A FORC in the Road?

Amy P. Chen
Ramon Egli
Bruce Moskowitz
IRM

1. Introduction

First-order reversal curves, called FORCs [Mayergoyz, 1986], have become popular in recent years as a tool for characterizing the properties of synthetic and natural assemblages of magnetic particles. The analysis of FORCs, represented on a two-dimensional plot called a FORC diagram [Pike et al., 1999], incorporates information about the statistical distributions of coercivities $H_c$ and interaction fields $H_i$ in the sample. One dimension of the FORC diagram is thus related to its “poor” cousin, the coercivity or switching field distribution, obtained from the analysis of remanent magnetization curves [Proksch and Moskowitz, 1994; Robertson and France, 1994].

The science of FORCs is relatively recent and is evolving rapidly: numerical models of assemblages of magnetic particles of different sizes — from viscous single-domain (SD) to multidomain — are revealing an unexpectedly rich “zoo” of FORC patterns [e.g. Carvallo et al., 2003; Muxworthy et al., 2004; Newell, 2005; Pike et al., 2001a; Pike et al., 2001b]. Some particular patterns arise from the high degree of homogeneity that characterizes the “numerical” particles used in the models. Nevertheless, many features of the numerical models have been observed in real samples, both synthetic [e.g. Muxworthy and Dunlop, 2002] and natural [e.g. Roberts et al., 2000; Wehland et al., 2005]. Since an inventory of FORC diagrams for natural sediments and rocks is at most in an embryonic stage, even the most simple question about the relevance of magnetostatic interactions in geologic materials cannot be yet answered. Yet interaction effects in natural samples are an important aspect to consider in both rock magnetic and unmixing models. Interaction fields have strong effects on the properties of superparamagnetic (SP) assemblages, and on all types of weak-field magnetization processes (e.g. anhysteretic, chemical and thermal remanent magnetizations). Furthermore, magnetic interactions are a problem for people working with unmixing models, since these models require that different magnetic components in a sample are non-interacting.

To address some of the abovementioned questions, we are planning to perform systematic measurements — FORCs among them — on a variety of selected synthetic and natural samples. Today we will travel down some back roads of FORCs related to interesting technical and scientific aspects of measurements, data processing and interpretation.

Fig. 1: (a) Standard deviation (SD) of FORC measurements performed on the VSM without the sample holder inserted. The horizontal dashed line refers to the nominal measurement error SD of the instrument. An increase of the apparent measured magnetic moment by one order of magnitude in proximity of $H_b=0$ is evident. A correlation between the error SD and the applied field exists at positive fields (see text for more details). (b) FORC diagram (Winkhofer and Zimanyi, in press) calculated from the measurements performed in (a). The absolute value of the FORC distribution is plotted. The scale is truncated at large values to show small features otherwise hidden by the major peaks along the diagonal defined by $H_b=-H_a$. (c) FORC measurements of sample BAIK that show mechanical stability problems. The partial hysteresis loops are in (press) calculated from the measurements performed in (a). The absolute value of the FORC distribution along the diagonal defined by $H_b=-H_a$. FORCs related to interesting technical and scientific aspects of measurements, data processing and interpretation. (d) FORC diagram of the measurements shown in (c). For sample BAIK, the statistical distribution of coercivities $H_c$ and interaction fields $H_i$ in the sample. One dimension of the FORC diagram is thus related to its “poor” cousin, the coercivity or switching field distribution, obtained from the analysis of remanent magnetization curves [Proksch and Moskowitz, 1994; Robertson and France, 1994].

2. Measurement artifacts

The calculation of FORC distributions $\rho(H_a, H_b)$ involves the use of second derivatives of partial hysteresis loops $M(H_a, H_b)$ with respect to the “preparation field” $H_a$ and the measuring field $H_b$. Any process of calculating a derivative is comparable to a high-pass filter that enhances the noise signal produced by measurement errors $\delta M$. A crude estimate of the resulting error in the FORC diagram is given by:

\[ \delta \rho(H_a, H_b) \approx \frac{\delta M}{M} \]

\[ \delta H_a \]

\[ \delta H_b \]
Magnetic properties of floodplain deposits along the banks of the Morava River (Czech Republic)

The purpose of our ten day stay at the IRM in early September 2005 was to elucidate what magnetic minerals were contributing the magnetic signals carried by fine-grained flood sediments deposited in the drainage basin (~10,000 km²) of the Morava River, Czech Republic. To that end we used the Magnetic Properties Measurement System (MPMS) by Quantum Designs, the Lakeshore Cryotronics AC Susceptometer, and the low and high temperature Princeton MicroMag Vibrating Sample Magnetometers (VSM). Support for the project came from a NATO Post-Doctoral Research Fellowship which brought J. Kadlec to MIU to work in the environmental magnetism lab with J. Diehl. NATO Post-Doctoral Fellowships are administered by the National Science Foundation and were created by NATO to bring promising young scientists from NATO Partner countries who are less than five years out from their Ph.D. These fellowships were established by NATO to promote the progress of science and closer collaboration between scientists and engineers of NATO Partner countries, and scientists and engineers in the United States; to recognize the accomplishments to date of beginning scientists and engineers; and to provide an experience in the U.S. which will increase professional competence.

Our samples were collected at 3 vertical sections along the Morava River located at distances ~5 km downstream from one another. At each section triplicate samples were collected at each stratigraphic level using plastic boxes (6.7 cm³) with a vertical separation of less than 0.5 cm between sampling horizons for a total of 1806 samples. Radiocarbon ages determined from charcoal and wood fragments from the three sections indicate that these sediments span all of the Holocene.

Magnetic parameters determined at MTU such as mass specific susceptibility (χ), ARM, SIRM and their intraparametric ratios (ARM/SIRM, S-ratio) all show similar variations from section to section. Here we show only the variations in mass specific susceptibility, χ, for Section 3 of our study (Fig. 1). As seen in Figure 1, the values of magnetic susceptibility are highest in the upper 50 cm of the section. Susceptibility values then show a noticeable decrease downward in the section to 200 cm depth and then stay low throughout the rest of the section decreasing to the lowest values at the bottom of the section. S-ratios near 0.9 in the upper 50 cm suggest the presence of a low coercivity mineral as the cause of the highest susceptibility values but drop to values of near 0.6 by 200 cm depth and then decrease to 0.5 at 300 cm depth. These low values of the S-ratio indicate the presence of a high coercivity mineral and may be the reason for the low susceptibility values seen in this portion of the section. Since magnetic susceptibility is a function of grain size, concentration, and composition of the magnetic carriers, we need to completely understand how these 3 components contribute to the susceptibility records measured in the flood sequences before applying any environmental interpretation to our results.

First of all, we were interested in how much the high field susceptibility, influenced by paramagnetic minerals or goethite content, contributes to the mass susceptibility values. Based on hysteresis data gained at room temperature at Michigan Tech we knew that paramagnetic or high coercivity components strongly dominate especially in the lower portions of the sections. Both low and high temperature VSM measurements conducted on the MicroMags at the IRM verified a significant paramagnetic contribution to the mass susceptibility. The high field susceptibility values vary between 3 and 10 x 10⁻⁸ m³/kg and generally correlate with the mass susceptibility variations shown in Figure 1.

To diagnose the magnetic carriers in our samples we used MPMS to evaluate (1) the magnetization acquired in a 2.5 T field while cooling a portion of the sample from 300K to 20K (FC), (2) the thermal demagnetization of a 2.5 T IRM imparted at 20K (ZFC), (3) the low-temperature cycling of a 2.5 T IRM acquired at room temperature (RTSIRM). RTSIRM-ZFC sweeps show the presence of an oxidized magnetite in the upper ~50 cm in all sections and in several underlying coarser sandy horizons. Drops in RTSIRM-ZFC magnetizations at 120 K indicate a suppressed Verwey transition (Fig. 2) suggesting the presence of low temperature oxidized magnetite (Özdemir et al., 1993). The same ordering related to the Verwey transition is revealed by a susceptibility increase at about 120K measured on the LakeShore (Fig. 3). However, at depths greater than 50 cm in all sections our ZFC-RTSIRM and FC-ZFC-RTSIRM sweeps, the goethite starts to appear. Below 200 cm depth in the sections goethite becomes the predominant magnetic phase. Figure 4 shows data of FC-ZFC-RTSIRM sweep for a sample located 125 cm below the floodplain surface. The large difference (~4x) in the FC magnetization at 20K and the ZFC magnetization at 20K as well as the large increase...
in RTSIRM on cooling suggests goethite. The presence of goethite throughout most of our section made it impossible to get meaningful Day plot information (Day et al., 1977) from our VSM data. Lastly, a steep magnetic moment drop between 20 and 50K on ZFC curves determined on sediments from the lower portion of sections (Fig. 5) could indicate a presence of ilmenite, which is ordered at 47K.

Most of the LakeShore results indicate a predominance of paramagnetic component in the magnetic signal. This paramagnetic influence often masks the ferrimagnetic signal. For example, the RTSIRM-ZFC sweep magnetic moments measured in the sample c32.8 (Section 3) indicate presence of the oxidized magnetite in the material (Fig. 6). However, the LakeShore susceptibility record from the same sample shows only paramagnetic component without any indication of in phase susceptibility increase caused by the Verwey transition. However, the presence of low-temperature oxidized magnetite was documented by the Curie temperature value (578ºC) revealed by thermal demagnetization conducted in the MTU lab on the magnetic extract from the same stratigraphic horizon. The LakeShore frequency dependent susceptibility values do not indicate a significant content of superparamagnetic particles in the sediments.

A preliminary interpretation of data gained in the IRM allows us to sketch following conclusions:

1. The paramagnetic influence strongly dominates in the flood sediments through all three sections masking the ferrimagnetic signal. The paramagnetic iron is most probably in clay minerals. Expandable clay minerals smectite and vermiculite were identified in the sediments by the X-ray diffraction. There is a general positive correlation between expandable clay mineral content and the mass susceptibility variations and negative correlation between the clay mineral content and sediment grain size in the upper 200cm of the sections.

2. Goethite is a common iron oxhydride presented in the flood sediments. The concentration of goethite increases downward in the sections. The goethite could be a product of dissolution of iron oxides and consequential iron precipitation under reduct conditions in the flood plain environment (Bremeen, 1988; Thompson and Oldfield, 1986), or the goethite could be eroded and re-deposited from goethite-rich loess deposits covering large areas in the Morava River catchment. The indication of ilmenite presence (a common mineral in central European loesses) would support the later possibility.

3. Detrital magnetite grains are partly oxidized to maghemite, which suppresses the Verwey transition. We surmise that cultivation of arable soil exposed magnetite grains that were then oxidized during erosion, transportation and re-sedimentation in the flood sequences. The increase of and other magnetic parameters in the uppermost 200 cm of each section is most probably the consequence of more intense erosion caused by agriculture activities, which were triggered by medieval colonization in the central Europe.

It is our pleasure to thank Mike Jackson, Peter Solheid and Brian Carter-Stiglitz for their instructions in using the IRM instruments and their help in interpreting the measured data. Lastly, we’re still trying to analyze all the data from our 68 Mbyte Excel file. We really haven’t spent much time looking at the VSM now that J. Kadlec is back in the Czech Republic, but hope to present that data at the next Castle Meeting.

References


FORC to the Rock Magnetic community.

In the 16th century, Catherine de Medici brought some of the Italian Renaissance to the rest of Europe by introducing the table fork to France. In the 20th century, Christopher Pike, et al., introduced the FORC to the Rock Magnetic community.

Current Articles

Note: Due to space limitations which have required the exclusion of an ever increasing number of superb abstracts, starting this issue most abstracts will no longer be printed in the Quarterly. Instead we will print a bibliography of current research articles. The complete abstract text can be found at: www.irm.umn.edu/abstracts. It is our hope that readers check the site frequently as it will be continuously updated as articles enter into the databases. We expect that the web-page will be a useful tool for keeping on top of the magnetic literature. Finally, selected "editor’s choice" abstracts will be printed in full. Please send comments or questions to the editor.

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 5200 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the IRM Quarterly are always welcome.

Anisotropy


Biogeomagnetism

Coby, A.J., and F.W. Picardal, Inhibition of NO3- and NO2- reduction by microbial Fe(III) reduction: Evidence of a reaction between NO2- and cell surface-bound Fe2+, Applied & Environmental Microbiology, 71 (9), 5267-5274, 2005.


Data Processing and Analysis


Environmental Magnetism and Paleoclimate Proxies


Extraterrestrial Magnetism
Dunlop, D.J., and J. Arkani-Hamed
Magnetic minerals in the Martian crust
Using rock magnetism and thermal modeling, we evaluate the candidate minerals responsible for strong magnetic anomalies in the Terra Sirenum and Terra Cimmeria regions of Mars’ southern highlands. We assume an early global dynamo field similar in strength to the present Earth’s field, enduring about 500 Myr after accretion and core formation, and a basaltic crust containing no more than 4 - 7 weight% of magnetic minerals. Thermal evolution models with a wide variety of initial crustal thicknesses, distributions of radioactive elements, and thermal expansion coefficients all yield similar thermal histories for the crust: warming in the first 1000 Myr (due mainly to radioactive heating) followed by monotonic cooling for the remainder of Mars’ history. Primary thermoremanent magnetization (TRM) acquired by intrusive and extrusive bodies during the first 500 Myr was in part thermally demagnetized by general crustal warming after the dynamo field disappeared, from 500 to 1000 Myr. The Curie point isotherms around 1000 Myr established the maximum depth of TRM-bearing crust. Shock and heating due to impacts demagnetized the uppermost similar to 10 km of the crust around the same time, resulting in potential magnetic layer thicknesses of 15 - 20 km for pyrrhotite, 40 - 50 km for magnetite, and 50 - 60 km for hematite. Other magnetic phases, such as iron and finely exsolved low-Ti titanohematite, are possible but less likely in a basaltic crust under oxidizing conditions. The prime candidates, in order of likelihood, are single-domain magnetite (0.2 - 0.4 weight% required), single-domain pyrrhotite (1 - 2 volume%) or 2 - 4 weight%), and either multidomain (> 15 mum) or 5 - 15 mum single-domain hematite or a mixture of both (1.5 - 3 volume% or 3 - 6 weight%). A composite source with different combinations of these minerals at different depths is entirely possible. Viscous decay of TRM is difficult to assess without detailed knowledge of the distribution of minerals and blocking temperatures with depth but would increase the amounts of magnetic material required. Glotch, T.D., and P.R. Christensen, Geologic and mineralogic mapping of Aram Chaos: Evidence for a water-rich history - art. no. E09006, Journal of Geophysical Research-Planets, 110 (E9), 2005.

Magnetic Anomalies

Magnetic Field Records and Paleointensity Methods

Magnetic Microscopy and Spectroscopy

Magnetization & Demagnetization Processes
Tauxe, L.
Inclination flattening and the geographic axial dipole hypothesis
William Gilbert first articulated what has come to be known as the geographic axial dipole hypothesis. The GAD hypothesis is the principle on which paleogeographic reconstructions rely to constrain paleolatitude. For decades, there have been calls for permanent non-dipole contributions to the time-averaged field. Recently, these have demanded large contributions of the axial octupole, which, if valid, would call into question the general utility of the GAD hypothesis. In the process of geological recording of the geomagnetic field, “Earth filters” distort the directions. Many processes, for example, sedimentary inclination flattening and random tilting, can lead to a net shallowing of the observed direction. Therefore, inclinations that are shallower than expected from GAD can be explained by recording biases, northward transport, or non-dipole geomagnetic fields. Using paleomagnetic data from the last 5 million years from well-constrained lava flow data allows
the construction of a statistical geomagnetic field model. Such a model can predict not only the average expected direction for a given latitude, but also the shape of the distribution of directions produced by secular variation. The elongation of predicted directions varies as a function of latitude (from significantly elongate in the up/down direction at the equator to circularly symmetric at the poles). Sedimentary inclination flattening also works in a predictable manner producing elongations that are stretched side to side and the degree of flattening depending on the inclination of the applied field and a “flattening factor” f. The twin tools of the predicted elongation/inclination relationship characteristic of the geomagnetic field for the past 5 million years and the distortion of the directions predicted from sedimentary inclination flattening allows us to find the flattening factor that yields corrected directions with an elongation and average inclination consistent with the statistical field model. The method can be tested using sediments deposited in a known field. Application of the elongation/inclination correction method to two magnetostratigraphic data sets from red beds in Asia and Pakistan brings the method to two magnetostratigraphic data sets from red beds in Asia and Pakistan brings the model for so long.


Mineral & Rock Magnetism


Mineral Physics & Chemistry


Modeling and Theory


Zou, G.F., K. Xiong, C.L. Jiang, H. Li, Y. Wang, S.Y. Zhang, and Y.T. Qian, Magnetic Fe3O4 nanodisc synthesis on a large scale via a surfactant-assisted process, Nanotechnology, 16 (9), 1584-1588, 2005.

NRM Carriers and Origins


Paleomagnetism and Chronology

Demory, F., N.R. Nowaczky, A. Witt, and
Magnetostratigraphic dating of hominoid-bearing sediments at Zhupeng, Yuanmou Basin, southwestern China

The hominoid fossils found in the Yuanmou Basin, southwestern China, are among the key fossils for understanding the evolution of early hominoids in eastern Asia and their relationship with coeval hominoids in Europe and Africa. However, the exact ages have not yet been well determined. We provide a new high-resolution magnetostratigraphy for the Zhupeng profile, which is one of the fossil-bearing type sections in the region. Based on magnetostratigraphy of 227 remnant directions, together with the age of micromammalian fauna, indicate that the hominoid-bearing layer is dated within polarity chron 3Br 2r or 3Br 1r, i.e. within the interval 7.43-7.38 Ma or 7.34-7.37 Ma. This unambiguously indicates that the Yuanmou hominoid has a late Miocene age, which therefore makes it the youngest hominoid found in Eurasia. It is possible that the Yuanmou Basin provided a refuge for hominoids during a time of major environmental changes.

Paleomagnetism and Tectonics


Coc, R.S., G.M. Stock, J.J. Lyons, B. Beiter, and G.J. Bowen
Yellowstone hotspot volcanism in California? A paleomagnetic test of the Lovejoy flood basalt hypothesis
Geology, 33 (9), 697-700, 2005.

In 2000, D.L. Wagner and colleagues hypothesized that the middle Miocene Yellowstone hotspot volcanism thought to have produced the great expanses of Columbia River and Oregon Plateau Basalts also gave rise to the Lovejoy Basalt of California. Paleomagnetic directions of lava flows of the Lovejoy Basalt in isolated localities scattered more than 200 km across northeastern and central California show that they were erupted rapidly and that some of them traveled great distances. Most of the paleomagnetic directions form a tight cluster distinct from the Miocene mean field direction for the region, indicating eruption within a relatively short time span compared to geomagnetic secular variation-that is, within a few hundred to a few thousand years. Directional correlations demonstrate that some flows traveled at least 50 km and likely as much as 200 km. These findings support the hypothesis that the Lovejoy flows are flood basalts that compose a large southwestern extension of Yellowstone hotspot volcanism.


Onderdonk, N.W., Structures that accommodated differential vertical axis rotation of the western Transverse Ranges, California - art. no. TC4019, Tectonics, 24 (4), 2005.

Pease, V., J.W. Hillhouse, and R.E. Wells, Paleomagnetic quantification of upper-plated deformation during Miocene detachment faulting in the Mohave Mountains, Arizona - art. no. Q09004, Geochronology Geophysics Geosystems, 6 (9004), 2005.


Taylor, G.K., B. Dashwood, and J. Grocott, Central Andean rotation pattern: Evidence from paleomagnetic rotations of an anomalous domain in the forearc of northern Chile, Geology, 33 (10), 777-780, 2005.


Synthesis and Properties of Magnetic Materials


We did not make significant progress until one of us started a FORC measurement and forgot to turn on the sample vibration on the VSM . . .

\[ \Delta H \text{ is the resolution expected from the FORC diagram (typically <10% of the coercivity of the sample), which is related to the so-called smoothing factor (SF) used by FORC programs to process the data [Pike et al., 1999]. On the other hand, a FORC distribution has a typical amplitude } \bar{\rho} \text{ that depends on the saturation magnetization } M_s \text{ of the sample (in Am}^2\text{kg}^{-1}), \text{its mass } m \text{ (typically 0.3 g for a VSM sample, and 10-20 mg for a sample suitable for the AGFM), and the standard deviations } \sigma(H_c) \approx H_c \text{ and } \sigma(H_o) \text{ of } H_c \text{ and } H_o, \text{ respectively:}
\]

\[ \bar{\rho} \approx \frac{mM_s}{2\pi H_c \max[\Delta H, \sigma(H_o)]} \]

Acceptable FORC diagrams are obtained when the signal-to-noise ratio } \rho/\delta \rho \text{ is large, typically >10. For example, common freshwater and marine sediments, and many soils, are characterized by } \sigma(H_c) \approx 30 \text{ mT and } \sigma(H_o) \approx 10 \text{ mT, } \Delta H \approx 5 \text{ mT. Using (1-2) we obtain } \rho/\delta \rho \approx 0.04-4 \text{ in the case of VSM measurement (} m = 0.3 \text{ g, } \delta M = 5 \text{ nAm}^2\text{), and } \rho/\delta \rho \approx 1-100 \text{ in the case of AGFM measurements (} m = 20 \text{ mg, } \delta M = 10 \text{ pAm}^2\text{). A rule-of-thumb for the feasibility of FORC measurements is given by the comparison of equations (1) and (2), which yields:}

\[ M_{\text{IFC}} \gg \frac{4\pi H_c \delta M}{m} \max[1, \sigma(H_o)/\Delta H] \]

Systematic errors are obviously not included in this crude error analysis. Since we experienced several problems in measuring weak sediments that were not explained by random measurement errors, we decided to investigate possible systematic error sources. We did not make significant progress until one of us started a FORC measurement and forgot to turn on the sample vibration on the VSM (a beautiful example of serendipity). Surprisingly, the partial hysteresis loops were not “flat” as expected. On the contrary, the measurements showed a sharp peak in proximity of } H_c = 0 \text{, whose amplitude was 20 times larger than the expected measurement noise. Excited by this discovery, we repeated the experiment (this time intentionally), without the sample holder mounted, and obtained the same result (Fig. 1a). Two systematic features characterize the partial hysteresis loops: (1) a peak that occurs always at } 0 < H_c < 10 \text{ mT, whose amplitude can be positive or negative, and (2) a random noise signal that corresponds to the manufacturer’s specifications at negative fields, superimposed on an additional noise signal with a standard deviation of } 100 \text{ nAm}^2/T, \text{ which was proportional to the positive applied field. Curiously, the peak in proximity of } H_c = 0 \text{ was systematically observed only with one of our two MicroMag VSMs (namely the high-temperature VSM here at the IRM). Therefore, all measurements presented in the following have been performed on our other MicroMag VSM or on the AGFM.}

[Editor’s Note: IRM staff is currently working with Princeton in order to understand the source of this peculiar noise pattern. The magnet power-supply, vibration head, and controller have all been ruled out as the source. The noise “glitch” at zero-field is thus from one of the following components: the sensing coils, the pre-amplifier, or the magnet.] The systematic offset of the peak toward positive fields is probably related to the direction of measurement of the partial hysteresis loops, with } H_c \text{ increasing from negative to positive fields.}

The typical FORC diagram that results from our “empty” runs is characterized by an alternation of narrow positive and negative peaks located along the diagonal } H_c = H_o, \text{ superimposed on a background noise that is proportional to } H_c \text{ (Fig. 1b). This noise pattern is effectively described by:}

\[ \text{var}(\delta \rho) = a^2 + \left( \frac{4}{S F} \right) \delta(H_c + H_o) + (\varepsilon(H_c))^2 \]

with } \delta(.) \text{ being the Dirac } \delta \text{-function, } SF \text{ the smoothing factor used for the data processing, and the empirical constants } a = 5 \text{ nAm}^2, b = 100 \text{ nAm}^2, c = 10 \text{ nAm}^2/T. 

In addition to possible instrumental effects, we found yet another source of artificial features in FORC diagrams
when measuring a powdered sediment sample from lake Baikal (Russia). The powder was pressed in a gelatin capsule and mounted on the sample holder of the VSM. Since the sample was magnetically weak, we stacked several repeated FORC measurements for the purpose of increasing the signal-to-noise ratio. Surprisingly, systematic artifacts appeared at $0 \leq H_b \leq 10$ mT during the second and all successive measurement (Fig. 1c). These artifacts are reflected in the corresponding FORC diagrams as a sequence of peaks located along the diagonal $H_u = -H_c$. Suspecting a possible mechanical instability of the sample, we repacked the sample after mixing the sediment with powdered calcium fluoride, and repeated the measurements. The repacked sample was stable, even after several measurements, and the corresponding FORC diagram did not show any localized peaks at $H_u = -H_c$.

The two examples discussed above show that measurement artifacts are associated with characteristic features of the FORC diagram that can be misinterpreted. For example, localized contributions to the FORC distribution along the diagonal $H_u = -H_c$ have been predicted for assemblages of pseudo-single-domain particles [Carvallo et al., 2003]. On the other hand, similar features might be observed when measuring weak samples or mechanically unstable powders with the VSM. Therefore, we recommend always to exclude possible artifacts inherited in the instrument or the sample itself, before detailed features of FORC diagrams are interpreted.

### 3. Effect of sample preparation

Now we will show how different methods of preparing a sample can affect the geometrical arrangement of the magnetic particles, producing different distributions of interaction fields. The starting material for the examples shown here is an aqueous suspension of cultured whole cells of the magnetotactic bacteria MV-1 or MV-2. Each cell contains a single chain of single-domain (SD) magnetite magnetosomes. In order to perform measurements at room temperature, the aqueous cell suspension must be processed to immobilize the magnetosomes. We tested three different sample preparation methods that have an increasing effect on the arrangement and the integrity of the chains. This example has relevance to synthetic sample preparation techniques and their subsequent magnetic measurement, which is routinely used as a reference and sometimes as analogues to natural samples.

The first sample was prepared by mixing a few ml of the cell suspension with a dense slurry of pure kaolin powder and distilled water. The mixture was then dried in air at room temperature. The powder obtained after drying was packed in a gelatin capsule and measured (Fig. 2a). This preparation method produces samples that are similar to dried or freeze-dried clay-rich sediments. The concentration of magnetite was approximately 25 ppb by weight. The second sample was prepared by direct freeze-drying of the whole cell suspension. In this case, the concentration of magnetosomes in the sample is much higher, typically 1-2% by weight (Fig. 2b). The chains are expected to be mostly intact, since the chain configuration and the magnetosome membrane give some mechanical stability to the chains [Sheberbakov, 1997]. The distance between the chains is controlled by the amount of dry cell material in the sample. The last two samples were obtained by extracting the magnetosomes from the cells using a French press. The samples are powders containing magnetosomes, presumably still partially arranged in strongly bent or collapsed chains (Fig. 2c,d).

The FORC distribution of the first sample shows a small dispersion along $H_u$ that results from the smoothing factor used to process the data. It is similar to FORC diagrams calculated for non-interacting SD particles with a narrow size distribution [Muxworthy et al., 2004]. The strong positive interaction field within chains was not detectable in the FORC diagram, suggesting that the magnetosomes of each chain reverse collectively. The chains are thus magnetically identical to large.

### Table 1--The ARM ratio of some natural and synthetic samples. Values are predicted for non-interacting Stoner-Wohlfarth particles.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>$k_{ARM}/M_{r\nu}$ ratio, mm/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV-1-KAOL</td>
<td>intact cells dispersed in kaolin</td>
<td>3.28</td>
</tr>
<tr>
<td>MV-1-FDR</td>
<td>freeze-dried cells</td>
<td>1.06</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
<tr>
<td>MV-1-EXT</td>
<td>extracted magnetosomes</td>
<td>0.52</td>
</tr>
<tr>
<td>MV-2-EXT</td>
<td>extracted magnetosomes</td>
<td>0.22</td>
</tr>
</tbody>
</table>
non-interacting uniaxial SD particles, as demonstrated independently with measurements performed on individual magnetotactic bacteria [Pennings et al., 1995]. The FORC distribution of freeze-dried cells gives evidence of a small interaction field, as expected from the smaller distances between the chains produced by the shrinkage of the cells. The difference in coercivity between the two samples is related to the fact that they have been prepared from different batches of MV-1. The FORC diagram of the extracted magnetosomes is drastically different from the other two samples. Two components can be clearly recognized: a low-coercivity distribution that peaks at \( H = 30 \) mT and is strongly interacting, and a high-coercivity distribution whose FORC distribution is very similar to that of freeze-dried magnetosomes. The relative contribution of the two components is different in the two samples. We hypothesize that the low-coercivity component is produced by collapsed chains that form clusters of closely packed magnetosomes. On the other hand, the high-coercivity component suggests that some chains survived the extraction process and maintained their original magnetic properties, with little influence from the surrounding magnetosomes. It is not clear if the organic matter was completely removed by the extraction process: intact chains could be possibly still surrounded by cell material. The increasing interaction field in the four samples affects strongly the ratio \( k_{\text{ARM}} / M_s \) (ARM ratio) of the susceptibility of anhysteretic remanent magnetization \( k_{\text{ARM}} \) to the saturation remanent magnetization (Tab. 1).

4. Interactions in sediments

The most immediate application of FORC measurements is the characterization of magnetostatic interactions. Other possible applications, such as granulometry and unmixing, are currently under development. In the following, we present two examples related to the determination of magnetostatic interactions and the solution of unmixing problems.

Detailed coercivity analysis of lake sediments have been used to unmix their remanence properties [Egli, 2004]. Up to 60% of the remanent magnetization at room temperature is carried by fossil magnetosomes. Egli [2004] calculated room-temperature magnetic properties of the magnetosomes in sediments, such as the median destructive field (MDF) and the ARM ratio. The ARM ratio, was found to be generally consistent with the large values predicted for non-interacting, uniaxial SD particles [Egli and Lowrie, 2002]. However, significant exceptions were found in some anoxic sediments, where the ARM ratio of the magnetosomes was up to two orders of magnitude smaller, while the corresponding coercivity distributions remained unchanged. This result cannot be explained in terms of changes in the grain size of the fossil magnetosomes. A decrease in grain size could be expected to arise from a partial dissolution of the magnetosomes under reductive conditions. However, grain size changes are reliably tracked by other parameters, such as \( M_s / M_r \) and the coercivity, which did not show any significant variation. Another explanation for the observed drop in \( k_{\text{ARM}} / M_s \) is related to magnetostatic interactions: low-field magnetizations, such as ARM, are drastically lowered by even small interaction fields [Sugitani, 1979]. To verify this hypothesis, we measured FORCs of two lake sediments described in Egli [2004], whose ARM ratio is lowered by a factor 10 and 100, respectively (Fig. 3).

The sample with the lowest ARM ratio (BAIK-GR) is a pellet of organic matter characterized with \( M_s = 2.56 \) Am\(^2\)/kg and \( M_s / M_r = 0.44 \). The distribution of \( H_c \) in this sample (Fig. 3c) is compatible with the calculated distribution \( f(H_c) \) of interaction fields \( H_i \) along a given direction in a random assembly of magnetic particles:

\[
(5) \quad f(H_c) = \frac{1}{2\pi a} \frac{1}{(x-H)^2 + \left(\frac{\alpha M_t}{2\pi a}\right)^2}
\]

where \( H_i \) is the demagnetizing field, \( M_t \geq M_r \) is the effective value of \( M_r \) at the location of the magnetic particles, and \( \alpha = \pi (\ln(2 + \sqrt{3})/(2\sqrt{3}) + 1) / 12 \approx 0.36 \) is a geometric factor [Egli, paper in preparation]. If the magnetic particles are homogeneously distributed within the whole sample \( M_t = M_r \). A best fit of equation (5) to the cross-section of the FORC diagram shown in Fig. 3c yields \( \mu_0 M_{\text{eff}} = 18.1 \) mT, or \( M_{\text{eff}} = 40 \) kA/m. Using the density of magnetite, \( M_{\text{eff}} = 8.1 \) Am\(^2\)/kg. For comparison, \( M_s = 5.8 \) Am\(^2\)/kg, only 28% less than \( M_r \). The other sample, AR23, shows a considerably smaller interaction field, as expected from its higher ARM ratio.

FORC measurements allow us to confirm that magnetostatic interactions are responsible for the lower values of the ARM ratio of magnetofossils observed in anoxic lake sediments. The reason for the higher local concentration of magnetofossils (e.g. clusters) in anoxic sediment is not clear. We hypothesize that microscopic organic remains buried in the sediment once hosted very dense populations of magnetotactic bacteria which have been subsequently decomposed. Organic remains would be consumed by bacteria and then living bacteria could grow on them, and are therefore not found in oxide sediments.

5. FORCs and unmixing

Our last FORCed road addresses the so-called linear unmixing problem. In the linear unmixing problem the magnetic properties of a natural sample are interpreted as a linear combination of magnetic components. A magnetic component is an assembly of particles with a common origin and biogeochemical history (e.g. detrital magnetite, magnetosomes, pedogenic magnetite). In this summer’s issue of the IRM Quarterly (vol. 15, 2005), the unmixing problem was discussed extensively for the example of a soil profile collected on the University of Minnesota’s St. Paul campus. The linear additivity required by current unmixing models is not guaranteed in the case of magnetostatic interactions between different components. Furthermore, interaction effects within a component can affect drastically its magnetic properties and invalidate some identification criteria. FORC diagrams can be very useful in this context, either as an independent unmixing method, or as a tool for the quantification of the interaction field. In the following, we will discuss these applications on the example of soil samples described in the summer issue of this journal. The soil profile has been modeled using a linear combination of two components: detrital magnetite D resulting from the weathering of the parent sediment (a glacial till), and an assemblage P of low-coercivity, non-interacting unmixed magnetosomes (oxidized magnetite or maghemite).

The magnetic properties of a component, say P, can be calculated using an appropriate linear combination of identical measurements performed on samples with a different composition.

For example, any magnetic property \( m_{\text{P}} \) of the pedogenic component can be calculated using the following linear combination:

\[
(6) \quad m_{\text{P}} = M_{\text{18cm}} - 1.33 M_{\text{70cm}}
\]

of measurements \( M_{\text{18cm}} \) and \( M_{\text{70cm}} \) performed on two samples collected at 18 cm depth in the B-horizon, and at 70 cm depth in the C-horizon, respectively.

To verify the validity of this unmixing model, we applied equation (6) to the FORC measurements of the two samples (Fig. 4). Since the samples were too weak to be measured on the VSM, we stacked multiple measurements performed with the AGFM. If magnetostatic interactions exist between components D and P, a FORC diagram of P calculated using (6) should reveal the presence of an interaction field.

To visualize better some features of the FORC diagram and compare \( \rho(H_0,0) \) with coercivity distributions calculated from remanence curves, we introduce a rescaled FORC distribution \( \rho(h_c, H_i) \) with \( h = \log H_c \). The rescaling rule for statistical distributions gives:

\[
(7) \quad \rho(h_c, H_i) = 10^{0.4h} \ln 10 \times 10^{0.4h} H_i
\]

so that the integrals of \( \rho(H, H_i) \) and \( \rho(h_c, H_i) \) over the area of the FORC...
In a landmark paper published in 1936, Inge Lehmann demonstrated the existence of the Earth’s inner core. She argued that P’ waves were not the result of diffraction, as thought at the time, but were due to a discontinuity, now known as the Lehmann Discontinuity. This major work was accomplished during her 25-year tenure in what was essentially a staff-scientist position; original research was not one of her duties as a “para-scientific” nor was it encouraged. The same could also summarize her contemporaries’ attitudes concerning her sex.

Inge Lehmann, b. May 13, 1888
d. Feb 21, 1993

6. Literature


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

The IRM staff consists of Subir Banerjee, Professor/Director; Bruce Moskowitz, Professor/Associate Director; Jim Marvin, Emeritus Scientist; Mike Jackson, Peat Solheid, and Brian Carter-Stiglitz, Staff Scientists.

Funding for the IRM is provided by the National Science Foundation, the W. M. Keck Foundation, and the University of Minnesota.

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

Brian Carter-Stiglitz
Institute for Rock Magnetism
University of Minnesota
289 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN  55455-0128
phone: (612) 624-5049
fax: (612) 625-7502
e-mail: cart0196@umn.edu
www.irm.edu

The U of M is committed to the policy that all people shall have equal access to its programs, facilities, and employment without regard to race, religion, color, sex, national origin, handicap, age, veteran status, or sexual orientation.

Mark your calendars, Santa Fe (IRM's biennial conference in rock magnetism) has been scheduled for June 22-25 2006!