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Rock Magnetism and First-Order Reversal Curve (FORC) Measurements

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Abstract

Mineral magnetism is one of the most powerful tools used by Earth scientists to study the large-scale structure and behavior of the Earth. Paleomagnetic and paleointensity data from rocks yield information regarding the strength of the Earth's early geomagnetic field which is of importance for understanding the evolution of the Earth's deep interior, surface environment and atmosphere.

In geomagnetic, geological and environmental magnetic studies it is important to have reliable methods to characterize the composition, and grain size distribution of magnetic minerals within samples. For example, identification of single-domain (SD) magnetic grains is important in absolute paleointensity studies because SD grains produce more reliable results than those obtained from multi-domain (MD) grains. In paleoclimatic studies, having a means for determining the magnetic grain size distribution is important because useful environmental information is often revealed by subtle changes in grain size distribution.[1]

Determining the composition of magnetic minerals in a rock is relatively straightforward; however identification of the domain state is more complicated. Measurement of a materials' hysteresis loop, *M(H)*, is very important, but suffers from the fact that it's a bulk magnetic measurement and represents the average magnetic properties of all particles in a sample. Also, the hysteresis loop does not differentiate between mineral composition, grain size or magnetic interactions between grains which can lead to ambiguous results. This is often the case for the commonly used Day plot, which summarizes bulk magnetic properties by plotting the ratios of M_{rs}/M_s versus H_{cr}/H_c where M_{rs} is the saturation remanent magnetization, M_s is the saturation magnetization, H_{cr} is the coercivity of remanence, and H_c the coercivity. Magnetostatic interactions among SD grains can cause the bulk hysteresis parameters of samples to plot within the MD region of the Day plot. Magnetic interactions are important in rock magnetism and methods for better discrimination between SD and MD behavior is needed than can be obtained from hysteresis loop measurements alone.

A first-order-reversal curve (FORC) measurement provides a means for distinguishing between SD and MD grains, as well as mixtures of different magnetic species in rocks. Measurement of a suite of FORCs provides detailed information from within the hysteresis loops, which enables determination of the distribution of switching fields and interaction fields for all of the particles that contribute to the hysteresis loop.

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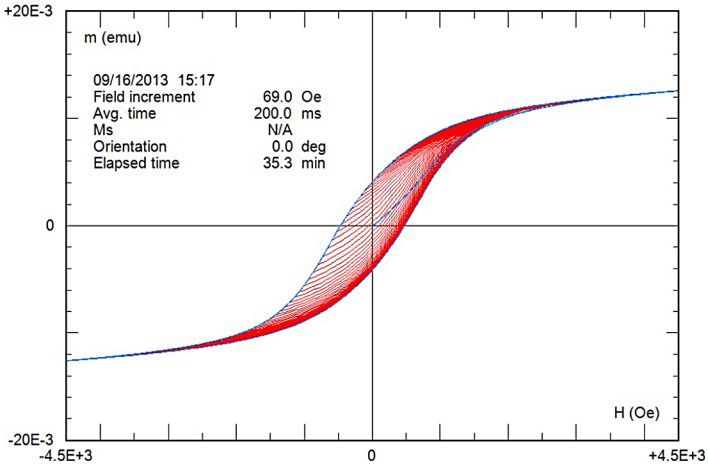


Figure 1 *The initial magnetization curve and major hysteresis M(H) loop (blue) and a series of FORCs (red) for sample A. There are 5,940 points in the FORCs, and the total measurement time was only 35.3 min, which illustrates the speed of the PMC VSM.*

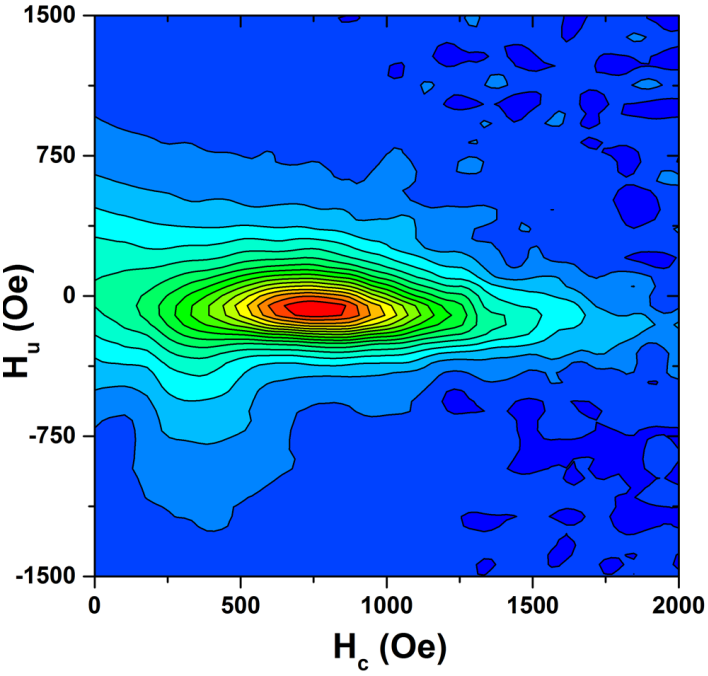


Figure 2 *FORC diagram for sample A.*

FORC Curves and FORC Diagrams

A FORC is measured by saturating a sample in a field, H_{sat}, decreasing the field to a reversal field, H_a, then sweeping the field back to H_{sat} in a series of regular field steps, H_b. This process is repeated for many values of H_a yielding a series of FORCs. The measured magnetization at each step as a function of H_a and H_b gives $M(H_a, H_b)$, which is then plotted as a function of H_a and H_b in field space. The FORC distribution $\rho(H_a, H_b)$ is the mixed second derivative, i.e., $\rho(H_a, H_b) = -\partial^2 M(H_a, H_b)/\partial H_a \partial H_b$, and a FORC diagram is a contour plot of $\rho(H_a, H_b)$ with the axis rotated by changing coordinates from (H_a, H_b) to $H_c = (H_b - H_a)/2$ and $H_u = (H_b + H_a)/2$ where H_u corresponds to the distribution of interaction fields, and H_c the distribution of switching fields.

The most commonly employed techniques for measuring FORCs are vibrating sample magnetometry (VSM) and alternating gradient magnetometry (AGM). Since the second derivative, $-\partial^2 M(H_a, H_b)/\partial H_a \partial H_b$, significantly amplifies measurement noise present in the magnetization data, the sensitivity of the measurement technique is important for magnetically weak samples. A typical sequence of FORCs may contain thousands of data points which can be unwieldy and cumbersome if the measurement is inherently slow; therefore, measurement speed is also very important. The following data were recorded using Lake Shore's PMC MicroMag™ VSM.

Typical Magnetic Measurement Results

In this section we present PMC VSM FORC measurement results for two rock specimens from the Greek island of Rhodes. For VSM measurements, flat plate-like samples were cut from larger rocks with sample volumes of 4.6 mm^3 (sample A) and 0.54 mm^3 (sample B).

Figure 1 shows the initial magnetization curve and major hysteresis M(H) loop (blue) and a series of FORCs (red) for sample A. There are 5,940 points in the FORCs, and the total measurement time was only 35.3 min, illustrating the speed of the PMC VSM.

Analysis of these FORC curves yields the local interaction H_u and coercive H_c field distributions shown in figures 2 and 3 which show the FORC diagram and the FORC distribution, respectively.[2]

Interacting SD grains have FORC distributions with closed contours, while MD grains have FORC distributions with open contours that diverge toward the H_u axis. If the MD grains are coarse as opposed to fine, the open contours will diverge even more toward the H_u axis. The FORC diagram shown in figure 2 includes both SD and MD (fine grains)-like components which is referred to as pseudo SD (PSD) behavior. While FORC diagrams for SP and MD grains are easily distinguishable (closed versus open contours), PSD grains contain a fundamental ambiguity since they have both SD and MD-like contours.

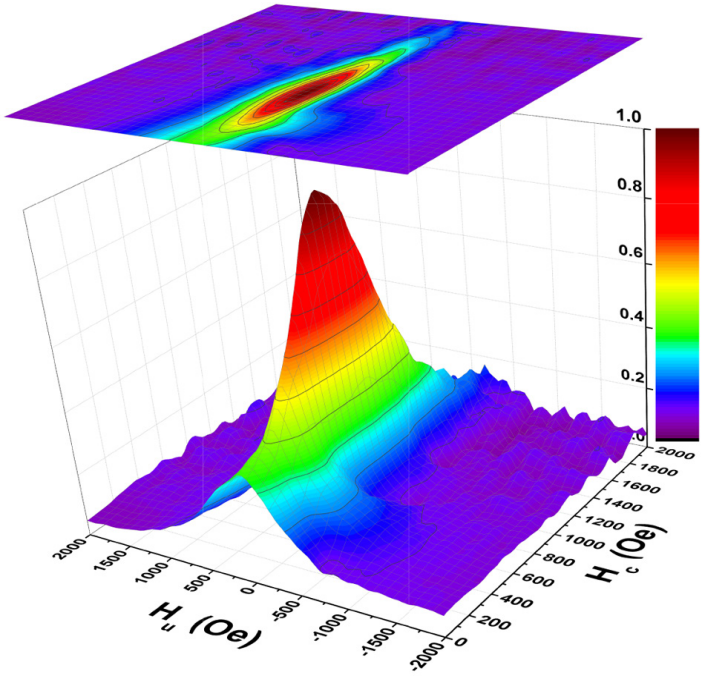
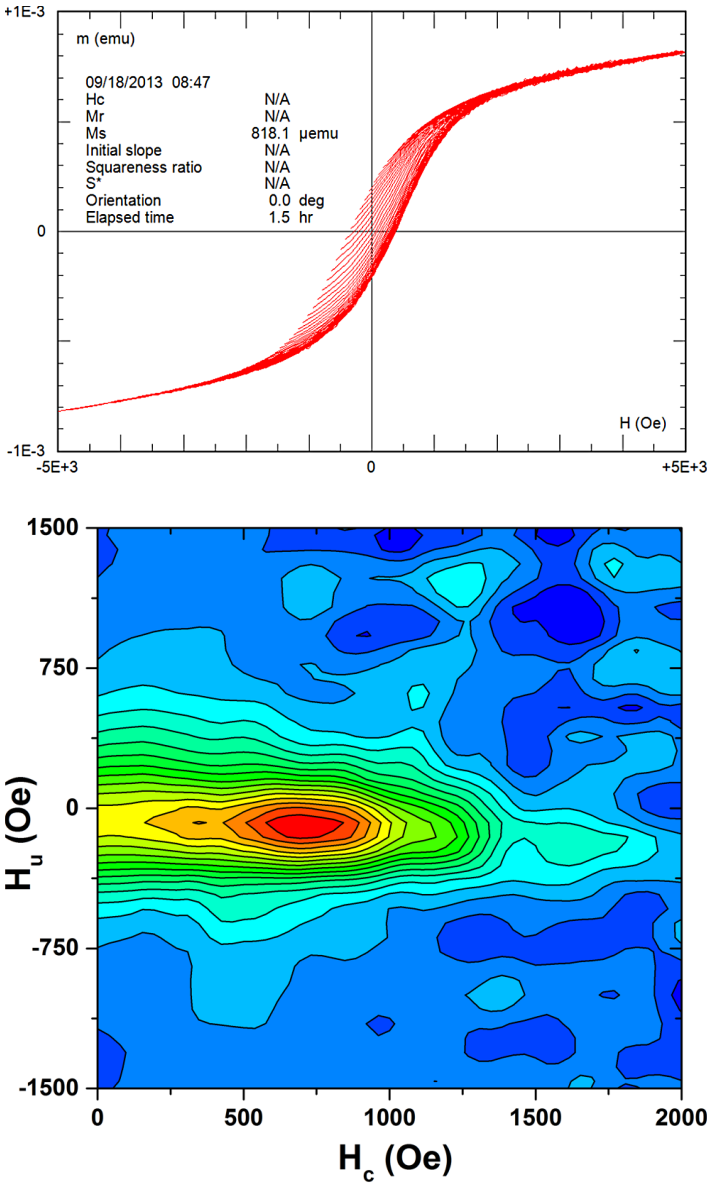


Figure 3 *FORC distribution for sample A.*

Figures 4 and 5 show the measured FORCs and the FORC diagram, respectively, for sample B.[2] There are 9,045 points in the FORCs and the total measurement time was 1.5 h. Note that the moment at maximum field is approximately 0.8 memu, which is approximately 25 times lower than sample A, thus illustrating the speed of the PMC VSM, even for relatively low moment samples.

In comparing the FORC diagram of sample B (figure 5) with that of sample A (figure 2) one can again see evidence of PSD behavior. A difference here is that sample B contains fewer closed contours (SD behavior) with a tighter distribution than sample A, and more open contours (MD behavior) that diverge toward the Hu axis. This would suggest that sample B is more MD-like, and possesses finer MD grains than sample A.



Figures 4 and 5 *show the measured FORCs and the FORC diagram respectively for sample B. There are 9,045 points in the FORCs and the total measurement time was 1.5 h. Note that the moment at maximum field is approximately 0.8 memu, which is approximately 25 times lower than sample A. This illustrates again the speed of the PMC VSM, even for relatively low moment samples.*

Conclusion

While hysteresis loop measurements are very important, they are of limited utility for characterizing the magnetic properties of rocks because, being a bulk measurement, they do not differentiate between mineral composition, grain size or magnetic interactions between grains. Consequently, these limitations can lead to ambiguous results. FORCs are indispensable in determining the distribution of switching fields and interaction fields for all particles that contribute to the hysteresis loop and provide for mineral and domain state discrimination. In this paper we have discussed the FORC measurement technique and subsequent analysis which leads to the FORC diagram, and presented measurement results for two rock specimens from the Greek island of Rhodes.

References

1 *A. R. Muxworthy, A. P. Roberts, First-Order-Reversal-Curve (FORC) Diagrams, Encyclopedia of Geomagnetism and Paleomagnetism, Springer, 2007 (and references contained therein)*

2 *R.J. Harrison, J.M. Feinberg, FORCinel: An improved algorithm for calculating first-order reversal curve distributions using locally weighted regression smoothing, Geochemistry, Geophysics, Geosystems, Volume 9, Issue 5, May 2008*



Figure 6 *FORC measurements are made using systems such as the PMC MicroMag™ VSM (top) and AGM (bottom)*

NOTE: The PMC MicroMag VSM referenced in this note has been discontinued, but its replacement, the 8600 Series VSM (now available as an option for the MagRS magnetic research platform), was designed with FORC measurement as a primary objective. The 8600 performs complex FORC data collection sequences in a fraction of the time required on previous systems and includes Real-Time FORC (RTForc™) software, which calculates and displays FORC distributions in real time, significantly reducing the time required to analyze FORC data. For more information, visit www.lakeshore.com/mag-rs.

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