. Total TRM was produced by cooling the cm-size natural hematite crystal from 700°C to room temperature with a 1 mT field applied parallel to the (0001) plane of the crystal. LTD was carried out by cooling the sample to 77 K in a liquid N_2 dewar, allowing the temperature to equilibrate for 30 min, and rewarming to room temperature all in the zero-field environment of a six layer mu-metal shield.

The intensity of TRM ($M_{TRM||(0001)}$) for the large crystal was much stronger than that of the submicron hematites. Stepwise thermal demagnetization had a minimal effect on TRM for heating runs up to 600°C. After heating above 667°C, $M_{TRM||(0001)}$ showed a sharp decrease, reaching zero at 669°C. The TRM memory was only 15% of the original TRM. The thermal demagnetization curve after LTD was flat between room temperature and 500°C. In further demagnetization above 550°C the memory increased, peaking just below the Néel temperature, indicating a reversely magnetized fraction of TRM which constitutes about 50% of the TRM memory. Low-temperature demagnetization is an effective way of removing the spin-canted remanence and isolating the defect moment in hematites. Crystal defects and resulting stress centers are likely responsible for the TRM memory in submicron and MD hematites. The reversed fraction of TRM memory in the large single crystal is probably controlled in part by the phase coupling between the antiferromagnetic phase and weakly ferromagnetic phase which resides in defect centers.

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“BAH!” - Humboldt

2001 Hysteresis Loops: A Rock-Magnetic Odyssey

I was awarded a visiting fellowship to return to the *IRM* (after a four year absence) to measure LOTS of hysteresis loops on various sorts of rocks, but more importantly to experience anew the joys of sub-zero temperatures during the month of March. Although I tried my best, I did not quite measure 2001 hysteresis loops, but I got nearly half of that number done during my stay. The primary aim of my study is to document the hysteresis properties of a suite of rocks that are being used for paleomagnetic studies of displaced terranes, or for possible cratonal reference poles. Some of these rocks may have been remagnetized, based either upon actual demagnetization behavior, or upon experience with similar rock units from the same general region. For this report, I will show data for three of these projects.

Morrison Formation, Black Hills, South Dakota and Wyoming
The goal of this paleomagnetic study is to resolve the longstanding discrepancy between late Jurassic paleopoles obtained from rocks from the Colorado Plateau region, which lie at relatively low latitudes, and high latitude paleopoles obtained from similar-aged rocks in New England and Colorado. The Black Hills of South Dakota and Wyoming contain mildly-deformed exposures of two rock units, the Sundance and Morrison Formations, that can be used to resolve this controversy over the North America APWP. One of my students, Phyllis Gregiore, has recently defended her MS thesis on the paleomagnetism of the Morrison Formation from the Black Hills. She found that the characteristic remanence was unblocked at either high (600-660) or low (250-450) temperatures. The characteristic remanence in these rocks has both normal and reverse polarity, passing the reversals test, and displaying polarity zonation within several outcrops. Fold tests of these directions display maximum clustering at low 0-60 % degrees of unfolding, suggesting remagnetization. Given the gentle dips, the fold tests are just barely significant. The paleopole from the Black Hills Morrison Formation is identical to that of the Front Range Morrison (Van Fossen and Kent, 1992), which passed both a reversals and fold test. Both poles are also identical to the Eocene pole for cratonal North America (Diehl et al., 1983). Clearly, remagnetization of the Black Hills Morrison Formation must be considered to be likely, so it is hoped that some additional information regarding the remanence carriers might be useful. Figure 1 shows a Day et al. plot, with bi-logarithmic axes, of the hysteresis data from the Morrison Formation. There are four types of sample plotted: samples with multiple (both a low and high T_{ub}) components, those with a low T_{ub} component, and either normal or reverse polarity high T_{ub} components. Of most significance, very few of either the low T_{ub} samples or the multi-component samples have hysteresis parameters which plot near the SD-MD mixture line typical of magnetite-bearing rocks. Instead, they plot on a mixing line that contains the other, hematite-bearing samples that all display high T_{ub} characteristic directions. This suggests an authigenic origin for even the low T_{ub} carriers.

Spieden Group, San Juan Islands, Washington
These San Juan Islands are a collage of terranes whose displacement history is still uncertain. This paleogeographic uncertainty is caused primarily by a pervasive remagnetization, most likely of Late Cretaceous age, that has affected the majority of rock units in this region (Burmester et al., 2000). All of the remagnetized rocks were subjected to high P, but low T (< 250 C) metamorphism. There are a few units within the San Juan Islands that have not been subjected to this metamorphism; these

VF Reports
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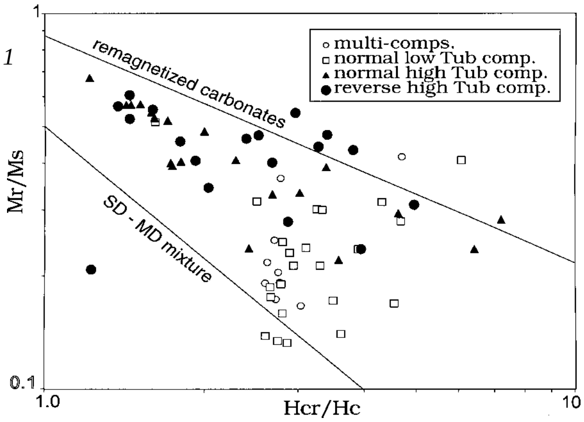
Fig. 1



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may also have escaped the remagnetization event as well. Successful paleomagnetic studies of these units may play a key role in resolving the paleogeography of these displaced terranes. The Late Jurassic to Early Cretaceous Spieden Group is a sequence of turbidites and conglomerates that have not been metamorphosed above the zeolite grade. A paleomagnetic study by another student, Allison Dean, will be defended this fall. She has found a complex magnetization history, with either two or three components of remanence in these rocks. Pending final analysis of her data, the characteristic direction obtained from the Early Cretaceous Sentinel Island Formation passes a fold test, but with peak clustering at 40 % unfolding. This may suggest a syn-folding remagnetization, however inclination-only fold tests indicate a high degree of clustering at 100% unfolding. The paleolatitude obtained from these rocks is high (between 50 and 55 degrees depending upon the degree of unfolding used). Hysteresis data from these rocks may be used to evaluate the possibility that they have been remagnetized during folding. Figure 2 shows a Day et al. plot of the hysteresis data from the Spieden Group. The data all plot along the magnetite SD-MD mixing trend. No indication of high Mrs/Ms ratios that are common to rocks that have been remagnetized by fluid-induced authigenesis can be seen in these data. We thus tentatively attribute the peak in remanence clustering at 40% unfolding to small block rotations, rather than synfolding remagnetization.

Ochoco Basin, Blue Mountains, Oregon
Recent geological work has suggested that a large, dextral strike-slip fault system along the western edge of the North American craton (the Mojave-Snow Lake, Sierra Crest, Western Nevada Shear Zone, and Salmon River Suture) was active during the Cretaceous. One consequence of this model would be that terranes in the Blue Mountains of eastern Oregon would have been displaced to their present latitude from a position further south by this fault system. Paleomagnetic data from this area exists for Permian and Triassic volcanic and sedimentary rocks, from Late Jurassic – Early Cretaceous plutonic rocks, and from Eocene volcanic rocks. A large marine basin, the Ochoco basin, contains Albian clastic sedimentary rocks that can be used to evaluate both possible displacement, and rotation of the Blue Mountains. A paleomagnetic study of 115 samples from 18 sites has revealed a characteristic remanence that passes fold tests, baked-contact tests, and conglomerate tests, all of which indicate these rocks retain their primary magnetization. There is one site (other than the baked-contact site), that does not fit the pattern of the remaining 17. It has a steep, reverse-polarity characteristic remanence; this direction is similar to that found in an Eocene dike and its adjacent baked zone. Visually, the samples from this site are similar to those of the other sites. The site is near a rhyolite body, however, and so may have been remagnetized despite outward appearances. Figure 3 shows the magnetic hysteresis results from the Ochoco basin rocks. On the bi-logarithmic Day et al. plot, the data trend very nicely along the PSD-MD or SD-MD mixing lines. The only real exceptions are three of the samples from the anomalous reverse-polarity site, which plot above the SD-MD mixture line. The remaining samples from the anomalous site plot at the SD end of the overall data cluster. A finer grainsize, and hysteresis results that suggest the presence of a significant amount of magnetic material with cubic magnetocrystalline anisotropy may in this case be consistent with growth of new magnetic minerals, in this case associated with a nearby rhyolite body.

Conclusions
Although aspects of the discussion of the data presented above are perhaps speculative, I think that the work I have done during my most recent stint as a Visiting Fellow has produced a dataset that is going to be a very useful compliment to several paleomagnetic studies that are ongoing at Western Washington University. This work builds upon some very successful work by Mike Jackson of the *IRM*, as well as visiting fellows Chad McCabe and Jim Channell. Their work has shown, very effectively I think, that remagnetization of sedimentary rocks often is manifested by hysteresis ratios that show a significant contribution to the bulk magnetic properties by magnetic minerals with cubic magnetocrystalline anisotropy. For magnetite-bearing rocks, this may be a clear signal of magnetite authigenesis. As such, hysteresis data forms a very useful role in evaluating the origin of remanence-carriers in sedimentary rocks.

I would like to thank all the *IRM*ers for their fine hospitality during my visit, with particular kudos for a successful BBQ performed during light snow with a wind chill of about –10 F.

Fig. 2

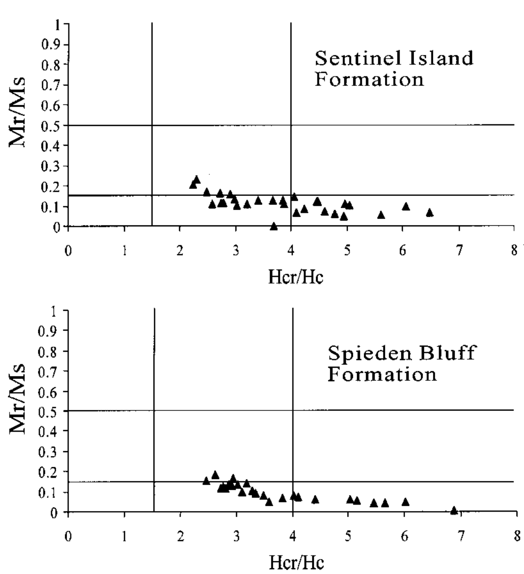
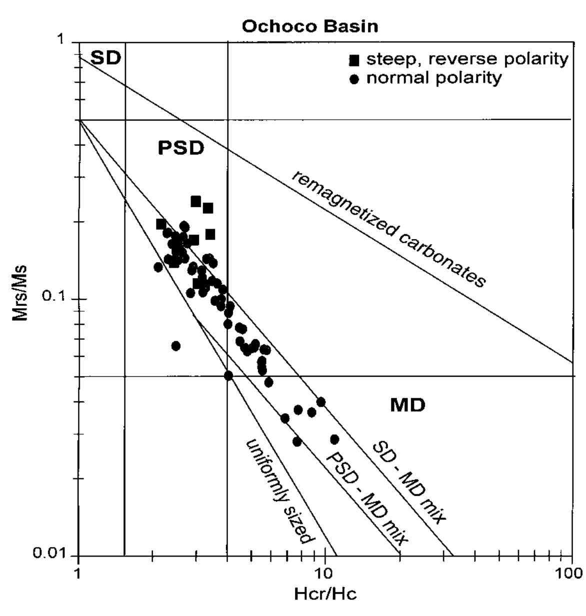


Fig. 3



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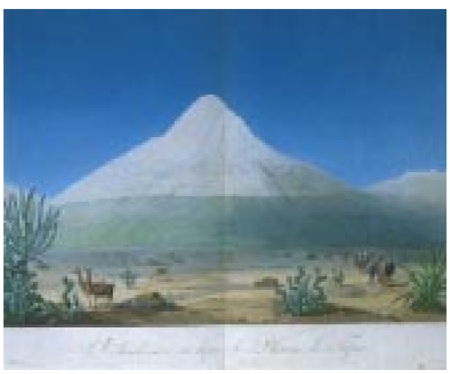
(Unbeknownst to Borda, and to Humboldt, the first successful measurements of the change in intensity with latitude had been made in 1785-1787 by Lamonon, but these results remained unknown until after Humboldt's measurements were published).

The first half of the nineteenth century was a golden age in the study of magnetism and geomagnetism, with highlights including: Ørsted's 1820 discovery that electrical currents produce magnetic fields; Faraday's 1831 discovery of magnetic induction (changing magnetic fields produce electrical currents); and Gauss's work in the 1830's that included his development of an absolute unit of measure for magnetic field strength, and his introduction of spherical harmonic analysis. Together these developments demonstrated that the geomagnetic field is mainly of internal origin, and paved the way for initial understanding of how it is generated. But none of this was yet known as Humboldt set sail, and accumulation of basic facts concerning changes in the field with latitude and elevation remained a priority.



Le Chimborazo, vu depuis le plateau de Tapia. Stich von Jean-Thomas Thibaut nach einer Skizze Humboldts, Tafel 25 in Alexander von Humboldt und Aimé Bonpland: ***Vues des Cordillères et monumens des peuples indigènes de l'Amérique*** *(http://www.hkw.de/deutsch/kultur/1999/humboldt/kapitel5/e_vulkan.html)*

In keeping with Humboldt's commitment to painstaking, accurate empirical investigation, he and Bonpland boarded the *Pizarro* with, among other things, "chronometers, sextants, theodolites, quadrants, a dipping needle, compasses, a magnetometer, a pendulum, several barometers, hygrometers, electrometers, a cynometer (for measuring the blueness of the sky), eudiometers (for measuring the quantity of oxygen in the atmosphere), an apparatus to determine the temperature at which water boils at different altitudes, a rain gauge, and reagents for chemical analysis... Everything that could be measured was to be measured."[1] These measurements, of course, were not an end in themselves, but a means of discovering and observing what Humboldt believed was the underlying unity of nature.

Humboldt and Bonpland reached Cumaná on July 16, 1799, and spent the next eighteen months exploring the Venezuelan llanoes and the Orinico River and its tributaries to the Rio Negro, nearly on the equator. They travelled on foot, by mule and by canoe, collecting thousands of plant and animal specimens and describing myriads more. This part of the voyage was later described in vivid detail for the general public in Humboldt's *Personal Narrative of a Journey to the Equinoctial Regions of the New Continent*. His description of studying electric eels, for example, is almost cinematic in its intensity: "Fishing eels with nets is very difficult because of the extreme agility with which they dive into the mud, like snakes. [Our guides] decided to fish with horses, *embarbascar con caballos*. There were about thirty [wild horses] and they forced them into the water. The extraordinary noise made by the stamping of the horses made the fish jump out of the mud and attack. These livid, yellow eels, like great water snakes, swim on the water's surface and squeeze under the bellies of the horses...[and] dazed by the noise, defended themselves with their electrical shocks. For a while it seemed they might win. Several horses collapsed from the shocks received on their most vital organs, and drowned under the water. Others, panting, their manes erect, their eyes anguished, stood up and tried to escape the storm surprising them in the water... a few managed to escape to the bank, stumbling at each step, falling on to the sand exhausted and numbed from the electric shocks. We were sure that the fishing would end with the deaths of all the animals, but gradually the violence of the unequal combat died down, and the tired eels dispersed. The eels timidly approached the shore of the marshy pond where we fished them out with harpoons tied to long strings."[2] After this, Humboldt calmly notes the temperature of the water, the lengths and weights of the fish caught, and detailed anatomical descriptions.

During the Orinoco explorations Bonpland contracted malaria and nearly perished. After allowing some time for recovery, they left for a few months in Cuba, returning to the South American mainland at Cartagena in March, 1801. There they began an eighteen-month trek along the Cordillera, which took them as far south as Lima (12°S). Humboldt made numerous climbs to investigate (among other things) the dependence of geomagnetic field strength on altitude, which ultimately proved inconclusive: "the effect of considerable heights on mountain journeys is rendered difficult, because the upper and lower stations are seldom sufficiently near one another, owing to the great mass of the mountain; and since, further, the nature of the rock and the penetration of veins of minerals, which are not accessible to our observation... modify the results. In this manner we often ascribe to the height or depth alone conditions which by no means belong to either."[3] Humboldt was unsuccessful in his attempt to scale the massive Chimborazo (6310 m), but in reaching a height of nearly 6000 m he established a mountaineering world altitude record that stood for 30 years.

The change in field strength with latitude proved more amenable to quantification: "I observed that the same needle which in Paris showed in ten minutes 245 oscillations... underwent within the same time 216 at San Carlos del Rio Negro (1°53'N); on the magnetic equator (i.e., the line where inclination is zero) in Peru (7°1'S) only 211; in Lima (12°2'S) again 219 oscillations. I observed therefore... that the total intensity, if it is set equal to one on the magnetic equator in the Peruvian Andes between Micuipampa and Cajamarca, can be expressed as 1.3482 in Paris, in Mexico as 1.3155, in San Carlos as 1.0480, and in Lima as 1.0773."[4] The trend is clear, and Humboldt suggested the simplest possible generalization, which (of course) subsequently required revision as others extended Humboldt's observations to the rest of the globe: "When I observed that the intensity increased to the north and south of this remarkable point, I was led, from an erroneous generalization of my own observations, and in the absence of all points of comparison..., to the opinion that the magnetic force of the Earth increases uninterruptedly from the magnetic equator toward both magnetic poles, and that it was probable that the maximum of the terrestrial force was situated at these points."[5] However "Sabine, by his own observations...from 1818 to 1822, has shown... that the minimum of the terrestrial force at many points lies far from the magnetic equator..."[6] and moreover, the work of Edward Sabine, Adolph Erman, James Clark Ross and others eventually demostrated that "in each hemisphere there are two points, or foci, of maximum intensity, a stronger and a weaker one, lying at unequal distances both from the poles of rotation and the magnetic poles of the Earth."[7] These workers identified maxima in Canada (1.878) and Siberia (1.74) in the northern hemisphere, and stronger foci (2.06 and 1.96) in the southern, as well as a minimum at 20°S in the Atlantic (0.7062). One of Humboldt's initial surmises was borne out by the subsequent work: "I do not think that the ratio which I formerly gave of the weakest to the strongest terrestrial force requires much modification. This ratio falls between 1:2.5 and 1:3, being somewhat nearer to the latter number."[8] The now-standard terms isoclinic, isogonic, and isodynamic were coined by Humboldt, for maps of constant inclination, declination, and intensity of the field, respectively.

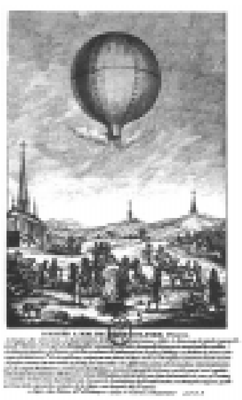
Humboldt and Bonpland left South America for Mexico in early 1803, and spent about a year there before stopping

Humboldt *continued on page 10...*

...Humboldt
continued from page 9

in Washington en route back to Europe, paying a brief visit to Thomas Jefferson just as the Lewis and Clark expedition was leaving St Louis on their own expedition of discovery. Humboldt spent most of the next 25 years in Paris, writing prolifically. The thirty volumes of *Voyage aux Régions Équinoxiales du Nouveau Continent,* published at Humboldt's expense, contained a mass of scientific observations as well as more popular fare including the *Personal Narrative* (*Relation Historique*; v.28-30) and the *Atlas Pittoresque du Voyage* (v. 15, 16) with plates made from Humboldt's sketches. At the same time, Humboldt continued his geomagnetic (and other) research, becoming particularly interested in the regular diurnal variations in the field, and in the transient disturbances for which he coined the term "magnetic storms."

"The mysterious course of the magnetic needle is equally affected by time and space, by the sun's course, and by changes of place on the Earth's surface. Between the tropics the hour of the day may be known by the direction of the needle as well as by the barometer. It is affected immediately, but only transiently, by the distant northern light as it shoots from the pole, flashing in beams of colored light across the heavens."[9] The regular "horary variations" were first detected by Graham in 1722, and later studied in detail by Celsius. Humboldt made thousands of careful measurements, and used his considerable prestige to advocate the establishment of geomagnetic observatories worldwide. "In the middle latitudes throughout the whole northern magnetic hemisphere... the north end of the magnetic needle... is most closely in the direction of that pole about 8:15 A.M. The needle moves from east to west from this hour till about 1:45 P.M., at which time it attains its most westerly position. From this most westerly point, the magnetic needle continues to retrograde toward the east throughout the whole of the afternoon... till midnight or 1 A.M., while it often makes a short pause about 6 P.M."[10]



http://duke.usask.ca/~vargo/barbauld/illustrations/annonay_engr1a.html

"In the present condition of our knowledge it is impossible to afford a satisfactory reply to all questions regarding the ultimate physical causes of these phenomena."[11] However "nothing that occurs on our planet can be supposed to be independent of cosmical influences."[12] Early explanations by Canton, Ampère and others had focused on diminished crustal magnetization due to solar heating until "Faraday's splendid discovery of the paramagnetic property of oxygen gas... removed [this] great difficulty,"[13] allowing field changes to be attributed more plausibly to changes in the induced magnetization of the atmosphere, due to its thermal expansion and contraction[14]. Yet even this elegant theory ultimately proved inadequate: "all the measurements and observations of Sabine have yielded this result, that the hitherto observed periodic variations of the magnetic activity of the Earth can not be based upon periodic changes of temperature in those parts of the atmosphere which are accessible to us. Neither the principal epochs of diurnal and annual alterations of declination at the different hours of day and night, nor the periods of the mean intensity of the terrestrial force, coincide with the periods of the maxima and minima of the temperature of the atmosphere, or of the upper crust of the Earth."[15]

One of Humboldt's principal collaborators was the physicist/chemist Joseph Louis Gay-Lussac, who in 1804 had attempted to measure magnetic field strength variations with altitude by making balloon ascents, once with Biot to 4000 m, and later alone to 7000 m (this was just 21 years after the first manned balloon flight, by the Montgolfier brothers in Paris; Gay-Lussac's altitude record was not broken for the next half century). Humboldt and Gay-Lussac made magnetic field measurements in the Alps in 1805, and also measured the oxygen content of the air at different altitudes. The latter experiments, carried out by igniting a spark in a mixture of air and a known quantity of hydrogen, led to the important law of fixed proportions in the chemical reaction of gases, known as Gay-Lussac's law, which in turn was instrumental in the development of the concept of chemical valency. Humboldt earnestly declined any credit in this: "Berzelius has reported that this fact is the germ of the subsequent discoveries on fixed proportions, but this discernment... is entirely due to Gay-Lussac's sagacity. I collaborated in this part of the experiments but he alone saw the theoretical importance of the results."[16]

The cost of the American travels and resulting publications took a heavy toll on Humboldt's finances, which were further depleted by his generous patronage of deserving young scientists of humble means, including Louis Agassiz. In 1827 Humboldt was obliged to relinquish his leisure and return to Berlin, where he earned his keep as tutor for the crown prince and as court chamberlain. Here he began his culminating masterpiece, *Cosmos*, a synthesis of everything then known about the physical universe. The first four volumes were published between 1845 and 1858, and the final volume posthumously in 1862. In his preface, Humboldt wrote: "In the late evening of an active life I offer to the German public a work whose undefined image has floated before my mind for half a century. Although the outward relations of life, and an irresistible impulse toward knowledge of various kinds, have led me to occupy myself for many years with separate branches of science, for instance, with descriptive botany, geognosy, chemistry, astronomical determination of position, and terrestrial magnetism... the actual object of my studies has been of a higher character. The principal impulse by which I was directed was the earnest endeavour to comprehend the phenomena of physical objects in their general connection, and to represent nature as one great whole, moved and animated by internal forces. Without an earnest striving to attain to a knowledge of special branches of study, all attempts to give a grand and general view of the universe would be nothing more than vain illusion."

In addition to synthesis, Humboldt's attention in his later years also turned (naturally) to history. In 1836 he published *A Critical Examination of the History of Geography of the New Continent and of the Progress of Nautical Astronomy in the 15th and 16th Century*. This work is now best remembered for solving the mystery of how the western continents came to be named after Amerigo Vespucci, but it also contains an interesting record of the magnetic measurements recorded by Columbus and an original idea about how they were put to use: "I have shown that, from the documents which have come down to us..., we can, with much certainty, fix upon three places in the Atlantic line of no declination, for 13 Sept 1492, 21 May 1496, and 16 Aug. 1498.... It then touched the South American continent a little east of Cape Codera... I believe that in my *Examen Critique* I have proved from documents that the celebrated line of demarcation by which Pope Alexander VI divided the western hemisphere between Portugal and Spain was drawn [on this line of zero declination] because Columbus wished to convert a physical into a political division. He attached great importance to the zone in which the compass shows no variation, where air and ocean... exhibit a peculiar constitution, where cooling winds begin to blow, and where (as erroneous observations of the polar star led him to imagine) the form (sphericity) of the Earth is no longer the same."[17]

Although Humboldt's original contributions to science were numerous, he is now remembered primarily as a great synthesizer (and perhaps the last to attain expertise across the whole spectrum of natural science), and a great popularizer of science. In the same way that Humboldt had been inspired by the writings of earlier travellers, his vivid

von Humboldt, Alexander

b. Sept. 14, 1769, Berlin
d. May 6, 1859, Berlin

A complete naturalist, Humboldt is remembered for his contributions in zoology, botany, mineralogy, meterorology and geomagnetism, as well as ethnography and political economy. During his 1799-1804 expedition to Central and South America, Humboldt discovered the latitudinal dependence of geomagnetic field intensity. Later he conducted detailed studies of diurnal magnetic field variations, and was instrumental in establishing network of geomagnetic observatories. Humboldt introduced various names to geomagnetic terminology, including *isodynamic* (constant intensity), *isogonic* (constant declination), *isoclinic* (constant inclination), and *magnetic storm.*

descriptions excited the interest of following generations. Charles Darwin, for example, wrote "Nothing stimulated my zeal so much as reading Humboldt's *Personal Narrative...*"[18]

Sources:

Borch, R., 1948, **Alexander von Humboldt: Sein Leben in Selbstzeugnissen, Briefen und Berichten**: Berlin, Verlag Des Druckhauses Tempelhof, 386 p.

Humboldt, A., first published 1814-1825; translation and Introduction by J. Wilson in 1995, **Personal Narrative of a Journey to the Equinoctial Regions of the New Continent**: London, Penguin Books, 311 p, including a Historical Introduction by M. Nicolson.

Humboldt, A., first published 1845-1862; translation in by E. C. Otté in 1870, **Cosmos: A Sketch of a Physical Description of the Universe**: New York, Harper.

Kellner, L., 1963, **Alexander von Humboldt**: London, Oxford University Press, 246 p.

XIV CONTENTS.

GENERAL REVIEW OF NATURAL PHENOMENA.

[1]Nicolson, p. xxiii; [2]*Personal Narrative*, p170-171; [3]*Cosmos* v5, p95; [4]*Cosmos* v1, p.185; [5]*Cosmos* v5, p.89; [6]*Cosmos* v5, p.90; [7]*Cosmos* v5, p89; [8]*Cosmos* v5, p94; [9]*Cosmos* v1, p.177; [10]*Cosmos* v5, p117; [11]*Cosmos* v1, p.190; [12]*Cosmos* v5, p80; [13]*Cosmos* v5, p81; [14]*Cosmos* v5, p78; [15]*Cosmos* v5, p82; [16]Kellner, p.68; [17]*Cosmos* v1, p.181-182; [18]Wilson, p. xxxvi

Visiting Fellows for Fall & Winter, 2001-2002

Next application deadline: December 14, 2001, for visits in the spring and summer of 2002. See our web site for details.

Stefanie Brachfeld (*Byrd Polar Research Center, Ohio State University*), Diamagnetic magnetic susceptibility: A tracer of biogenic content in sediments?

Laurie Brown (*Department of Geosciences, University of Massachusetts*) and **Suzanne McEnroe** (*Geophysics Division, Norwegian Geological Survey*), Rock magnetism and magnetic nanostructure of exsolved ilmenite-hematite

Eric Cox and **R. Douglas Elmore** (*Department of Geology and Geophysics, University of Oklahoma*), Remagnetization and Deformation

Helen F. Evans (*Department of Geological Sciences, University Of Florida*), Sulfide Diagenesis down core at ODP Site 1092 (sub-Antarctic South Atlantic): a comparison to ODP Site 1089.

Peter Riisager (*Danish Lithosphere Centre*), Rock magnetic properties of submarine basaltic glass

Alexei Smirnov (*Department of Earth and Environmental Sciences, University of Rochester*), Study of low-temperature magnetic properties of pelagic sediments as indicators of magnetic mineral diagenesis

Yongjae Yu (*Department of Physics, University of Toronto – Erindale*), Is stepwise low-temperature paleointensity determination feasible?

Xixi Zhao (*CSIDE, IGPP, University of California Santa Cruz*), Probing Magnetic Carriers from Rock Magnetic Characterization of Ontong Java Basalts

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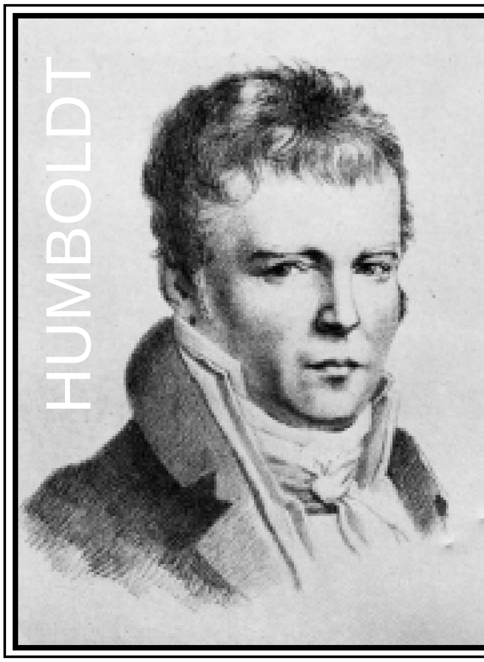

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Self-portrait, 1814 (pencil drawing). Source: Alexander von Humboldt, *by L. Kellner, 1963, Oxford University Press, London.*

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