The Philosophy of Rock Magnetism
What we do, how we do it, and why...

Richard J. Harrison and Ioan Lascu
Department of Earth Sciences, Cambridge
The philosophy of rock magnetism

• Introduction to rock magnetism and paleomagnetism

• First-order reversal curve (FORC) diagrams for rock magnetic applications

• Case study: dusty olivine – measuring magnetic signals from the solar nebula
Magnetic Minerals

Oxygen (O) and iron (Fe) are the 1st and 4th most abundant elements in the Earth’s crust. These elements readily combine to form magnetic iron oxides such as magnetite (Fe₃O₄) and hematite (Fe₂O₃). Magnetic minerals occur everywhere in the natural environment (rocks, sediments, soils, meteorites). These minerals turn rocks into magnetic hard drives: they retain a memory of the **direction and intensity of the geomagnetic field** that was present when the rock formed.
The magnetic memory of rocks

The direction and intensity of the field varies systematically with latitude.

Rocks retain a memory of the field that was present at its formation.

Memory is caused by presence of magnetic minerals.
The magnetic memory of rocks
Southern hemisphere of Mars displays magnetic anomalies 1-2 orders of magnitude stronger than those observed on Earth. The magnetic field on Mars switched off around 4 billion years ago, yet the crust still has not forgotten...
What do we need to know to interpret the remanence with confidence?

Which magnetic minerals?
Positions?
Separations?
Volumes?
Shapes?
Crystallographic orientations?
Chemical Compositions?
Internal microstructures/defects?
Domain States?
Coercivities?
Reversal mechanisms?

Region of Interest
Magnetic domain state versus particle size

Arguably the most important concept in rock magnetism is the transition from superparamagnetic (SP) to single-domain (SD) to pseudo-single-domain (PSD) to multi-domain (MD) behaviour as function of particle size.

Non-interacting uniaxial single-domain (SD) particles: the holy grail of rock magnetism!
Bulk hysteresis measurements

Plotting $M_r/M_s$ vs $H_{cr}/H_c$ gives some indication of where a rock lies within the SD-PSD-MD spectrum.

Only non-interacting SD particles have a theory that is of practical use for paleomagnetism. The problem is that the vast majority of rocks plot in the PSD range.

This can be interpreted in a number of different ways. Rocks are a complex mixture of interacting and non-interacting particles with a range of particles sizes and separations.

Hysteresis loops on their own are of limited use - we need much more detailed information...
First-order reversal curves (FORCs)

FORC diagrams are now a standard tool for rock magnetic studies:

- Domain state fingerprinting
- Coercivity distributions
  - Interactions
- Magnetic mixtures
- Quantitative modelling
FORC measurements
FORC measurements
The FORC surface is a plot of magnetisation $M$ as a function of $H_a$ and $H_b$.

The FORC distribution is defined as the mixed second derivative of $M$ with respect to $H_a$ and $H_b$.

$$\rho(H_a, H_b) = -\frac{\partial^2 M(H_a, H_b)}{\partial H_a \partial H_b}$$

What does the FORC distribution tell us?
Preisach Interpretation
Original $H_a$-$H_b$ axes

Transformation of axes

‘Coercivity’ axis

$H_c = (H_b - H_a)/2$

‘Interaction field’ axis

$H_u = (H_a + H_b)/2$

Rotated $H_c$-$H_u$ axes
FORC fingerprints
Non-interacting uniaxial single domains
e.g. sediment containing magnetotactic bacteria

**Central ridge**
-ve
+ve

\[ H_u (T) \]
\[ H_c (T) \]

\[ \text{Egli 2012} \]

(d)
\[ +M_S \]
\[ -H_c \]
\[ +H_c \]
\[ -M_S \]

\[ \frac{H_u}{H_k} \]
\[ \frac{H_c}{H_k} \]

\[ \text{Newell 2005} \]
FORC fingerprints

Weakly interacting uniaxial single domains

e.g. concentrated sample of magnetotactic bacteria
FORC fingerprints

True PSD particles with intermediate grain size between SD and MD

Wright Industries magnetite 3006 (particle size: 1.06 +/- 0.71 microns)

Fire obsidian (1st ever FORC measured on our new Lakeshore AGM!)
FORC fingerprints

Mixture SD + PSD: Central ridge superimposed on PSD background
FORC fingerprints

True MD behaviour: titanomagnetite

Weak Pinning

R.T.

50 K

Strong Pinning
FORC fingerprints
Highly-correlated interacting system
FORC fingerprints
Highly-correlated interacting system
FORC fingerprints

Highly-correlated interacting system

‘Wishbone’ structure with vertical offset peak
FORC fingerprints

Random distribution of 1000 uniaxial single domain magnetite particles (70x70x70 nm) with log-normal distribution of switching fields and randomly oriented easy axes inside a gradually shrinking box.

Volcanic glass
FORC fingerprints

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Volcanic glass
Case study: dusty olivine – measuring magnetic signals from the solar nebula

Richard J. Harrison¹
Sophie Lappe¹
Sara Russell²
Josh Feinberg³
Geoff Bromiley⁴
Nathan Church¹
Alice Bastos da Silva Fanta⁵
Rafal Dunin-Borkowski⁵

1. Earth Sciences, Cambridge
2. Natural History Museum, London
3. Institute for Rock Magnetism, Minnesota
4. Earth Sciences, Edinburgh
5. Centre for Electron Nanoscopy, Copenhagen
Motivation

Chondrules provide evidence of the processes that operated within the protoplanetary nebula, yet the exact environment and mechanism of chondrule formation is still debated.

Chondrules may acquire a pre-accretionary thermoremanent magnetisation (TRM) during their formation. The intensity of the magnetising field could yield important clues to the mechanism and location of chondrule forming events. However, to make any firm conclusion the uncertainties must be reduced...
Dusty olivine: a potential carrier of pre-accretionary remanence

- Olivine grains containing submicron particles of ~pure metallic Fe
- Found in unequilibrated and carbonaceous chondrites
- Formed from reduction of Type I (Mg-rich) chondrules
- May appear as relict grains that survived the chondrule forming event without melting
- Alignment and clustering controlled by crystallography of host olivine
First-order reversal curves (FORCs)

1 = Non-interacting SD particles with coercivity distribution extending to 600 mT

2 = Positive satellite peak at average values
   $H_c \sim 56 \text{ mT} \quad H_u \sim 117 \text{ mT}$

3 = Negative satellite peak at average values
   $H_c \sim 180\pm30 \text{ mT}$

Relative proportions of signals 1 vs 2/3 vary from sample to sample
Single vortex (SV) nucleation and annihilation

Signal 2 is associated with the nucleation (SD to SV) and annihilation (SV to SD) of vortex magnetisation states in particles that are just above the critical size for SD behaviour.

\[
\{H_c, H_u\} = \{(H_A - H_N)/2, -(H_A + H_N)/2\}
\]

\[
H_N = -H_c - H_u
\]

\[
H_A = H_c - H_u
\]

For dusty olivine:

\[
H_N \sim 58 \text{ mT}
\]

\[
H_A \sim 170 \text{ mT}
\]
3D imaging using FIB slice-and-view


Alice Bastos da Silva Fanta, Sophie Lappe, Richard Harrison
3D imaging using FIB slice-and-view

Image resolution: 1024 x 884

Pixel size: $1.92 \times 10^{-8} \mu m = 19.2 \text{ nm}$

Slice thickness: 20nm

Number of slices: 61
3D imaging using FIB slice-and-view

Image resolution: 1024 x 884
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Slice thickness: 20 nm
Number of slices: 61
Electron holography: magnetic imaging at the nm scale
Electron holography: magnetic imaging at the nm scale
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Electron holography: magnetic imaging at the nm scale
Domain states, volumes and coercivities can be determined. Together these are the necessary parameters to apply Néel’s SD theory to model the acquisition of thermal remanence.

Predicting Domain States

![Graph showing domain states and axial ratio relationship]

- Single domain
- Vortex (core out-of-plane)
- Vortex (core in-plane)

Calculated SD/vortex boundary (Butler & Banerjee 1975)
Using FORC information to predict paleomagnetic behaviour

Using Néel theory, plus an empirical relationship between coercivity and volume, Muxworthy and Heslop (2011) proposed a method to use the information in a FORC diagram to predict thermal remanence acquisition

Quantitative modelling of thermal remanence using FORC diagrams

First steps: FORCintense

Adrian Muxworthy and Richard Harrison

Quantitative modelling of thermal remanence using FORC diagrams
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Application to dusty olivine

- FORC diagram
- Simulated AF demag at 340 μT (equal to lab field)
- Electron holography
- Non-linear TRM acquisition
- Calculated vs observed REM'
- REM’ acquisition curve compared to experimental data

Electron holography

Quantitative modelling of thermal remanence using FORC diagrams
Scanning magnetic microscopy - paleomagnetism at small length scales

Scanning SQUID microscopy of synthetic dusty olivine

Eduardo Lima, Ben Weiss, Sophie Lappe, Nathan Church, Richard Harrison

5 mm
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B_x and B_y can be calculated from a measurement of B_z (Lima and Weiss 2009 JGR 114, B06102).

Fitting dipole equation to B_x, B_y, and B_z simultaneously provides robust M_x, M_y, and M_z (and x, y, z positions of particle).
Scanning magnetic microscopy - paleomagnetism at small length scales

\( B_{\text{total}} \)

63 dipoles fitted

Observed

Fit
Demagnetising TRM and ARM

Note that ARM is carried predominantly by SD particles, whereas the original TRM is carried by both SD and SV. Demagnetisation spectra agree only when the SD component is isolated above 170 mT.
Calibrating non-heating paleointensity measurements

Remanence behaviour changes dramatically as a function of the SD/SV ratio (identified by FORC diagrams). Best results are when SD component is isolated.

Figure 6.12 shows the plot of the slope of TRM lost versus ARM lost for all samples introduced in chapter 4. The data obtained from the SQUID microscopy measurements are added. To determine the slope for the TRM lost versus ARM lost curve for all individual samples a straight line was fitted to an AF demagnetising field range from 100 to 150 mT (cf. chapter 4). In the case of the individual cube samples no demagnetisation data beyond 150 mT could be obtained. The TRM lost versus ARM lost plot for the bulk samples showed an approximately constant slope from 100
The philosophy of rock magnetism

- Microscopy
- Tomography
- NanoPaleoMag
- Scanning Magnetic Microscopy
- Holography
- Computer simulations