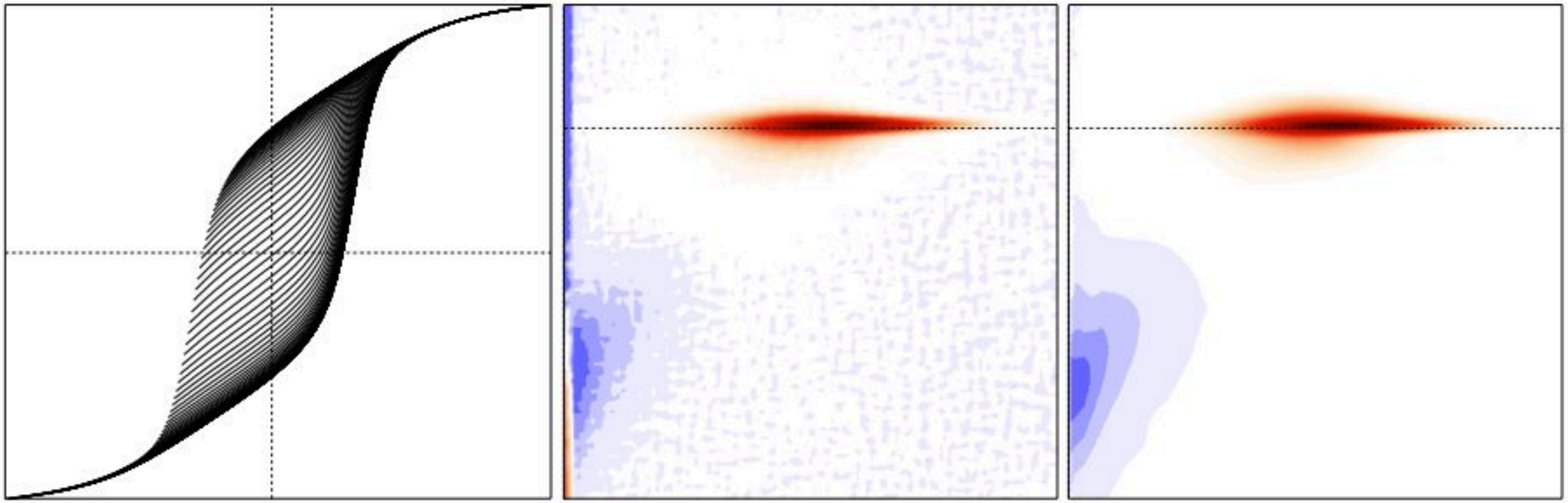
The Philosophy of FORCs
What to do, how to do it, and why...



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European Research Council
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The Philosophy of FORCs
What to do, how to do it, and why...

Part I

-Overview of the FORC method
-Interpretation
-Smoothing
-Domain state fingerprinting
-Coercivity distributions
-Interactions
-Magnetic mixtures
-Quantitative modelling

Part II

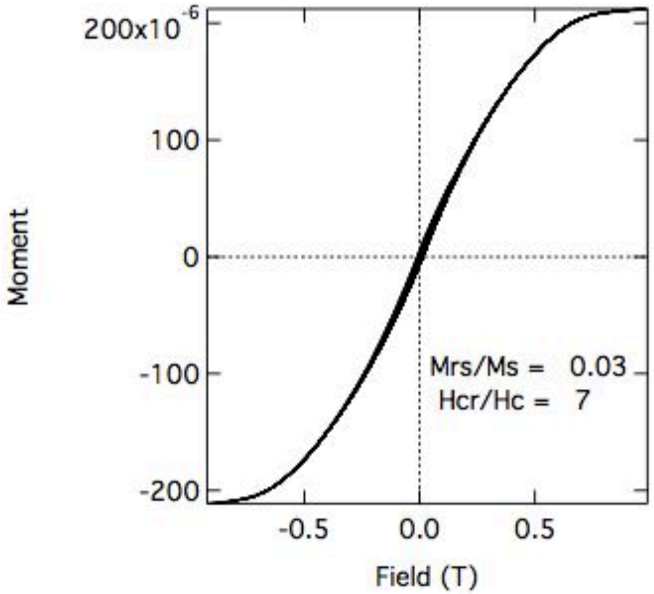
-Demonstration of FORC processing using FORCinel
-Smoothing and presenting FORCs
-Recognising and removing artefacts
-Extracting central ridge

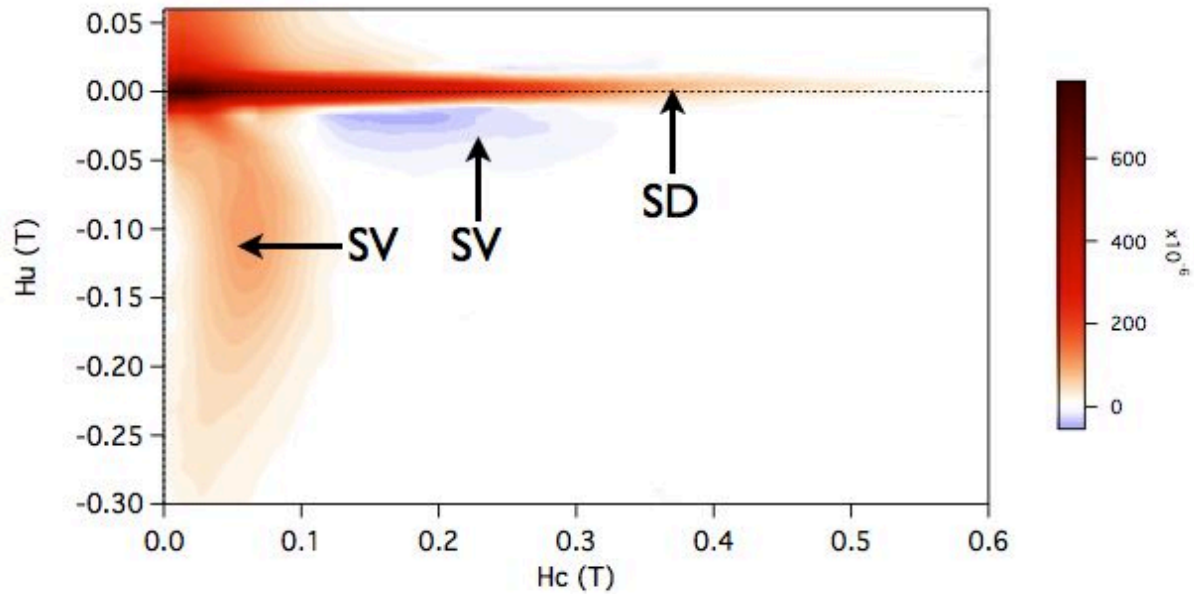
Overview of the FORC method

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

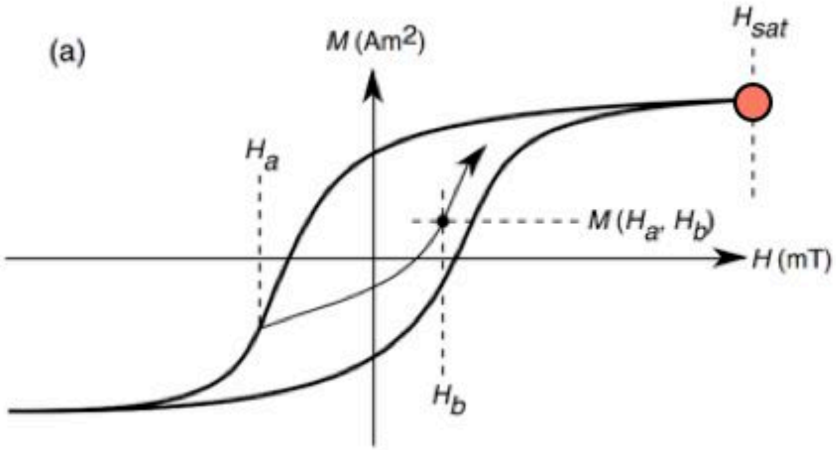
– Domain state fingerprinting
– Coercivity distributions
– Interactions
– Magnetic mixtures
–Quantitative modelling

e.g. FORC diagram of 'dusty olivine' containing mixture of SD and SV signals



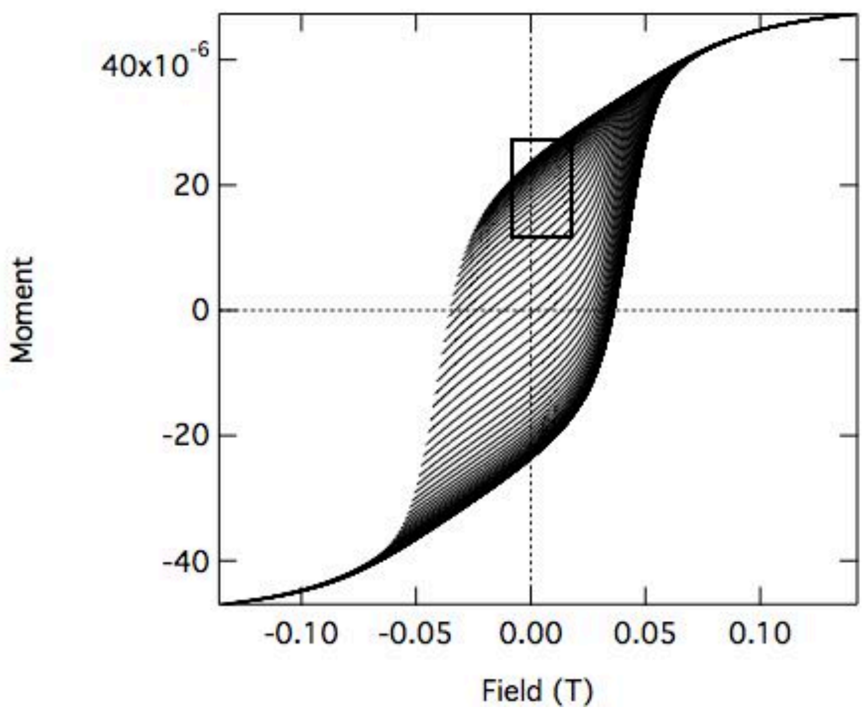


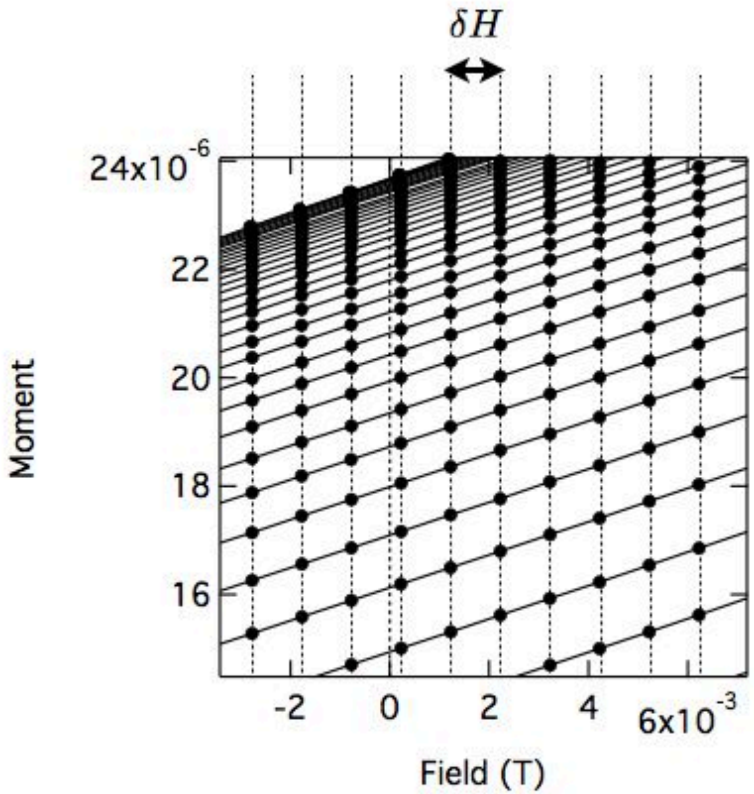
What is a FORC?



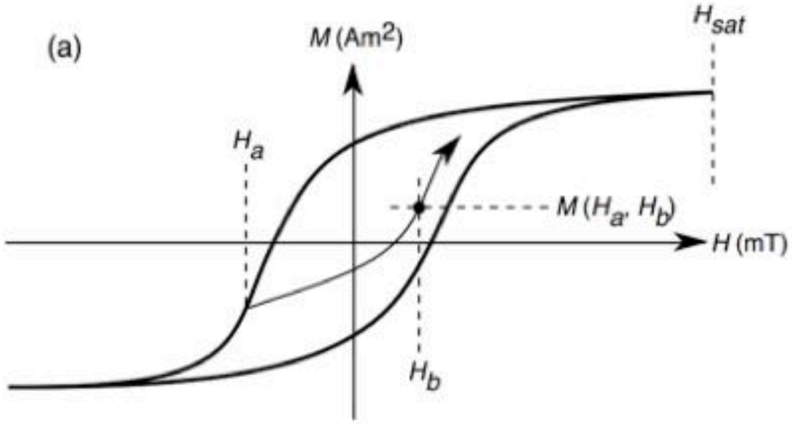
Repeat × 100-300

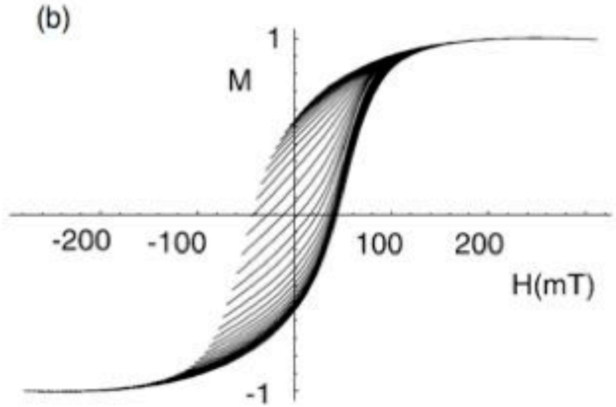
- Apply saturating field H_{sat}
- Reduce field to H_a (the reversal field)
- Measure M as a function of increasing field H_b ($H_b \geq H_a$) to obtain $M(H_a, H_b)$

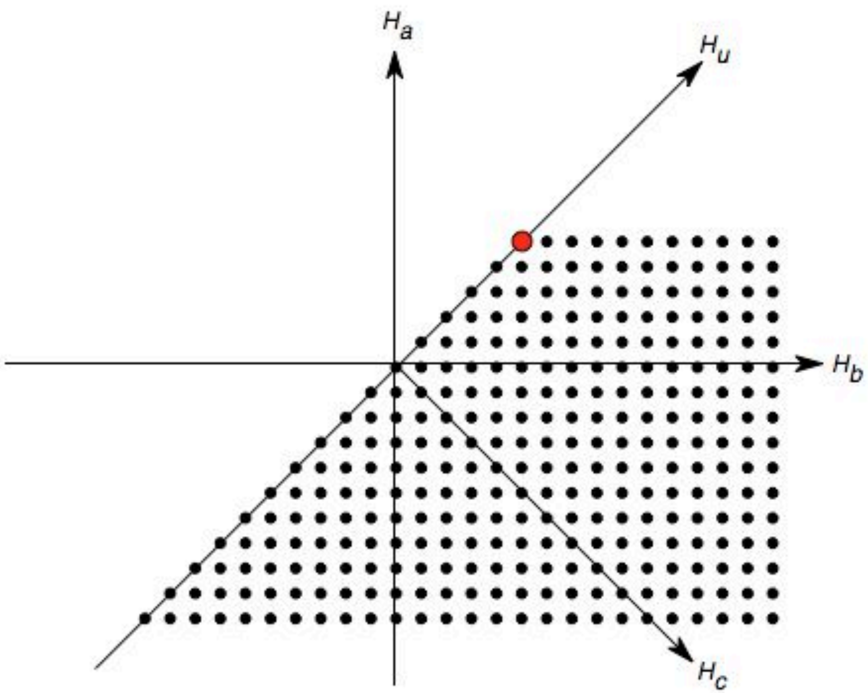


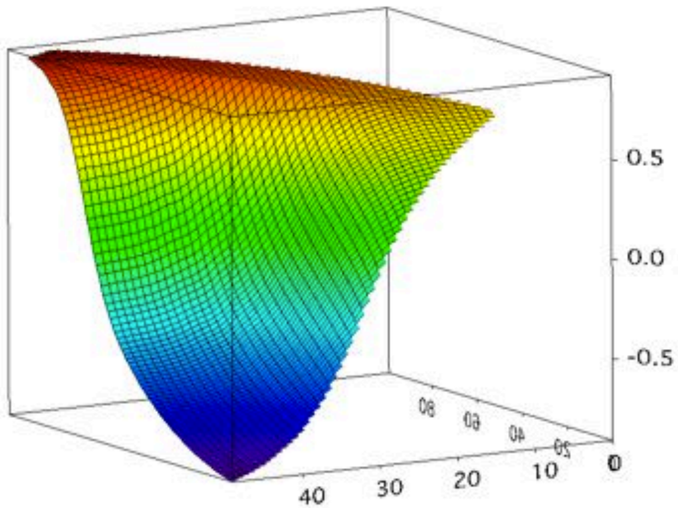


The FORC surface $M(H_a, H_b)$

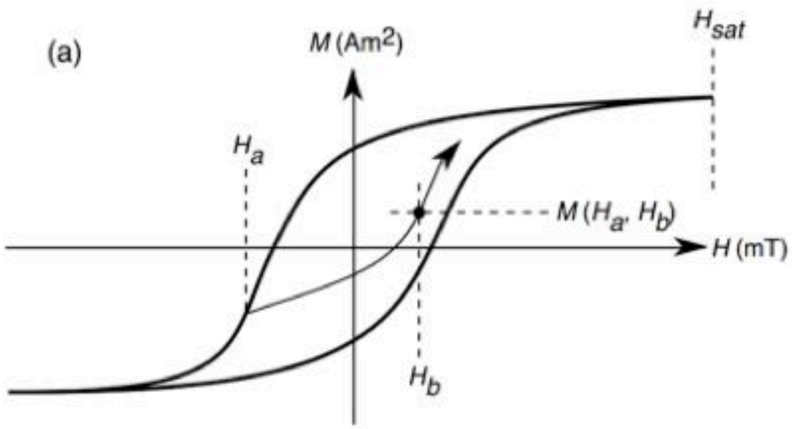


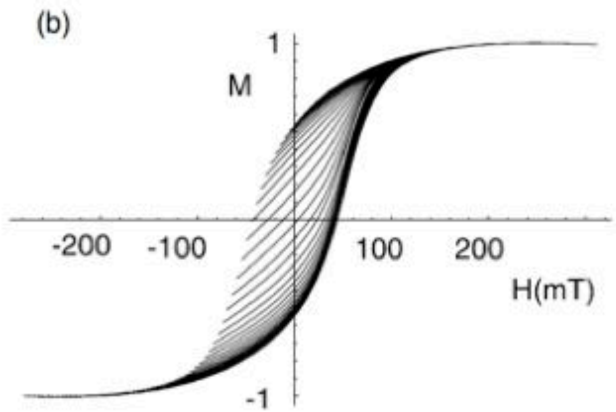


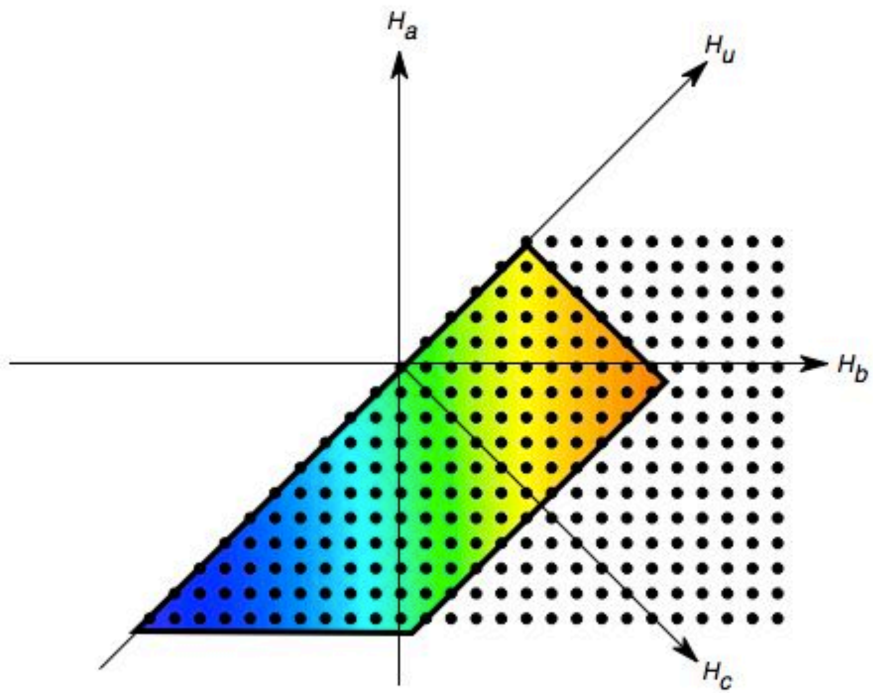


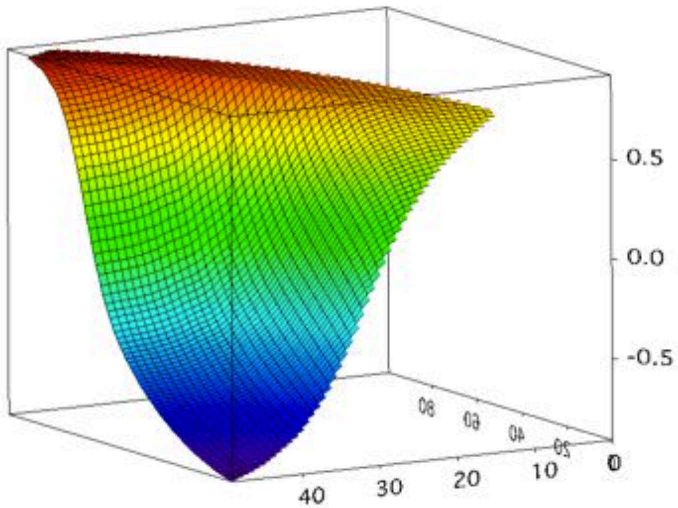


The FORC surface $M(H_a, H_b)$

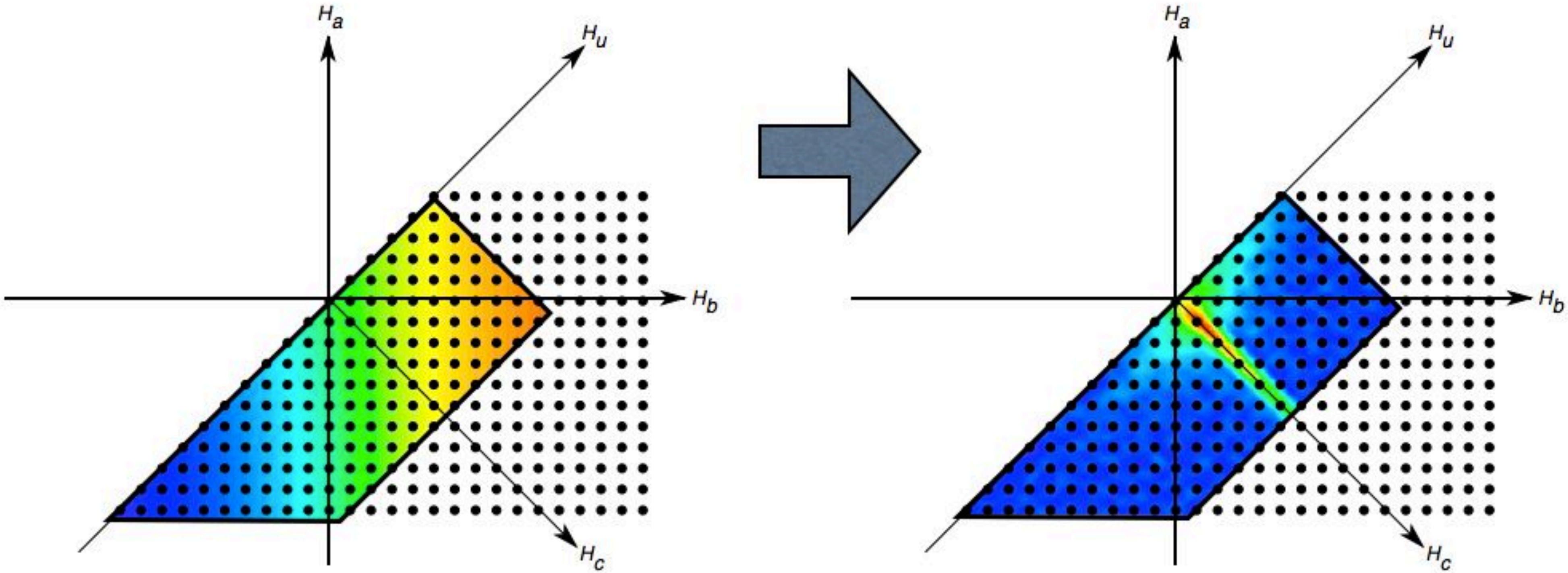








The FORC distribution

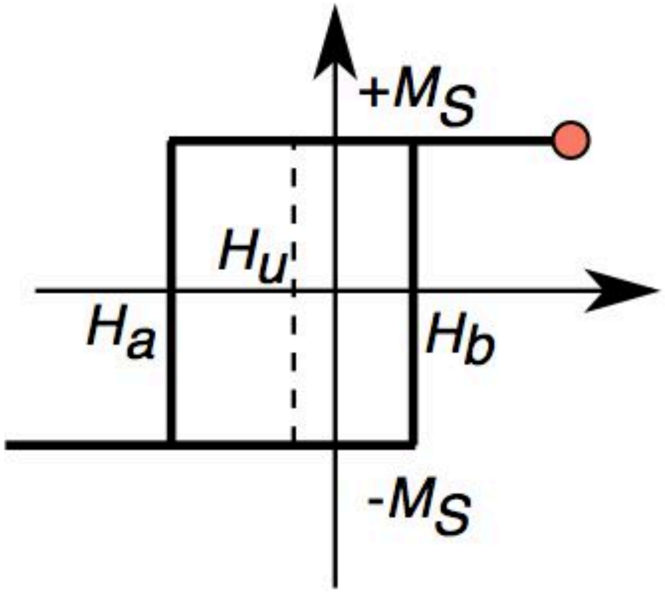


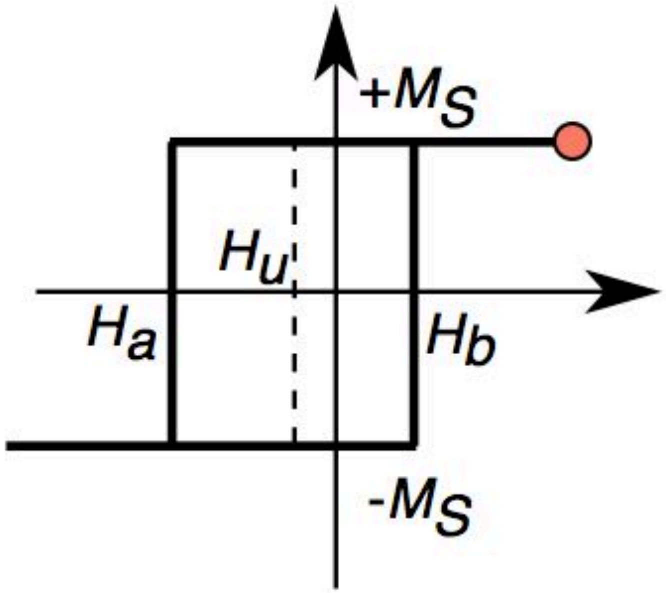
The FORC distribution is defined as the mixed second derivative of *M* with respect to H_a and H_b.

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

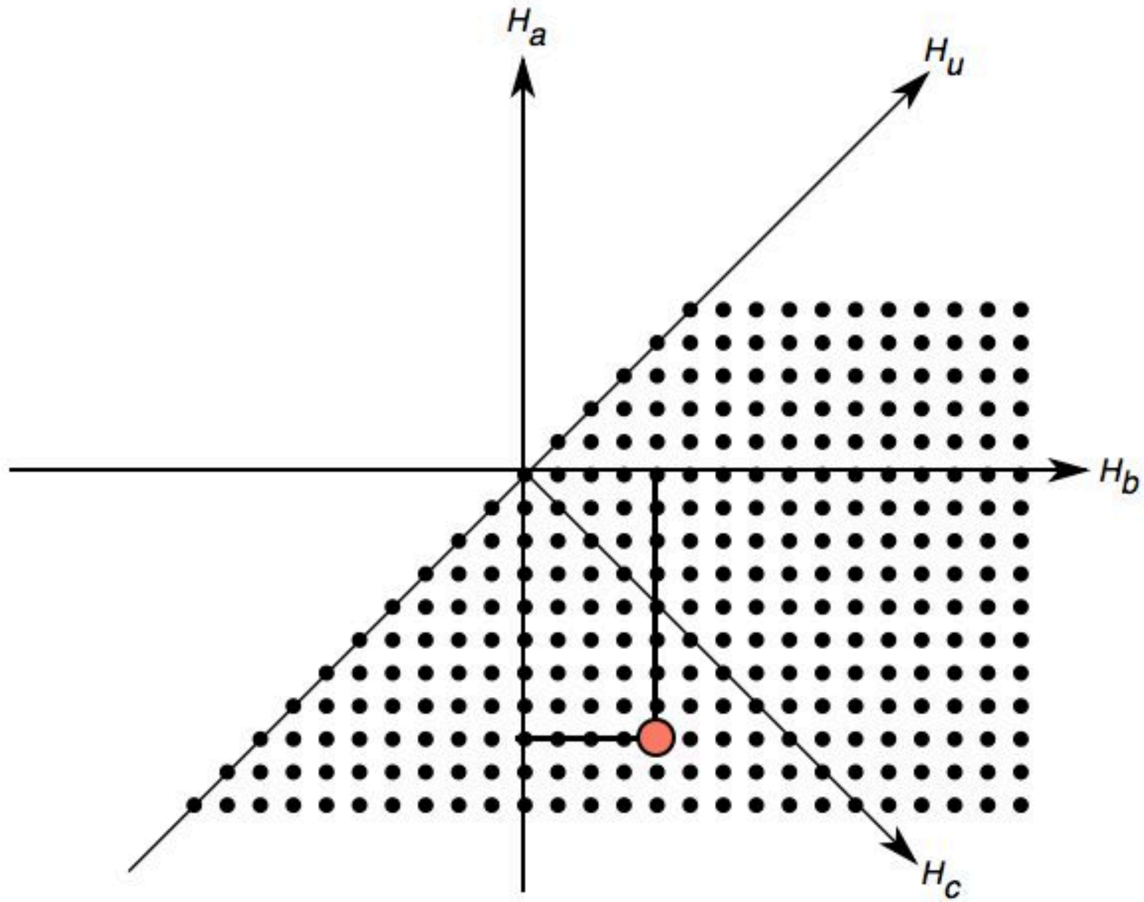
What does the FORC distribution tell us?

What does the FORC distribution tell us?



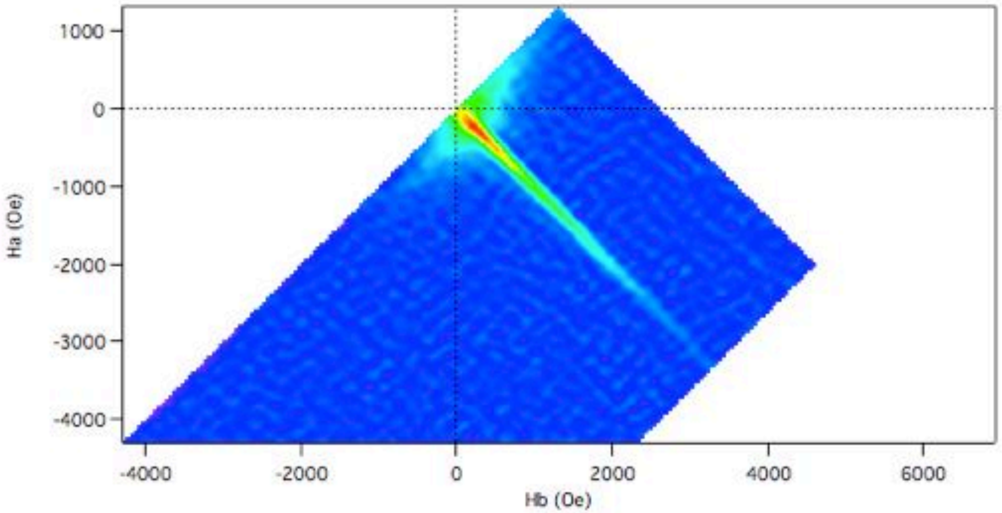


For $H_r = H_a$ there is a sudden change of dM/dH from 0 to ∞ at $H = H_b$, hence a positive contribution to the FORC function at coordinates (H_a, H_b).



Transformation of axes

Original H_a-H_b axes



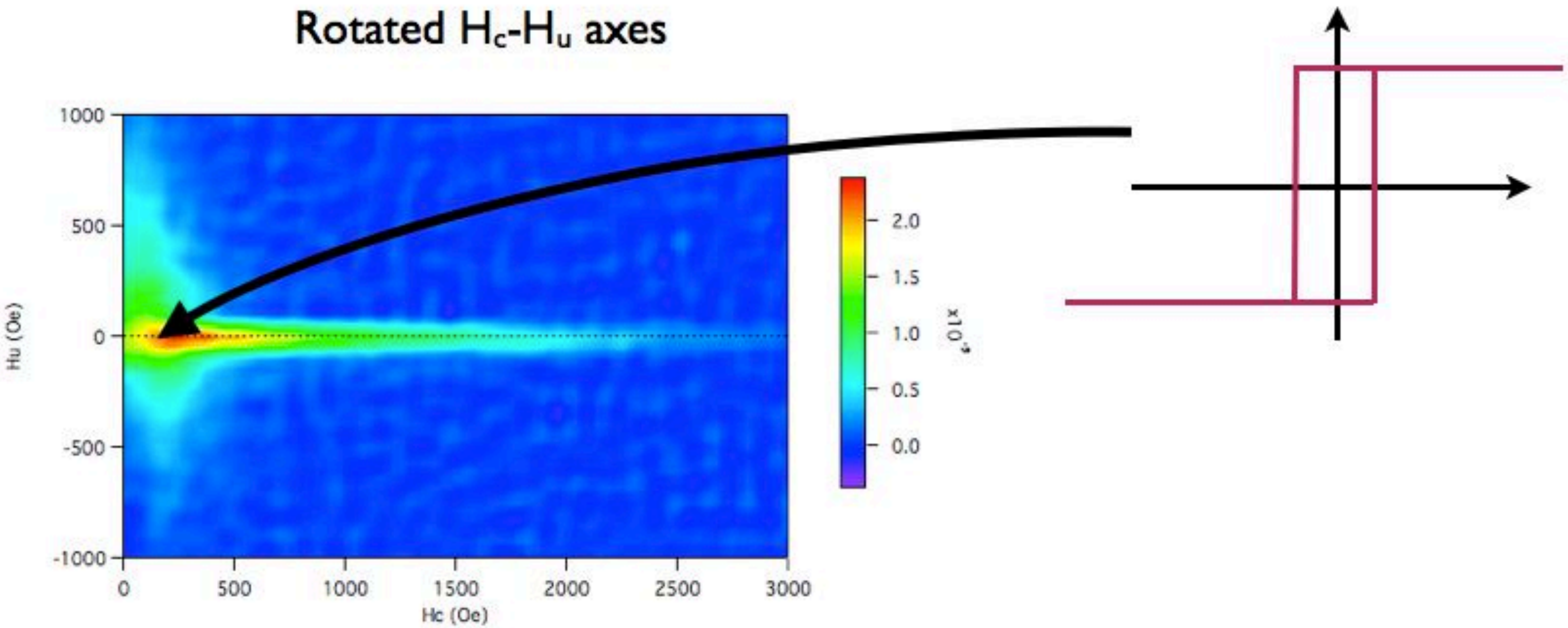
'Coercivity' axis

$H_c = (H_b - H_a)/2$

'Interaction field' axis

$H_u = (H_a + H_b)/2$

Rotated H_c-H_u axes



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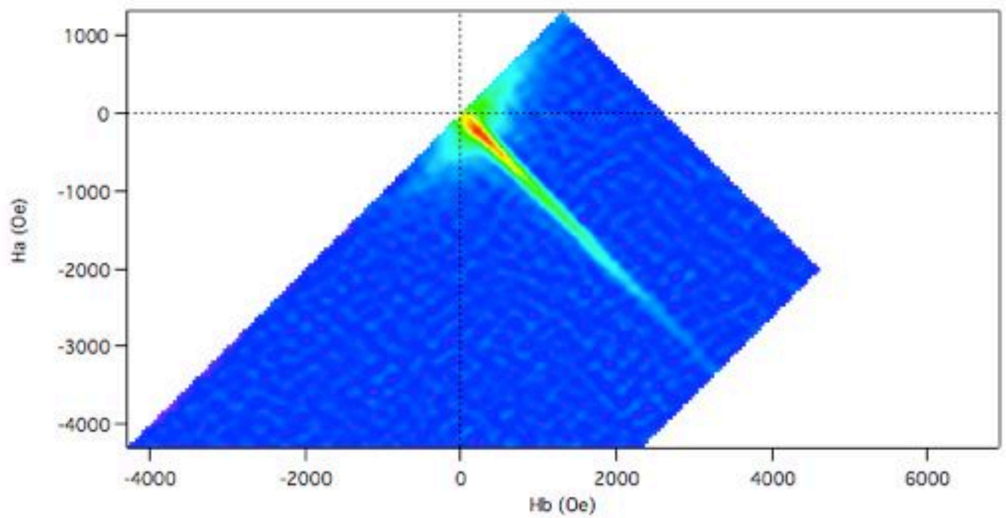

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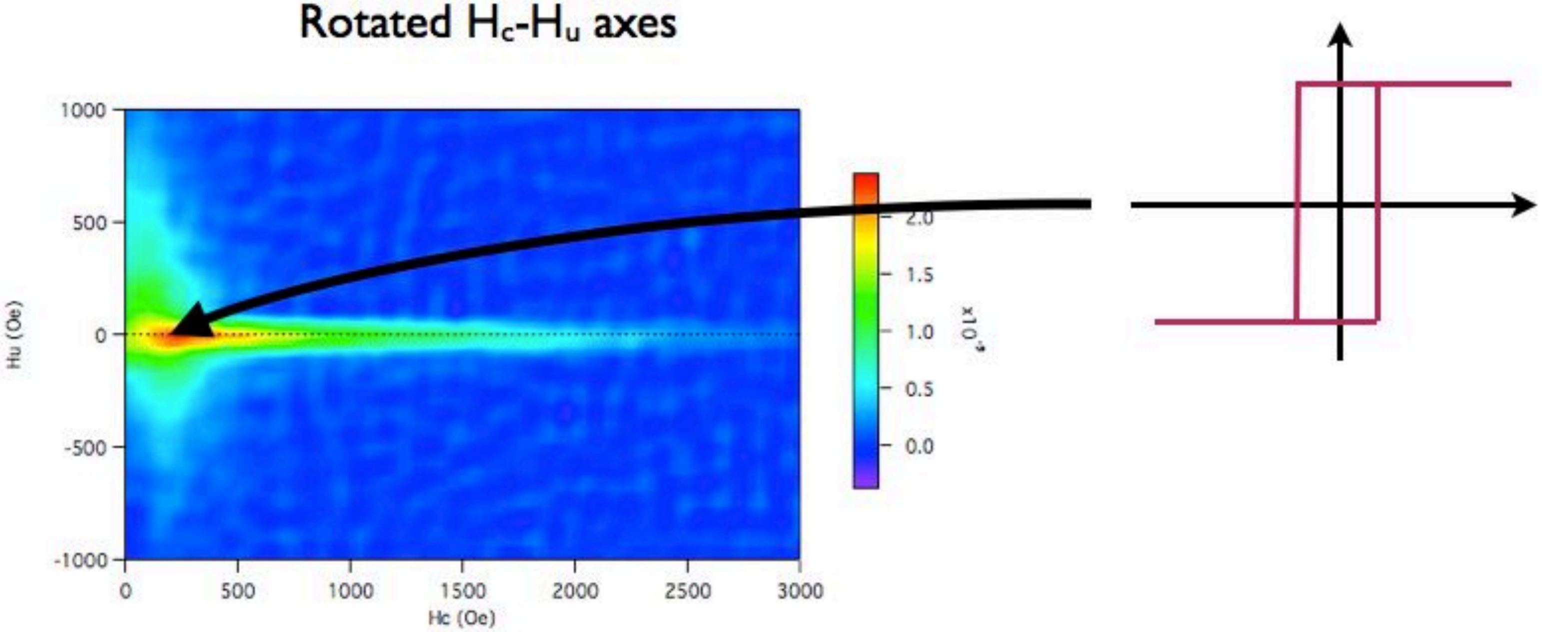
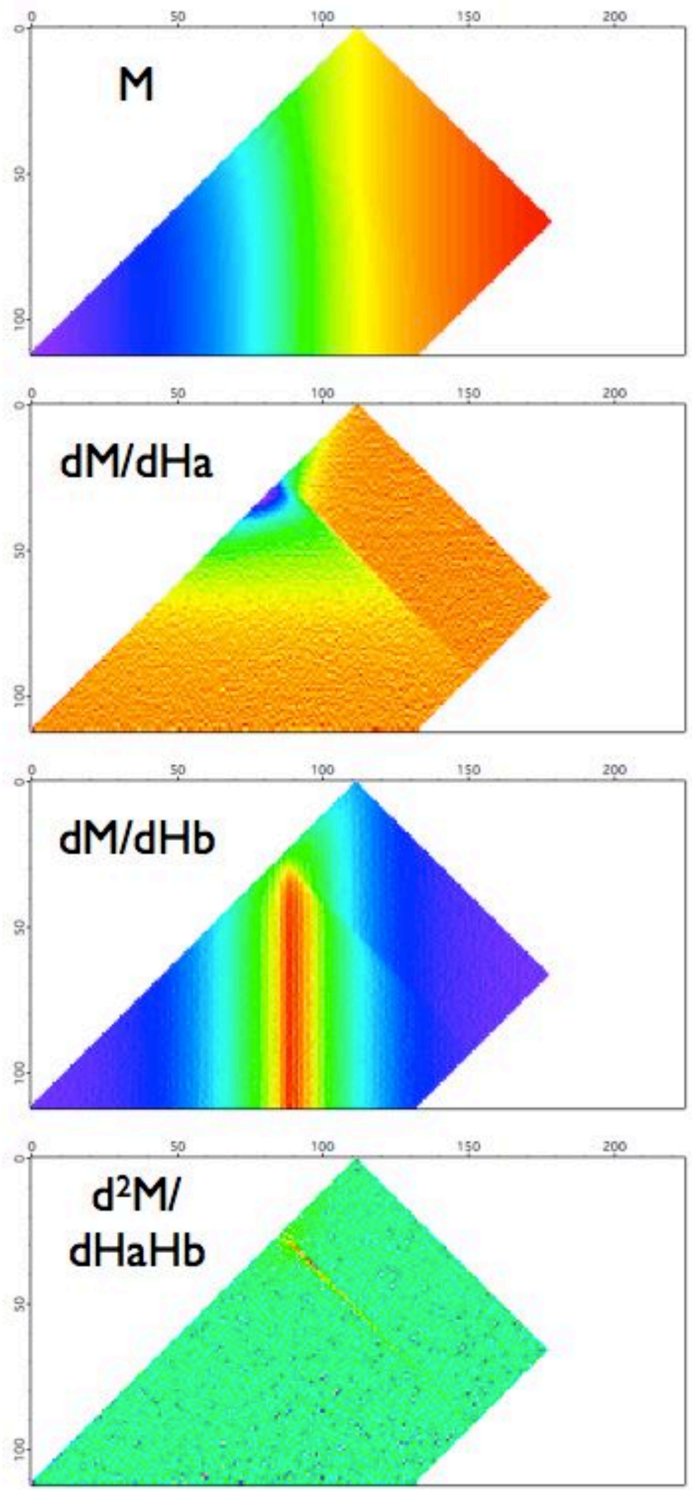
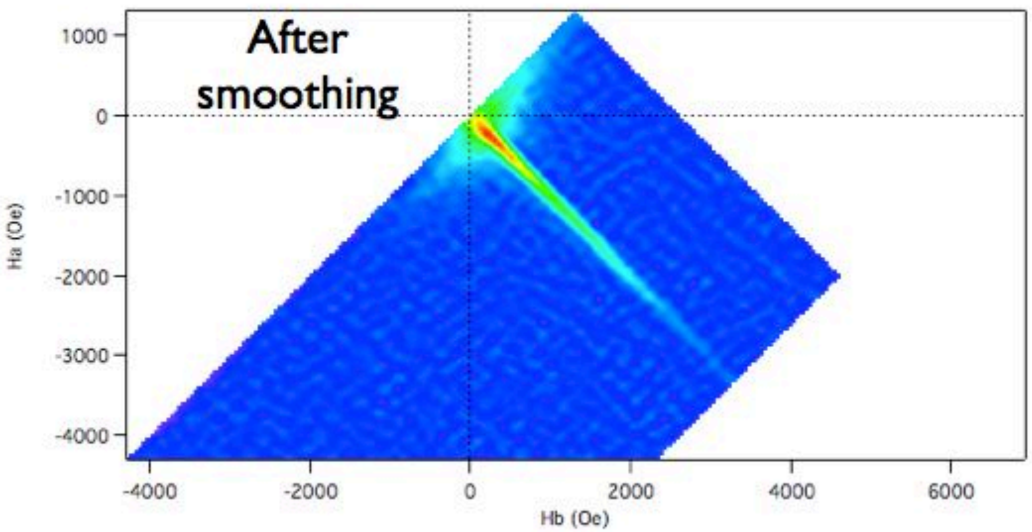
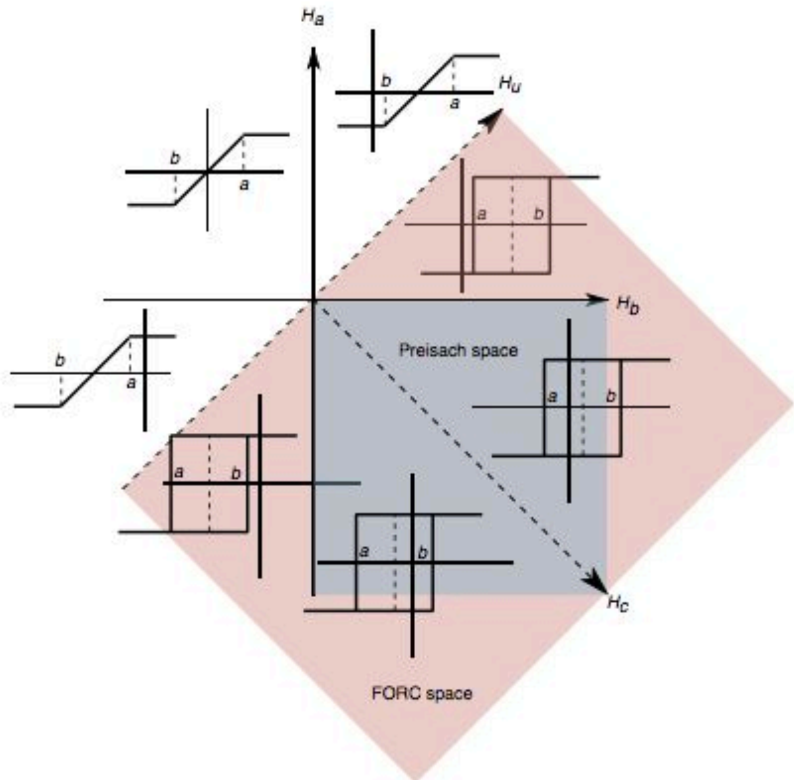




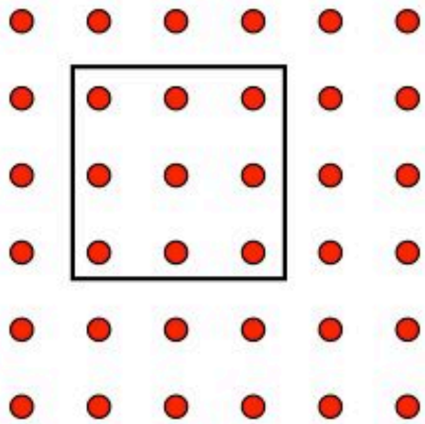


Preisach Interpretation



Conventional smoothing

Conventional smoothing with SF = 1 (N = 9)



The usual method of smoothing involves fitting a second-order polynomial to a square region of the FORC surface containing $N = (2SF + 1)^2$ points. Each square is centred on a measured data point, and each point within the square is given equal weight in the fit. The FORC distribution is equal to the a_6 coefficient.

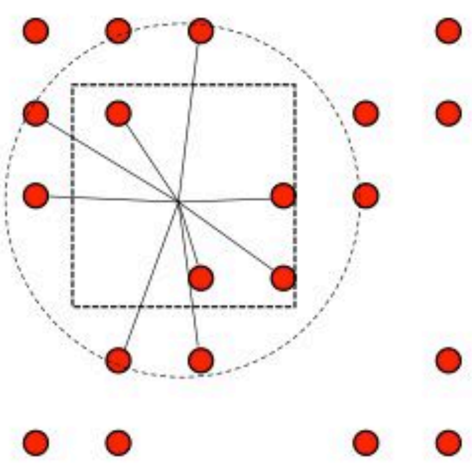
Until now, a constant value of N has been used across the entire FORC surface...

$$M(H_a, H_b) = a_1 + a_2 H_a + a_3 H_a^2 + a_4 H_b + a_5 H_b^2 + a_6 H_a H_b$$

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

LOESS Smoothing

LOESS smoothing with SF = 1 (N = 9)



LOESS smoothing (Cleveland and Devlin 1988) differs in three ways:

1. The area used for fitting is a region of arbitrary shape encompassing N nearest-neighbour data points.

2. Data inside the fit region are weighted using a tricube function:

$$w_i = \left(1 - \left|\frac{x - x_i}{\max(x - x_i)}\right|^3\right)^3$$

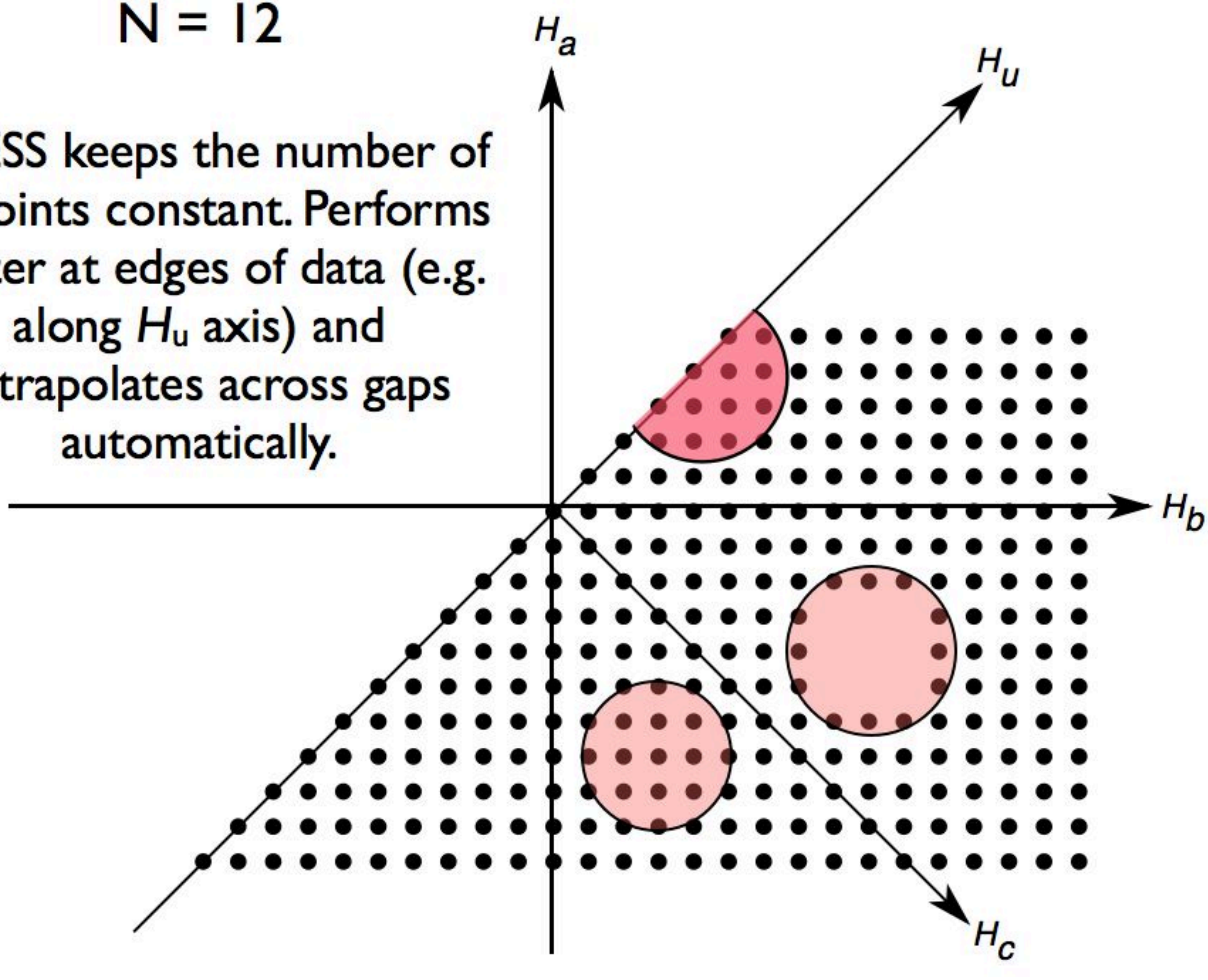
3. The fit region may be centred on and/or span across gaps or undefined regions of FORC space.

Cleveland, W.S. and Devlin, S.J. (1988) "Locally Weighted Regression: An Approach to Regression Analysis by Local Fitting," Journal of the American Statistical Association, Vol. 83, pp. 596-610.

LOESS Smoothing

N = 12

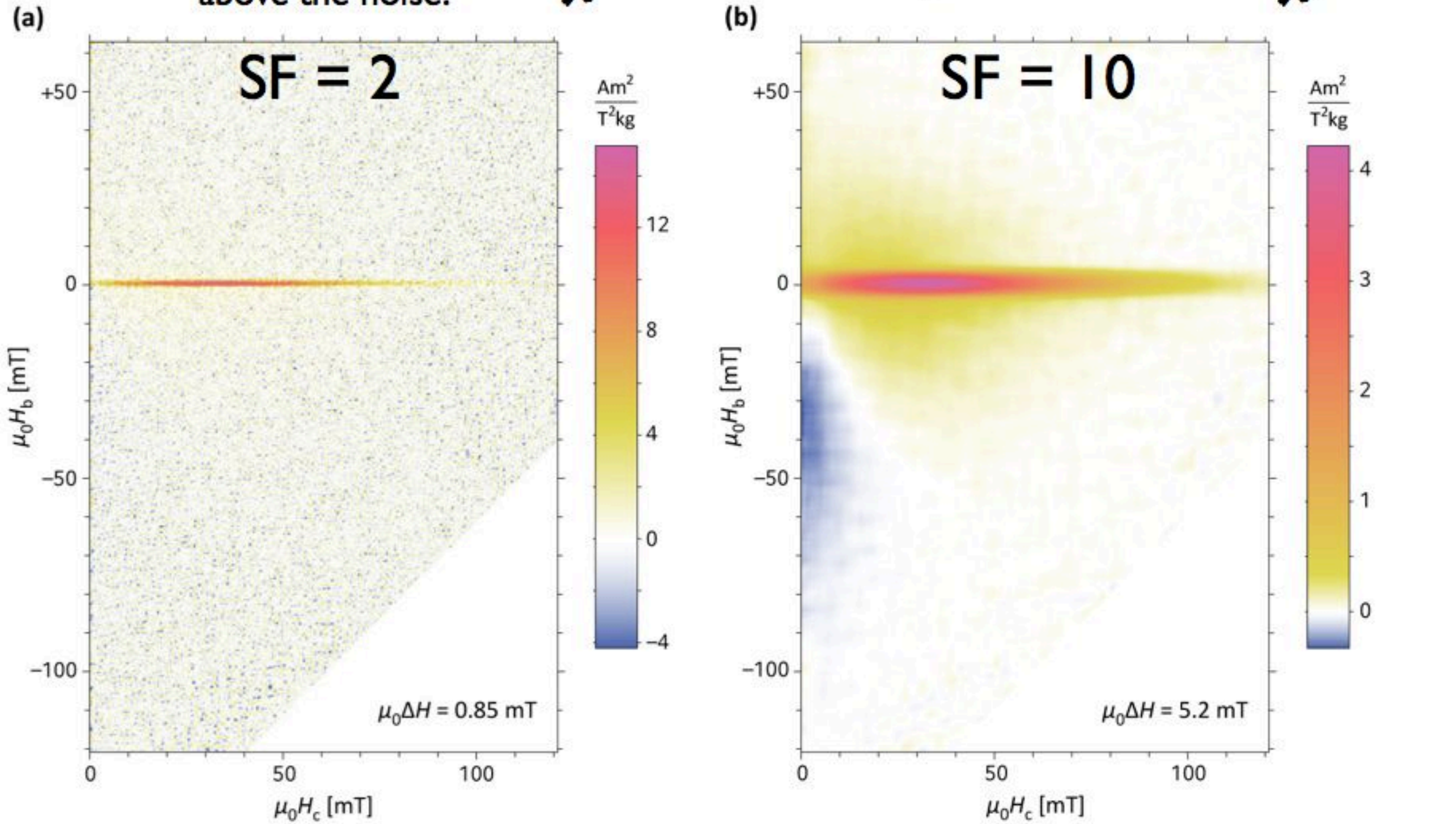
LOESS keeps the number of fit points constant. Performs better at edges of data (e.g. along H_u axis) and extrapolates across gaps automatically.



Problems with conventional smoothing

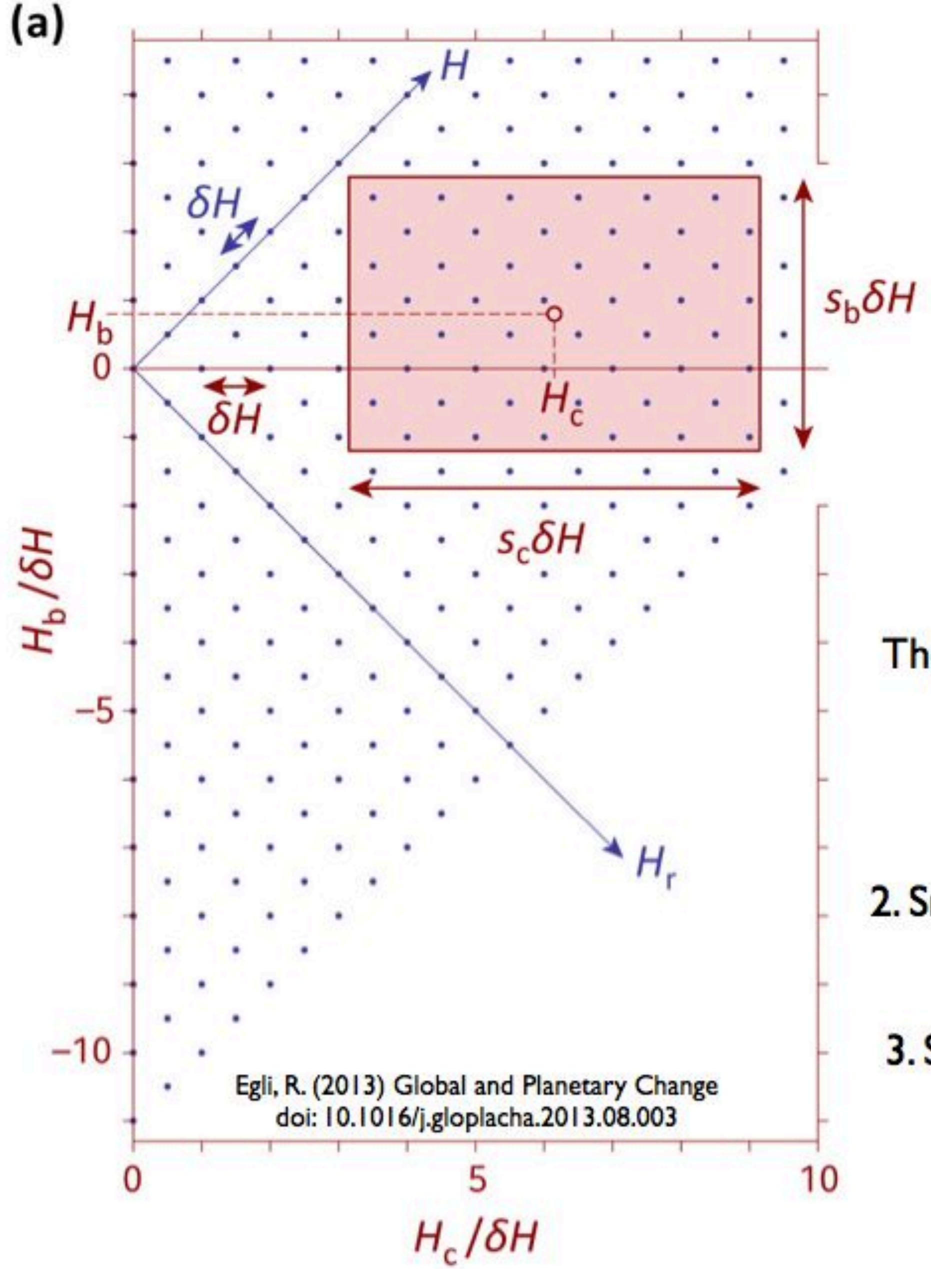
Small SF preserves sharp ridge structure. ✓
Background signal not visible above the noise. ✘

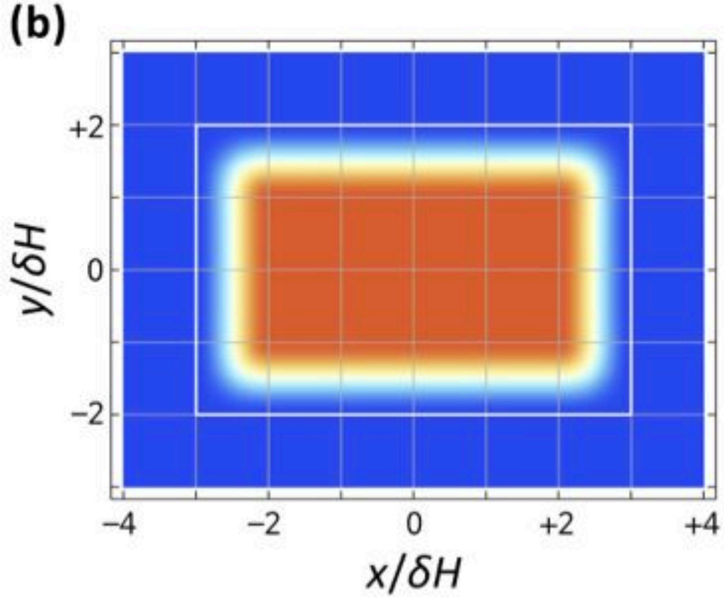
High SF reveals background signal. ✓
Ridge is smeared out. ✘



Egli, GPC 2012: Fig. 1

VARIFORC: Adapts level of smoothing according to local properties of the FORC diagram (best of both worlds)





The VARIFORC method make several fundamental changes to the way in which FORC diagrams are smoothed.

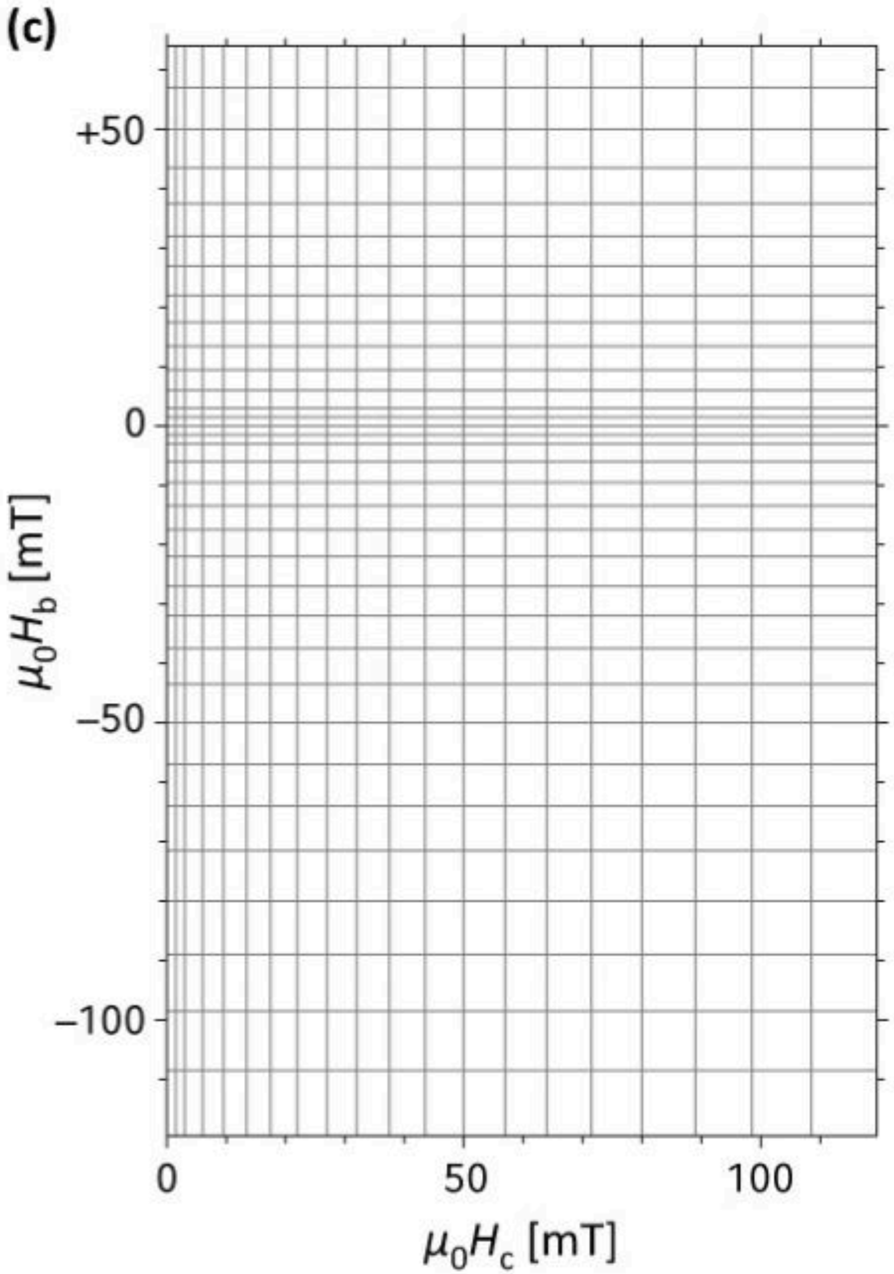
1. H_c and H_u coordinate system is used

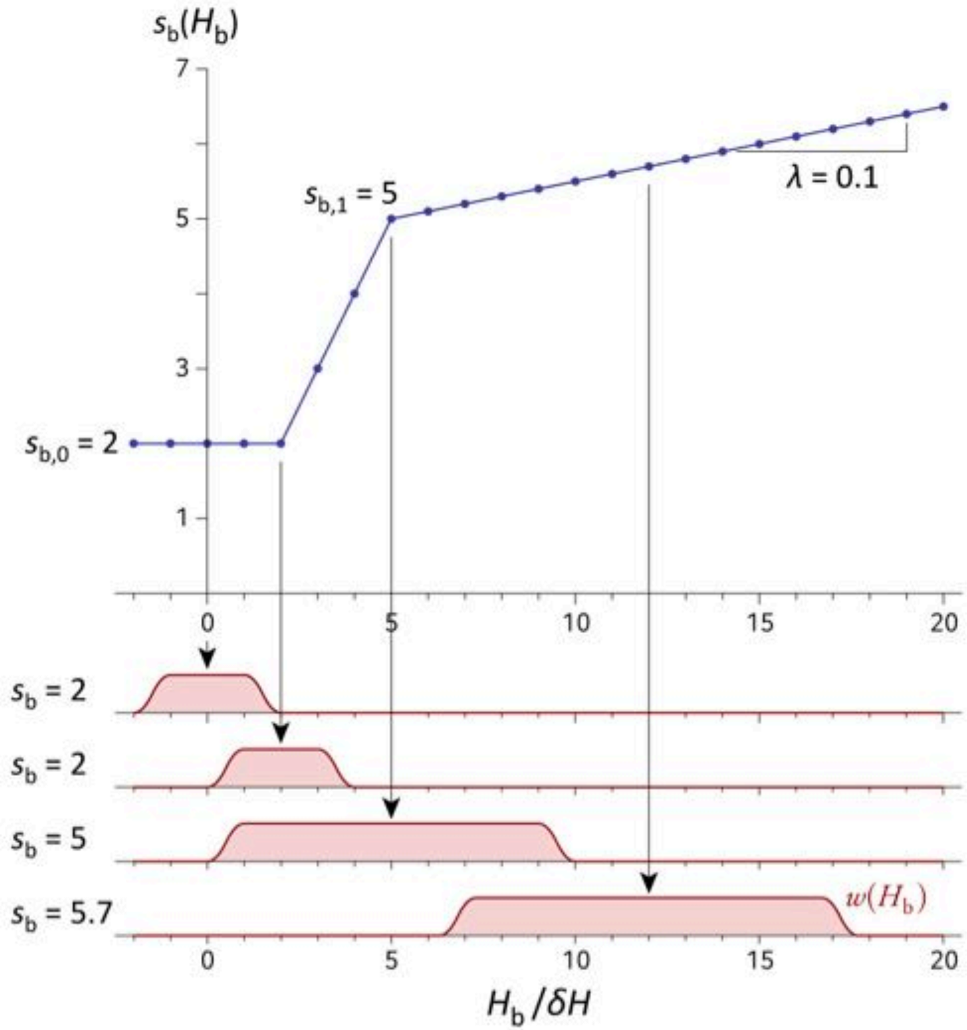
2. Smoothing box is rectangular (i.e. different smoothing factors for H_c and H_u directions)

3. Smoothing factors vary according to local properties of the FORC diagram

4. More efficient weighting function

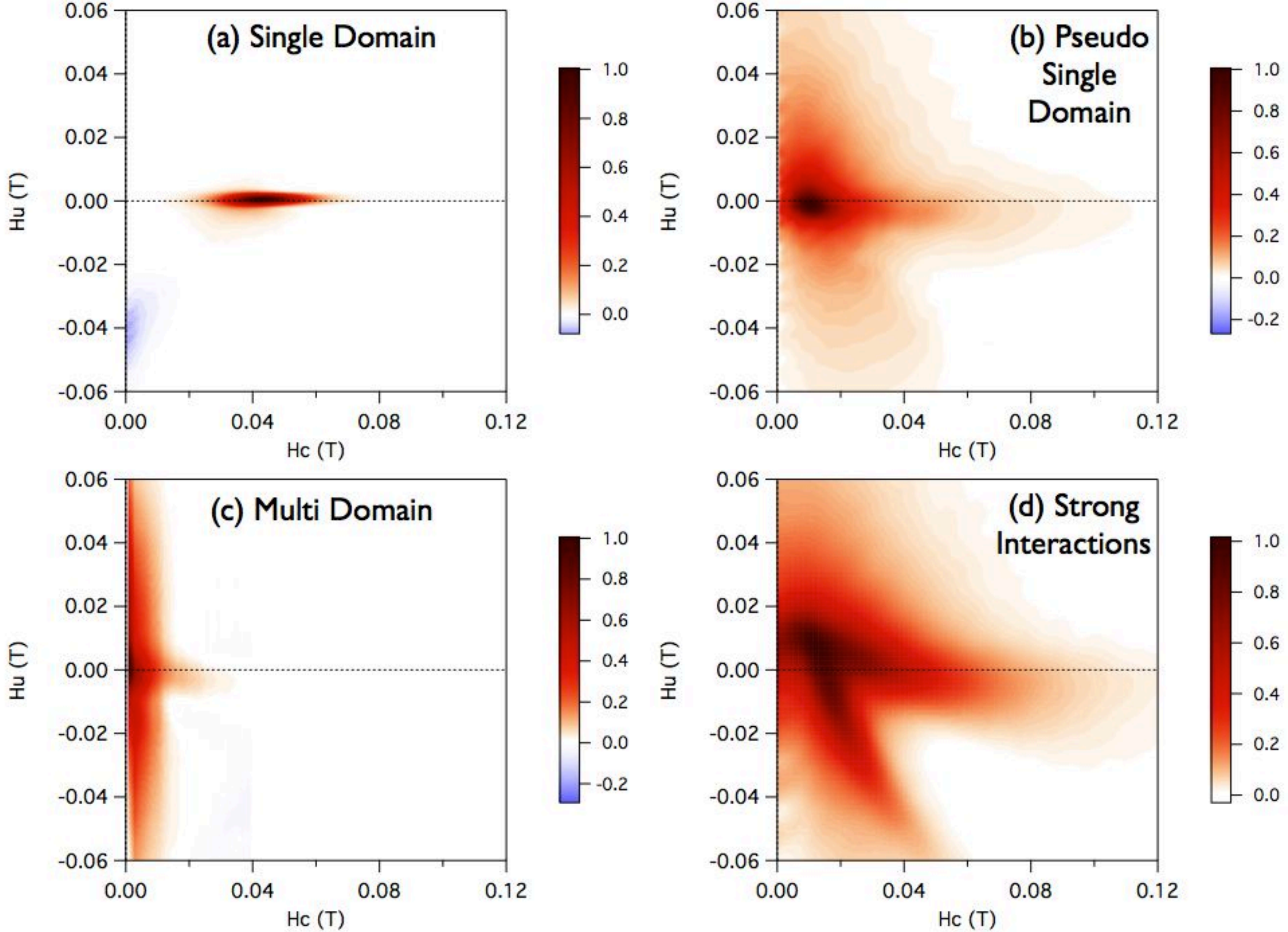
Adapting level of smoothing for vertical and central ridges





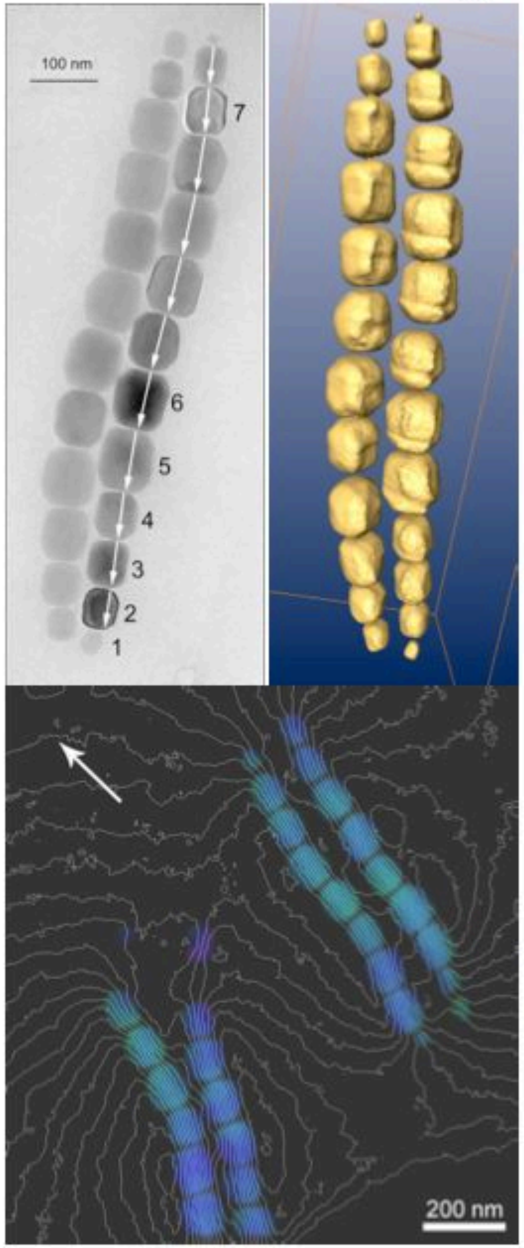
Egli, R. (2013) Global and Planetary Change
doi: 10.1016/j.gloplacha.2013.08.003

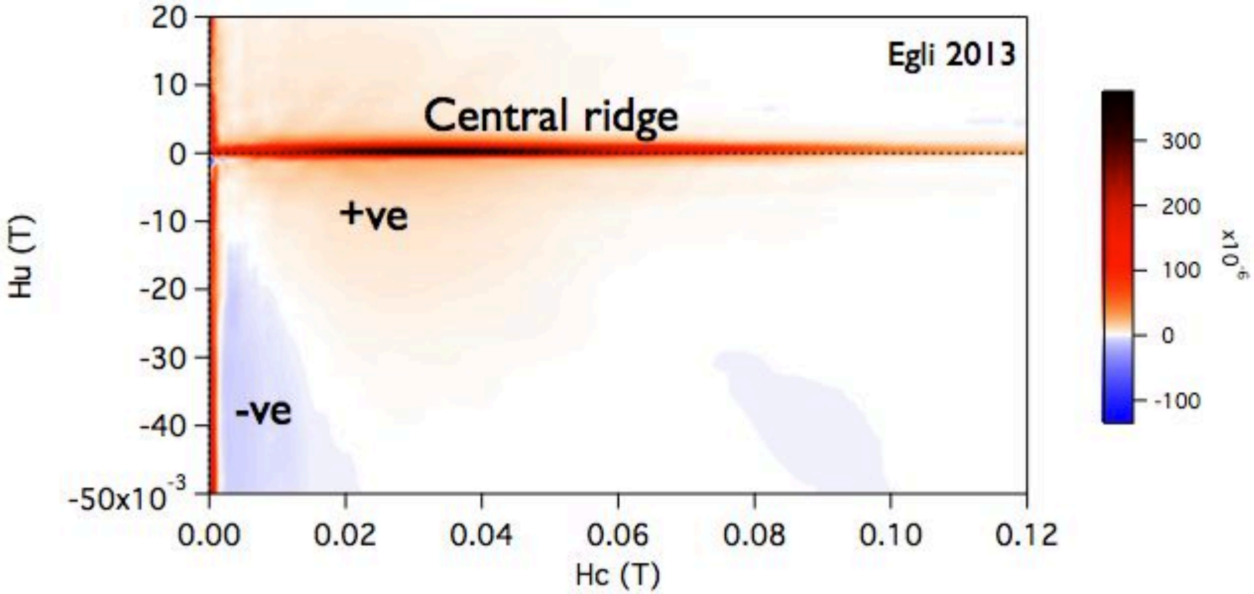
Domain state fingerprinting

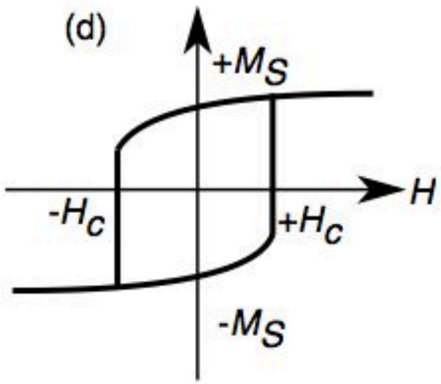


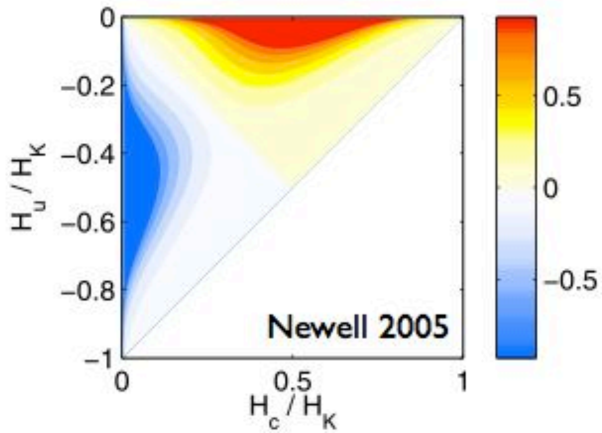
FORC fingerprints

Non-interacting uniaxial single domains
e.g. sediment containing magnetotactic bacteria



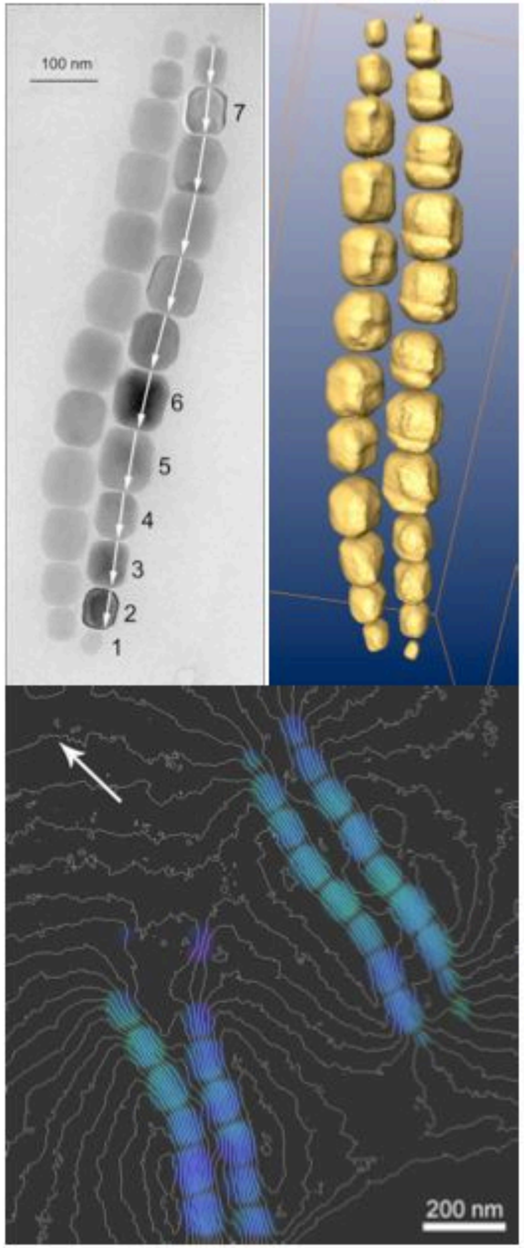


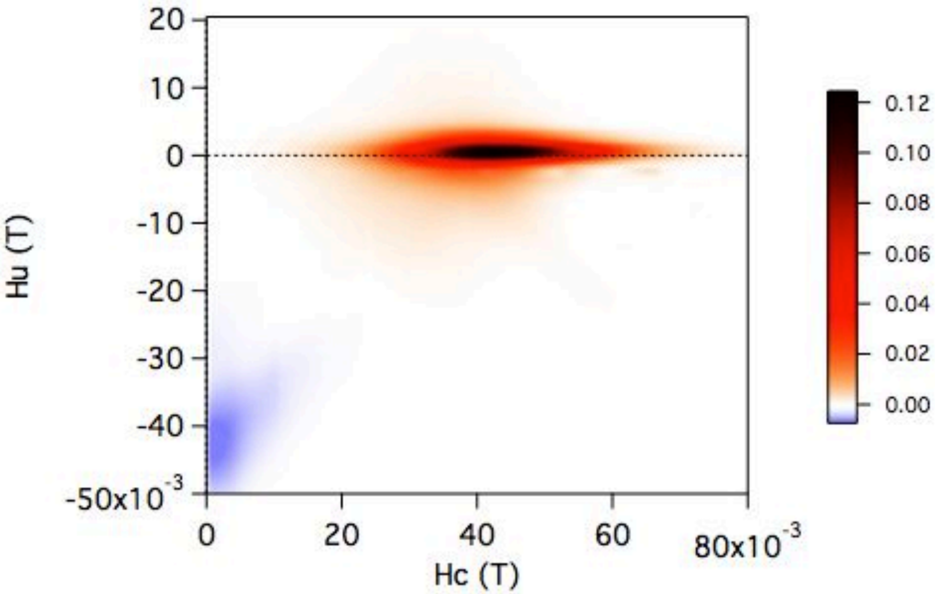


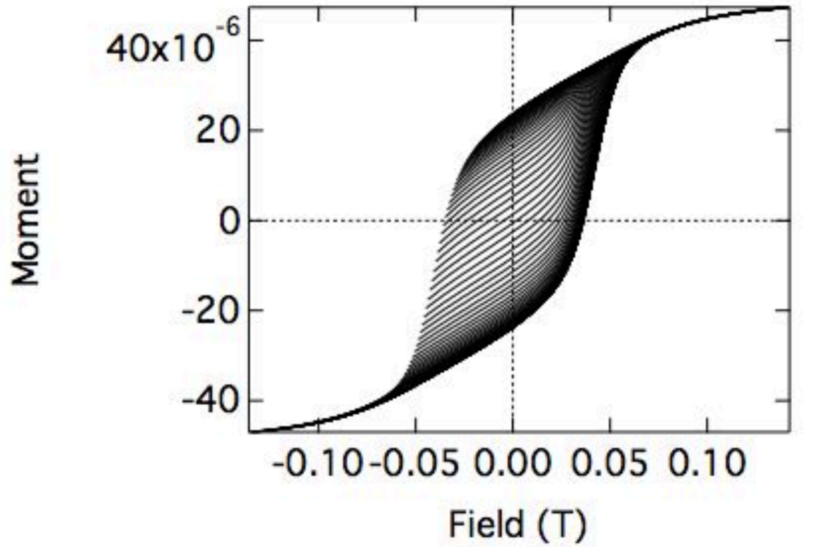


FORC fingerprints

Weakly interacting uniaxial single domains
e.g. concentrated sample of magnetotactic bacteria

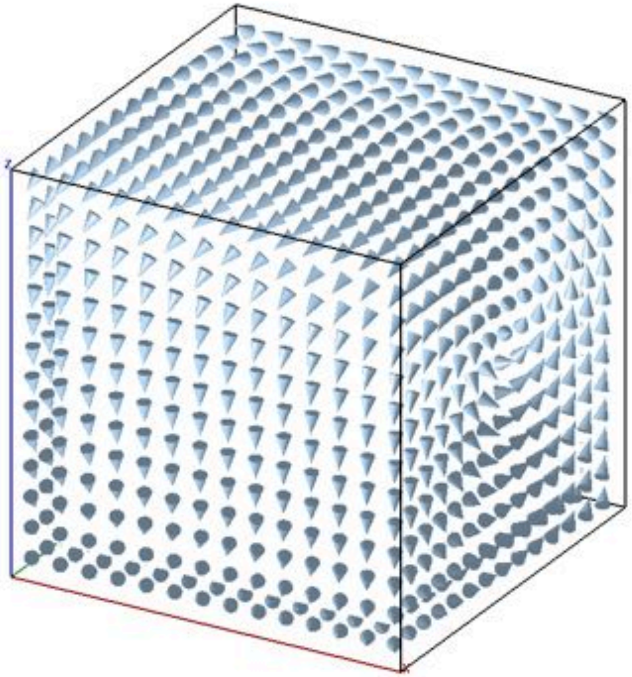


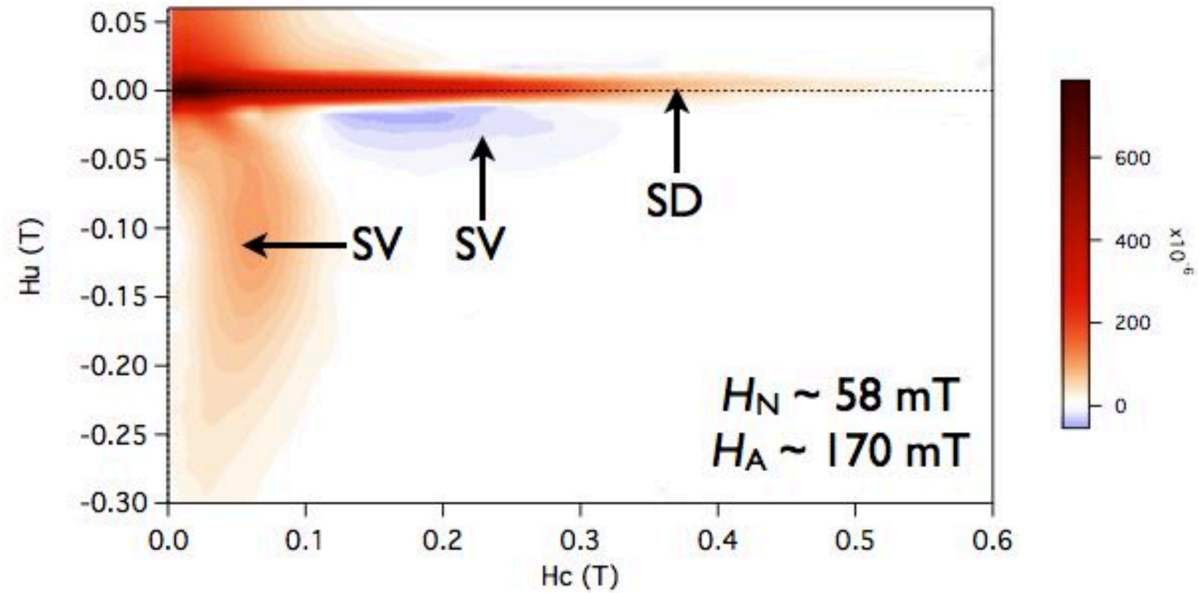




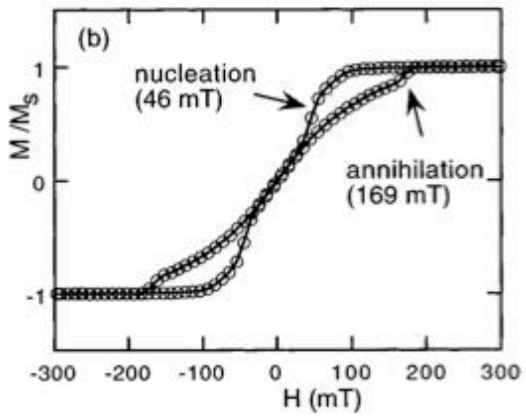
FORC fingerprints

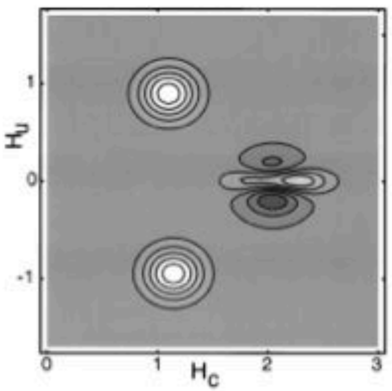
Single vortex (SV) nucleation and annihilation





Pike and Fernandez 1999 SV nucleation and annihilation in Co nanodots





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

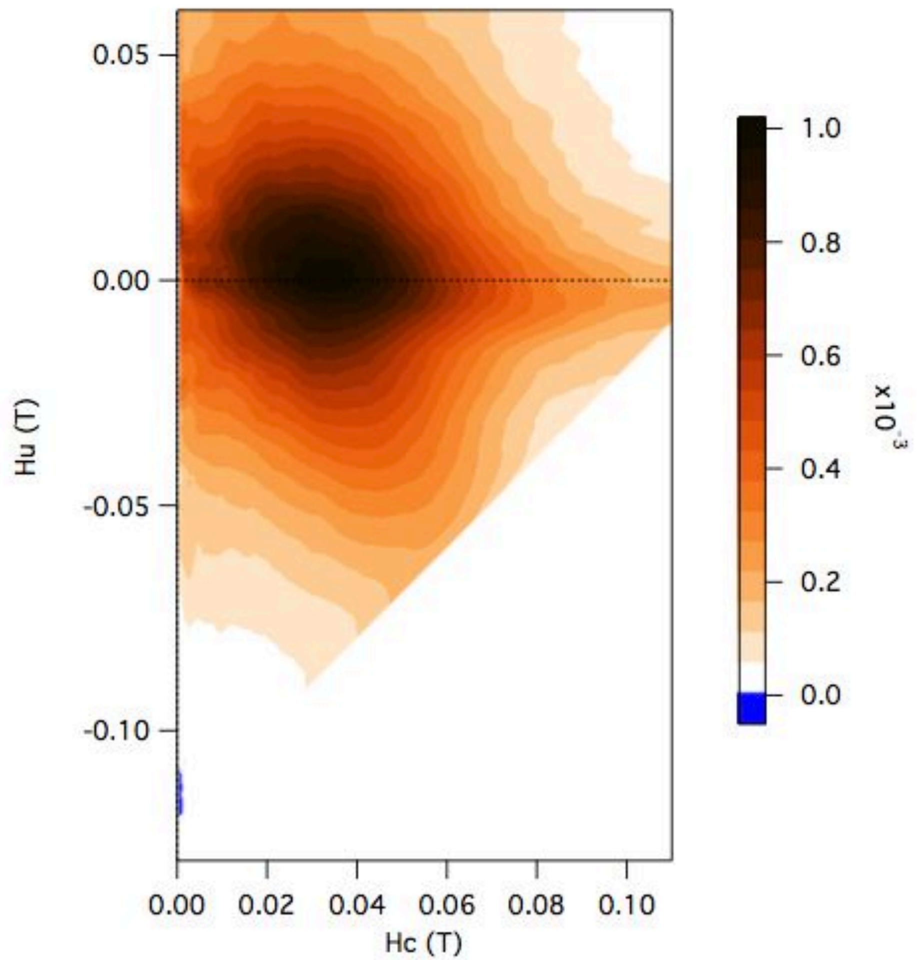
$$H_N = -H_c - H_u$$

$$H_A = H_c - H_u$$

FORC fingerprints

True PSD particles with intermediate grain size between SD and MD

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

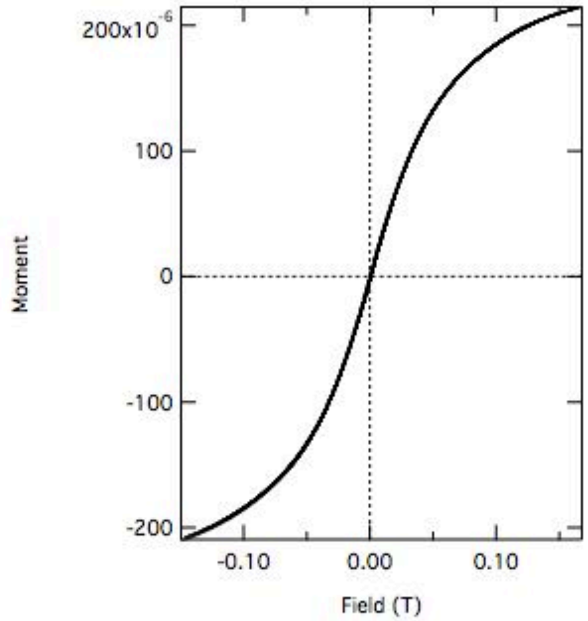


Fire obsidian (1st ever FORC measured on our new Lakeshore AGM!)

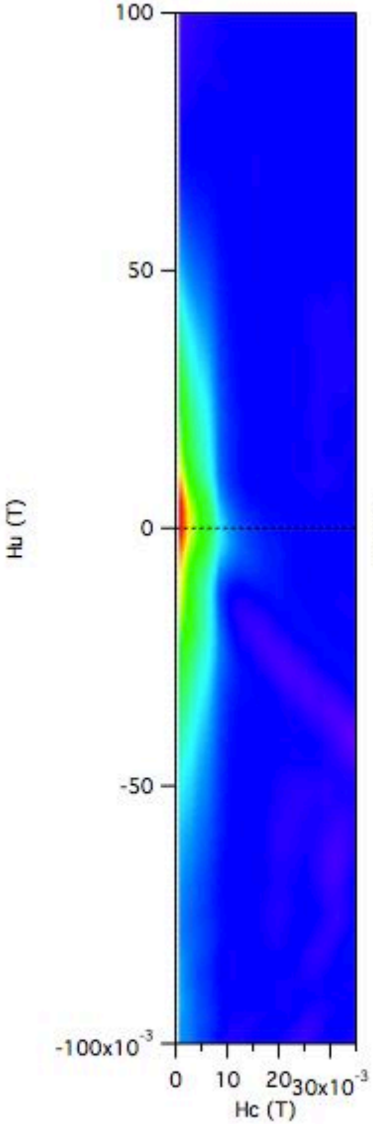
FORC fingerprints

True MD behaviour: titanomagnetite

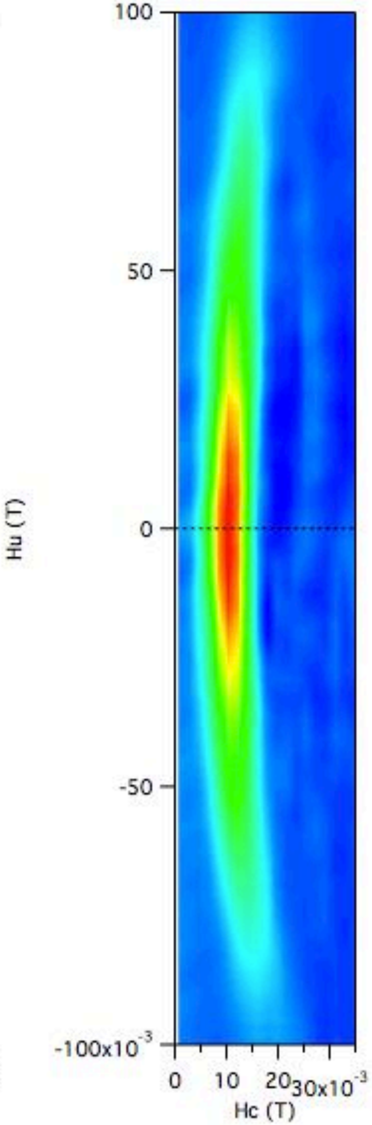
Weak Pinning



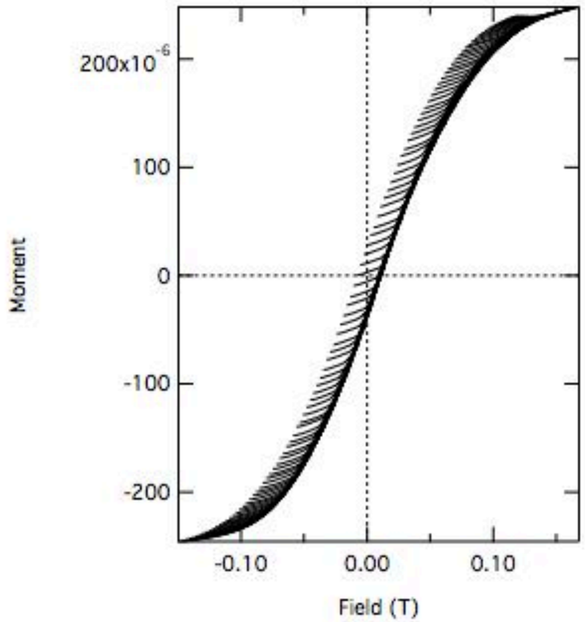
R.T.



50 K

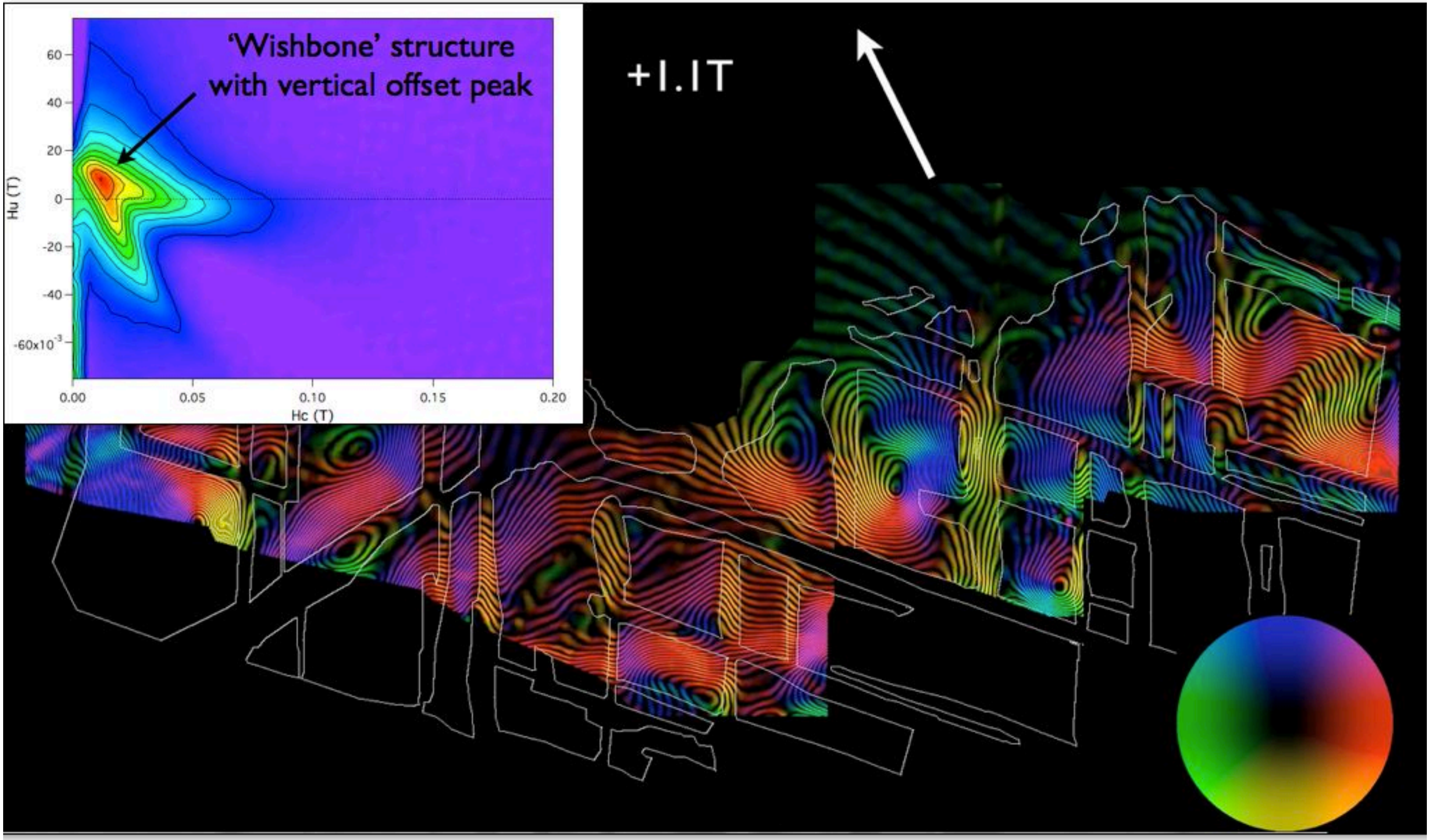


Strong Pinning



FORC fingerprints

Highly-correlated interacting system



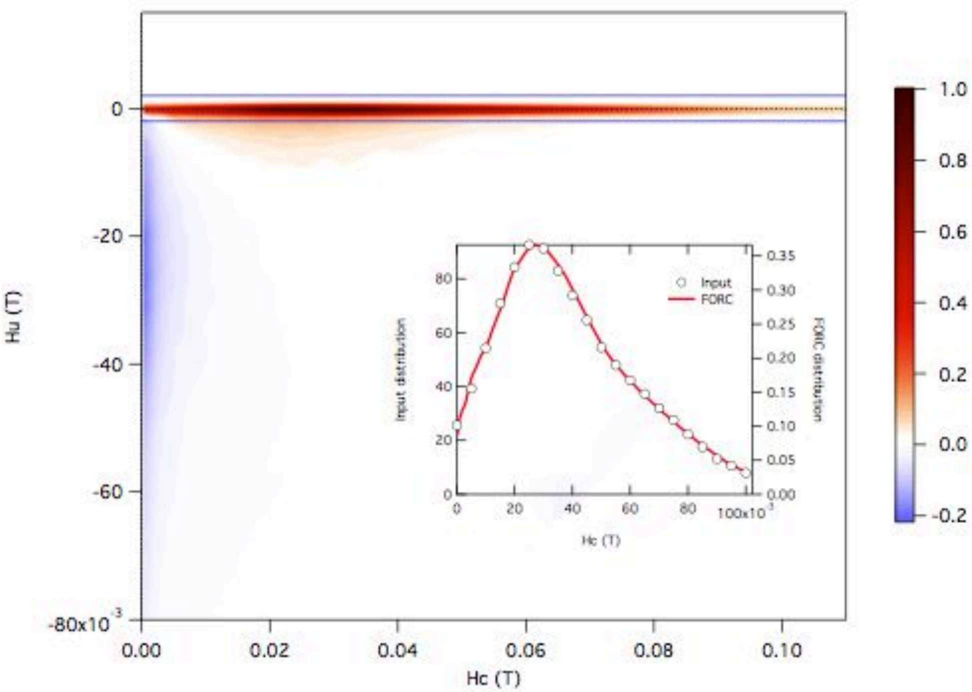
Coercivity distributions

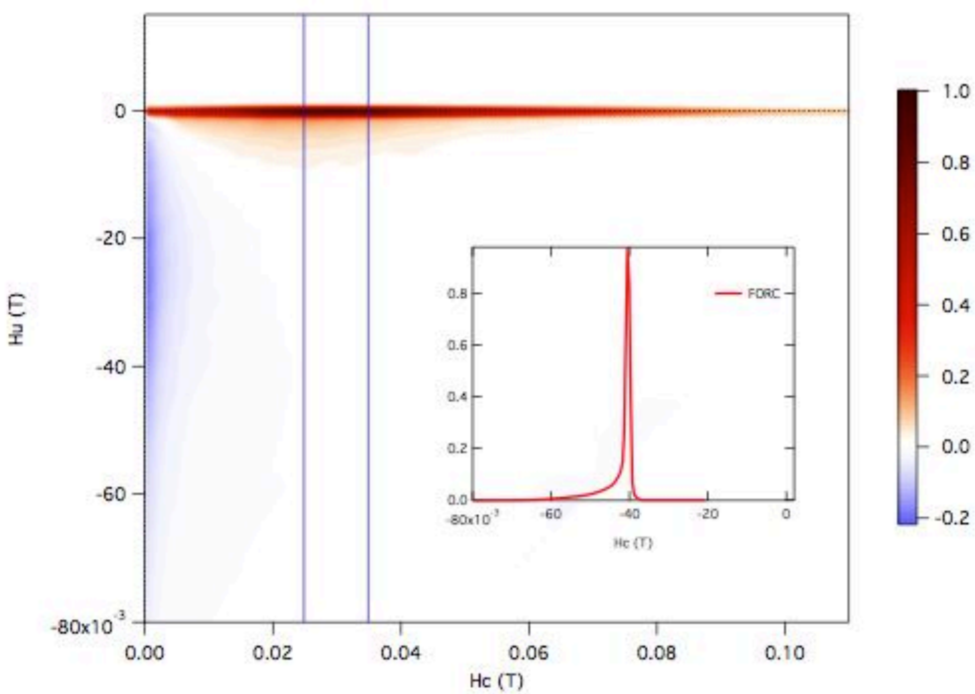
Simulation of weakly interacting Stoner-Wohlfarth particles with a prescribed coercivity distribution.

FORC diagram displays the characteristic combination of central ridge along the H_c axis, positive and negative background features for H_u<0, and zero for H_u > 0.

An average horizontal profile of the central ridge demonstrates that the input coercivity distribution is accurately reproduced by the FORC diagram.

Sharpness of the vertical profile indicates absence of interaction fields.

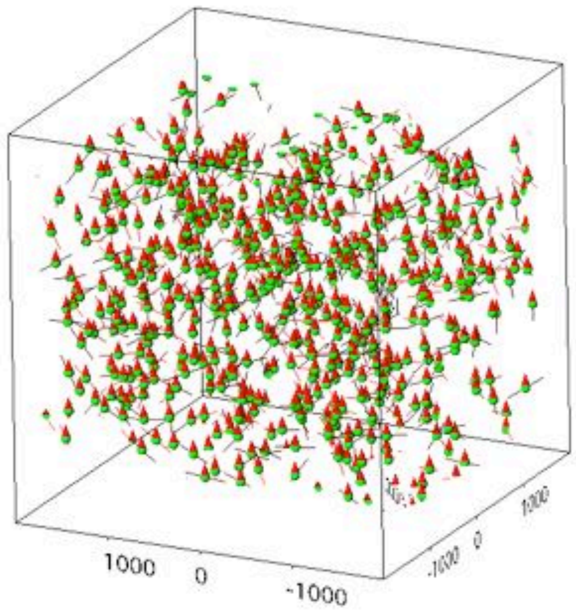


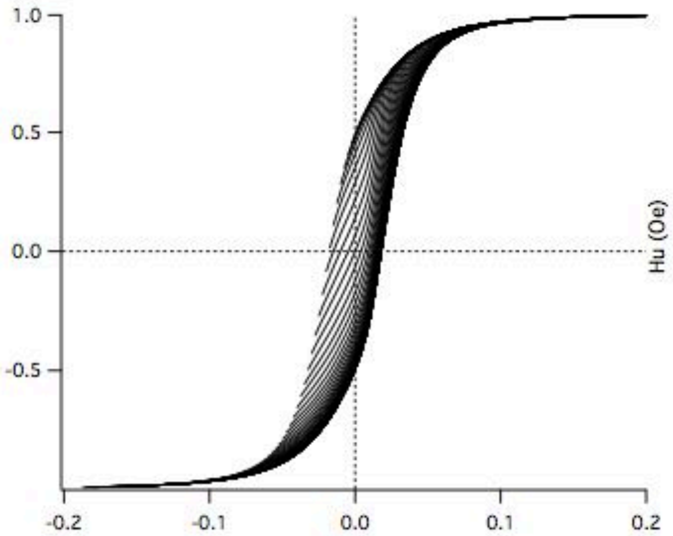


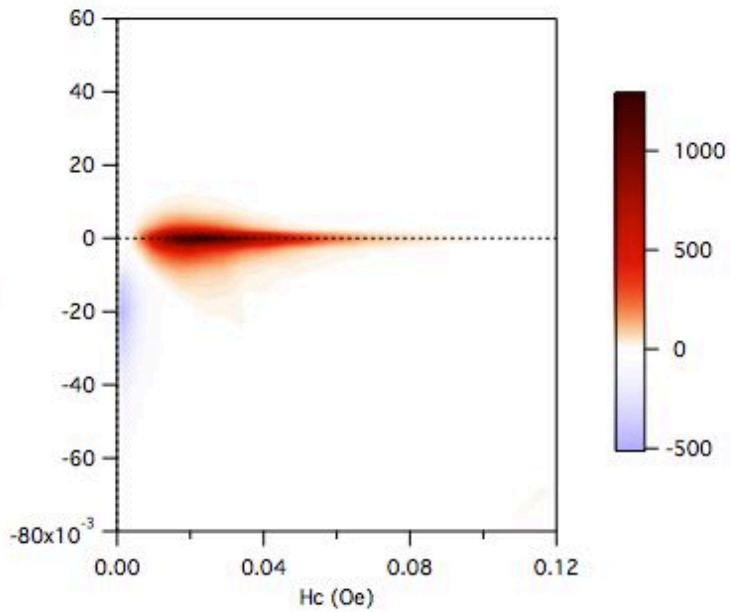
Interactions

FORCulator: Coming soon!

Generate arbitrary arrangements of SD particles.
Choose anisotropy type and orientation of easy axes.
Specify coercivity distribution.
Solve LLG equations taking full account of magnetostatic interactions.
Perform simulation over same FORC space as experiments.
Smooth simulation in same way as experiments.

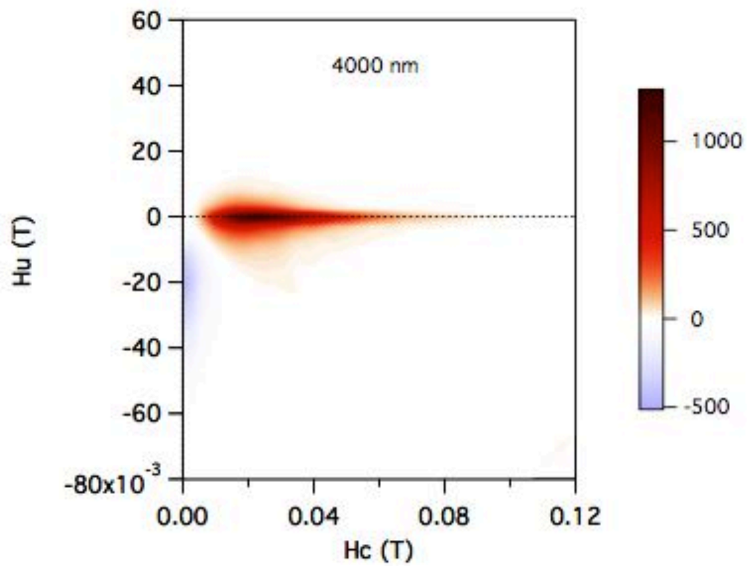


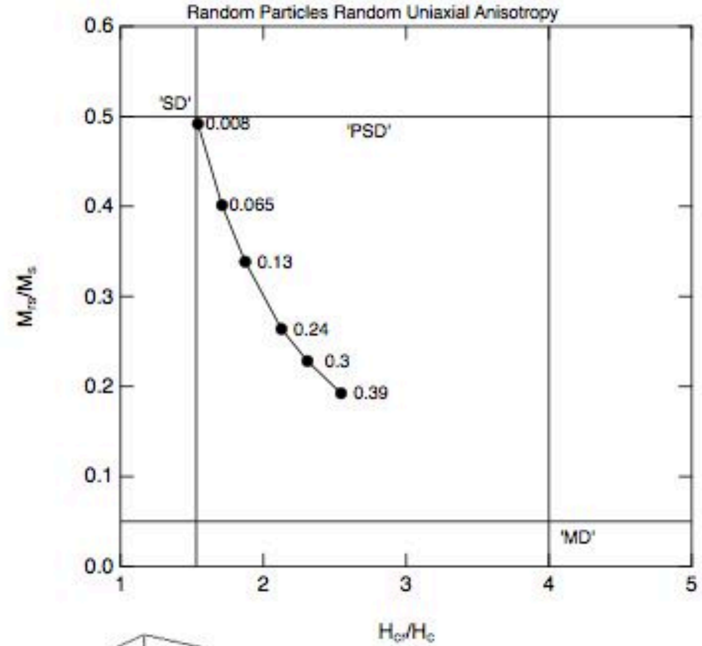




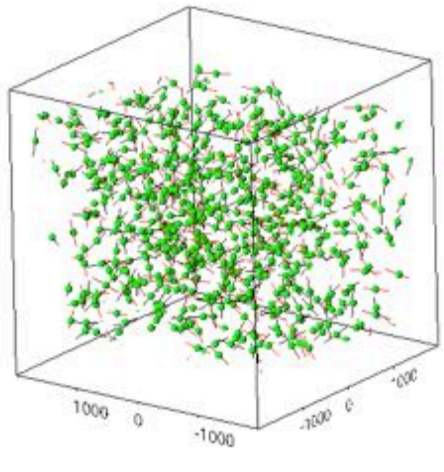
Random packing uniaxial particles

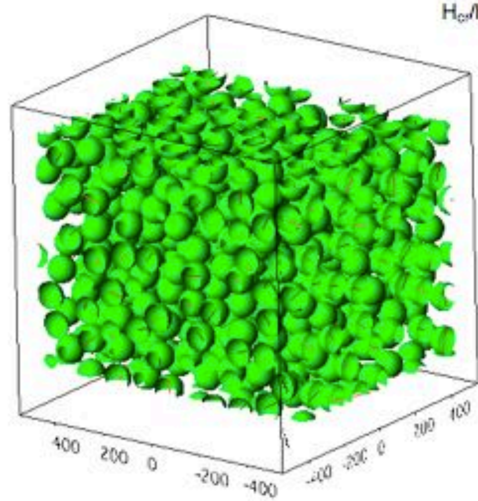
1000 x 100 nm diameter magnetite particles
Log normal coercivity distribution
Random (non-overlapping) packing in box length 4000-1100 nm





4000 nm

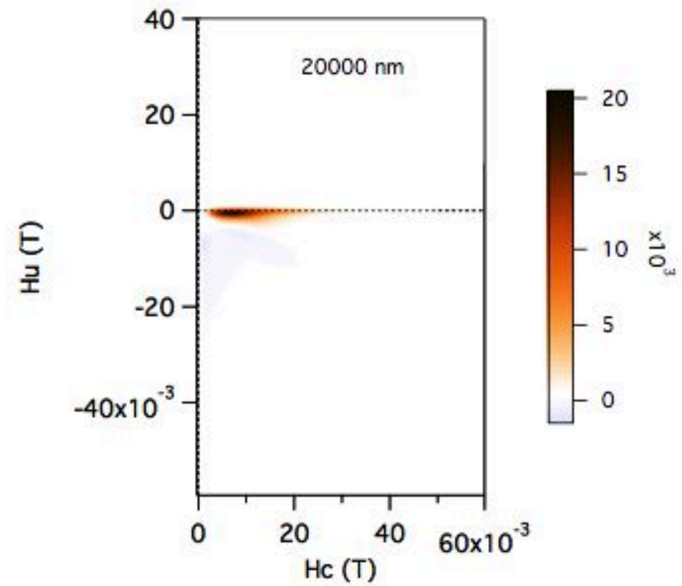


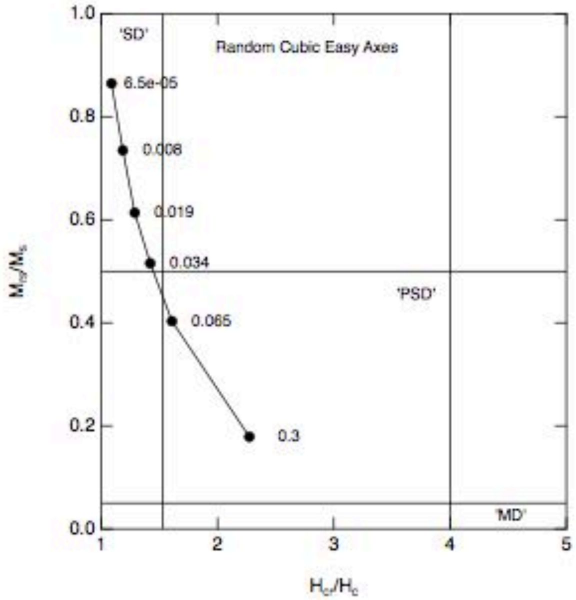


1100 nm

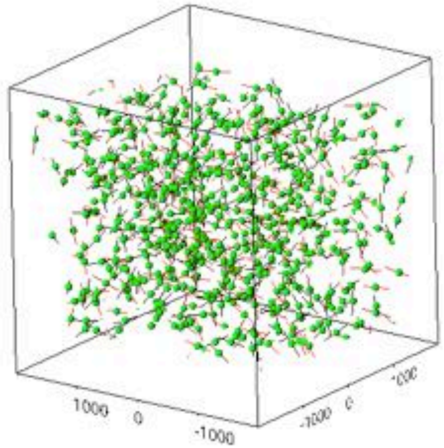
Random packing cubic particles

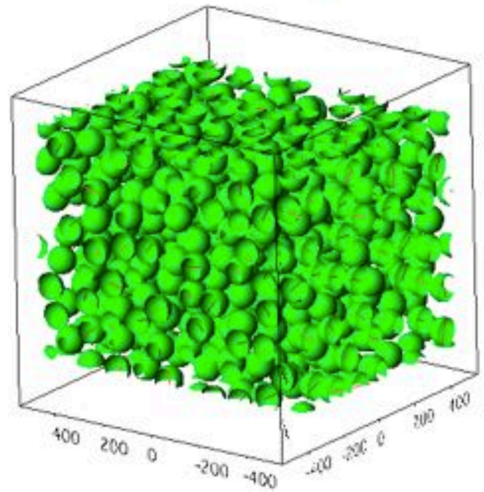
1000 x 100 nm diameter magnetite particles
Log normal coercivity distribution
Random (non-overlapping) packing in box length 20000-1200 nm





4000 nm

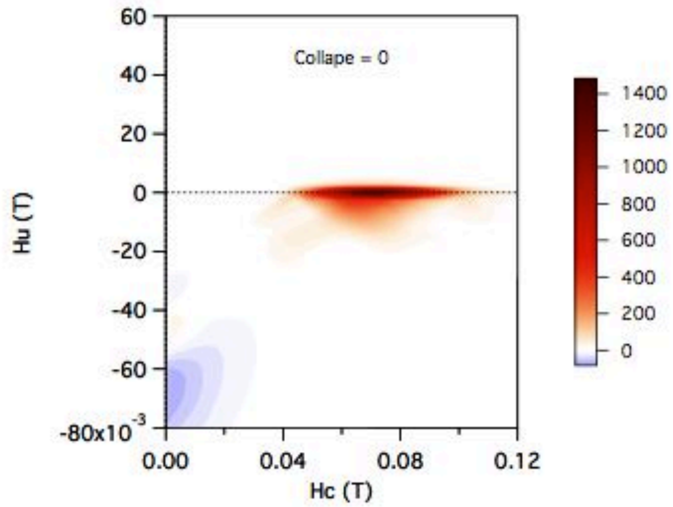


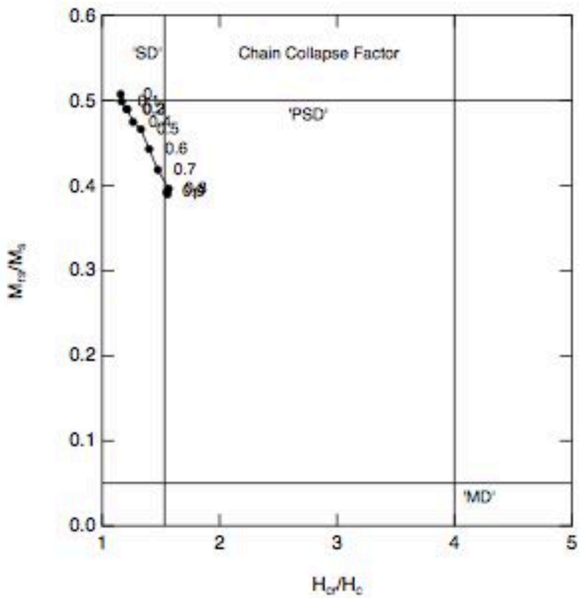


1100 nm

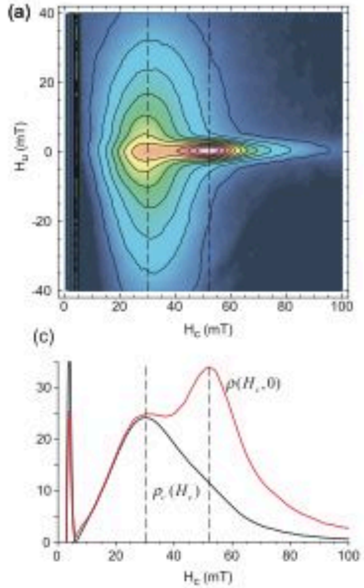
Chains of particles (bacteria)

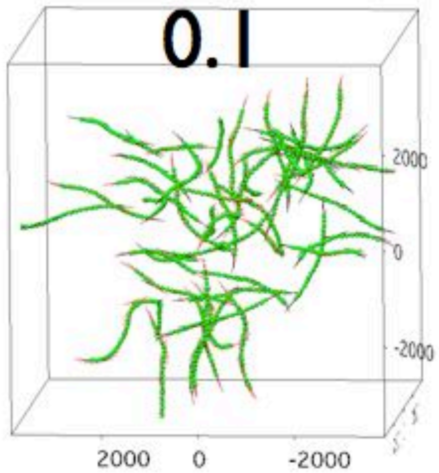
50 x 20 particle chains of 100 nm magnetite particles
Log normal coercivity distribution
Uniaxial anisotropy along chain axis
Varying degrees of chain collapse

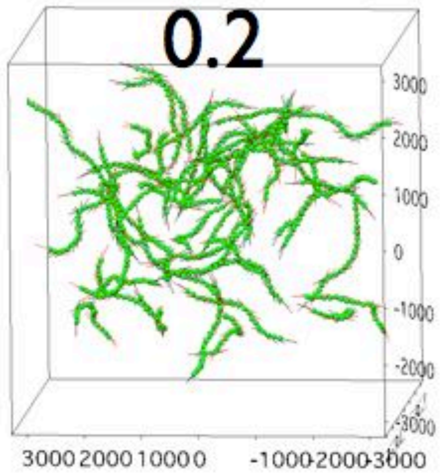


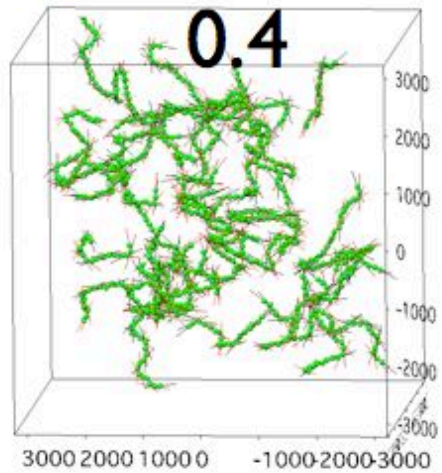


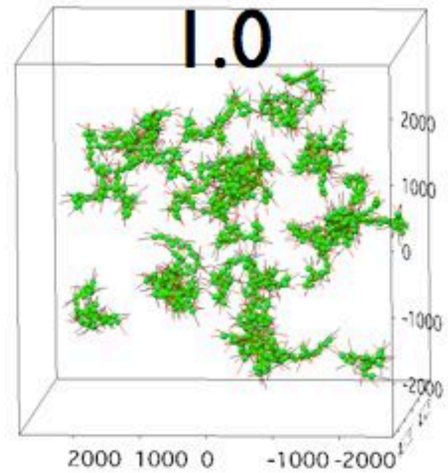
Chen et al. 2007











Magnetic mixtures

Most rocks contain a mixture particles in different domain states.

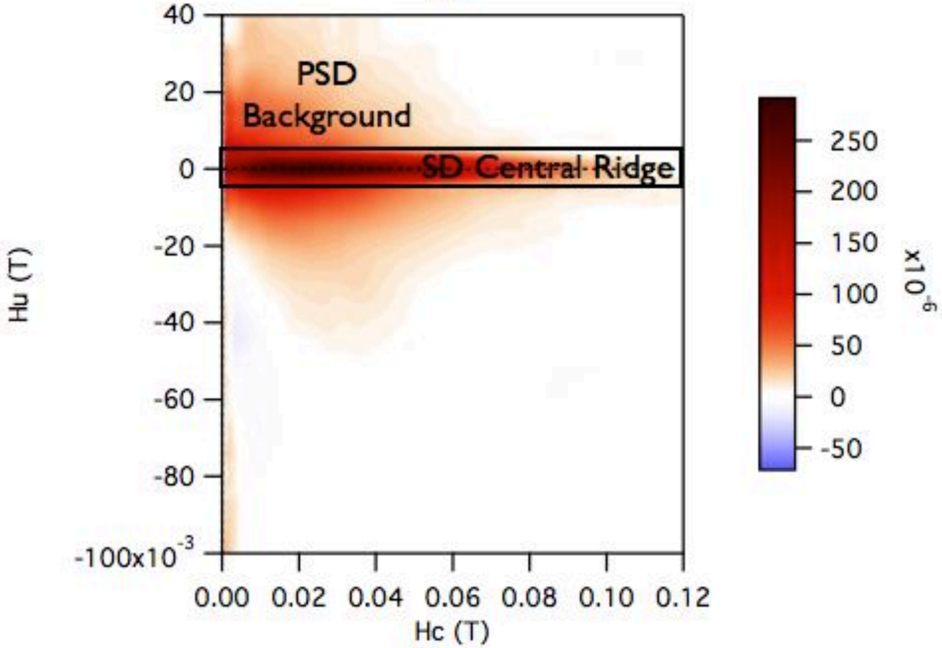
2D FORC distributions provide a more effective way to unmix these signals than 1D coercivity distributions.

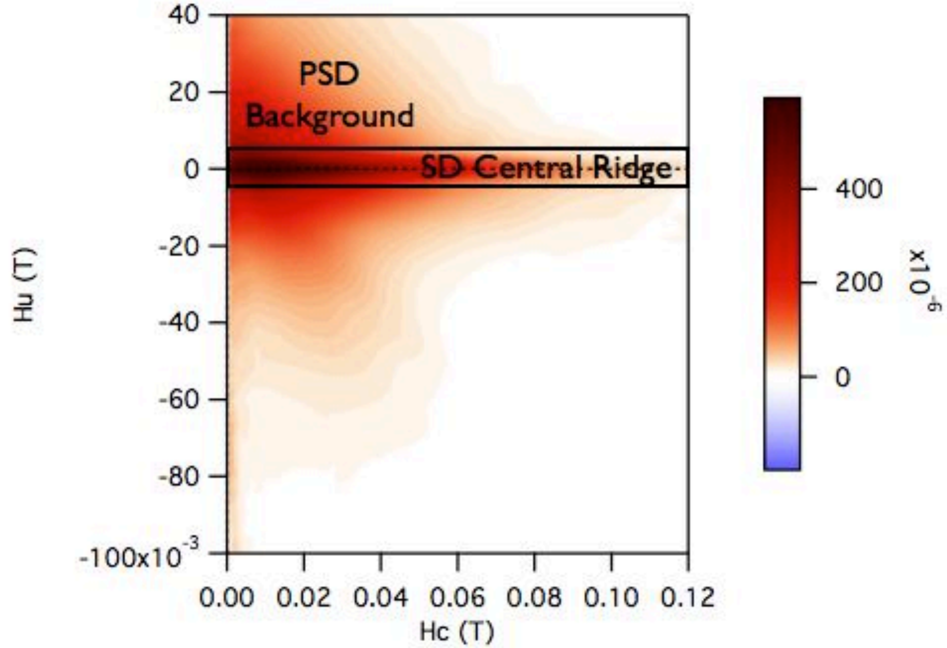
e.g. Non-interacting SD particles produce a sharp central ridge, whereas PSD signals produce the smooth background (pirate hat). These signals are well defined along the H_u direction.

Interglacial

Data courtesy of Jim Channell

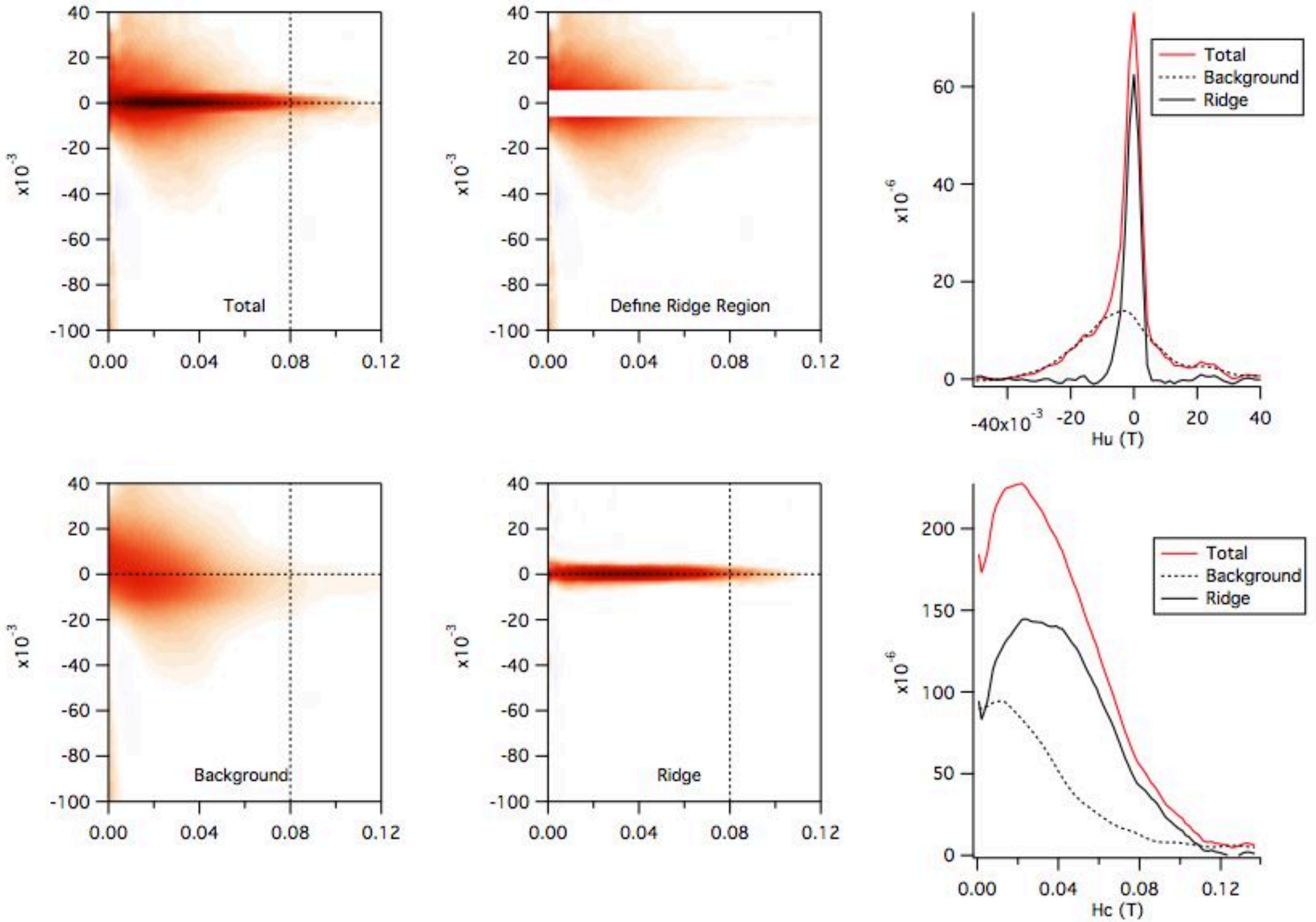
Glacial



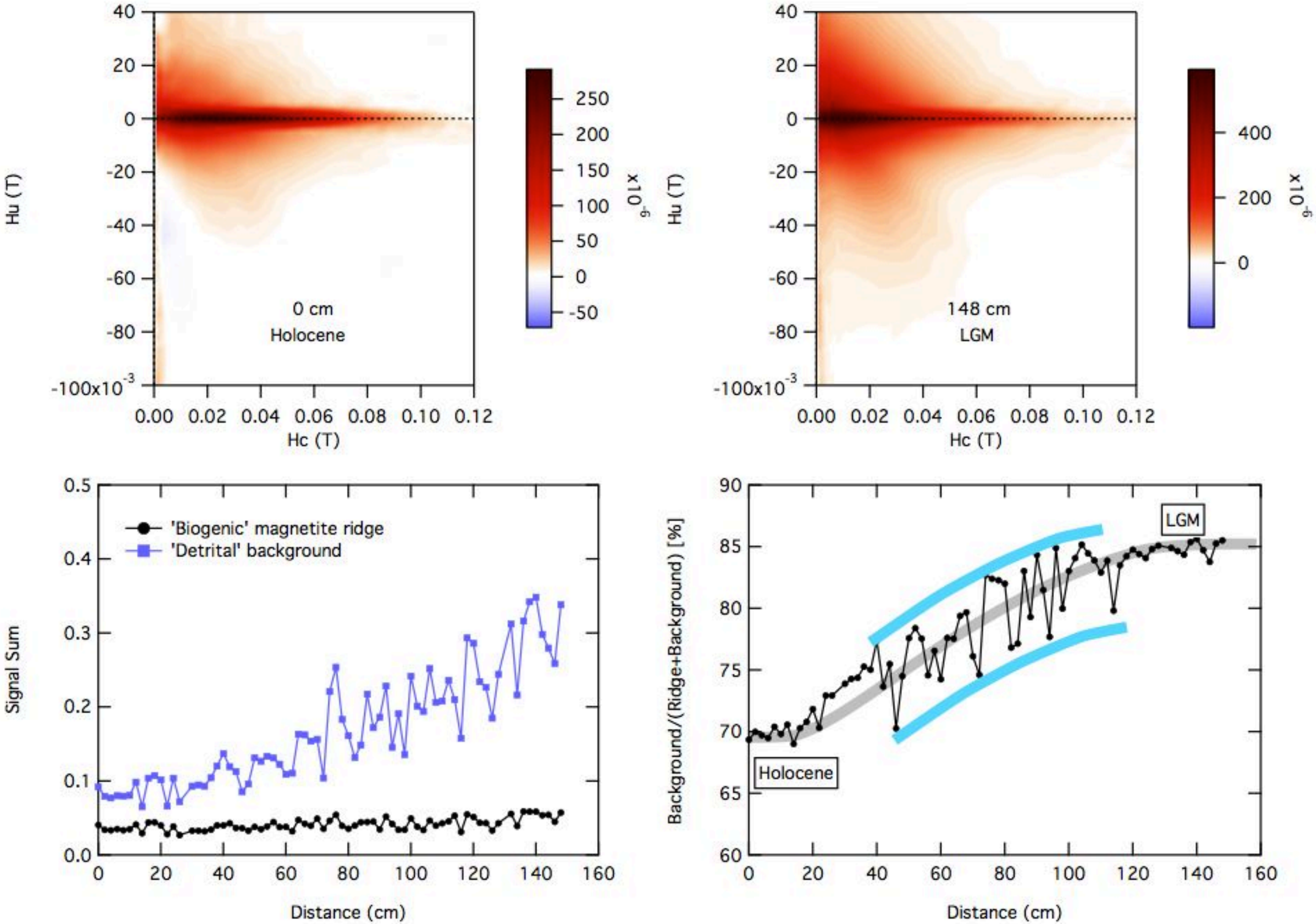


Central Ridge Extraction (FORCinel method)

FORCinel uses a 2D background fitting method to isolate the central ridge. The ridge region is masked out and the LOESS algorithm is applied to the background FORC distribution.

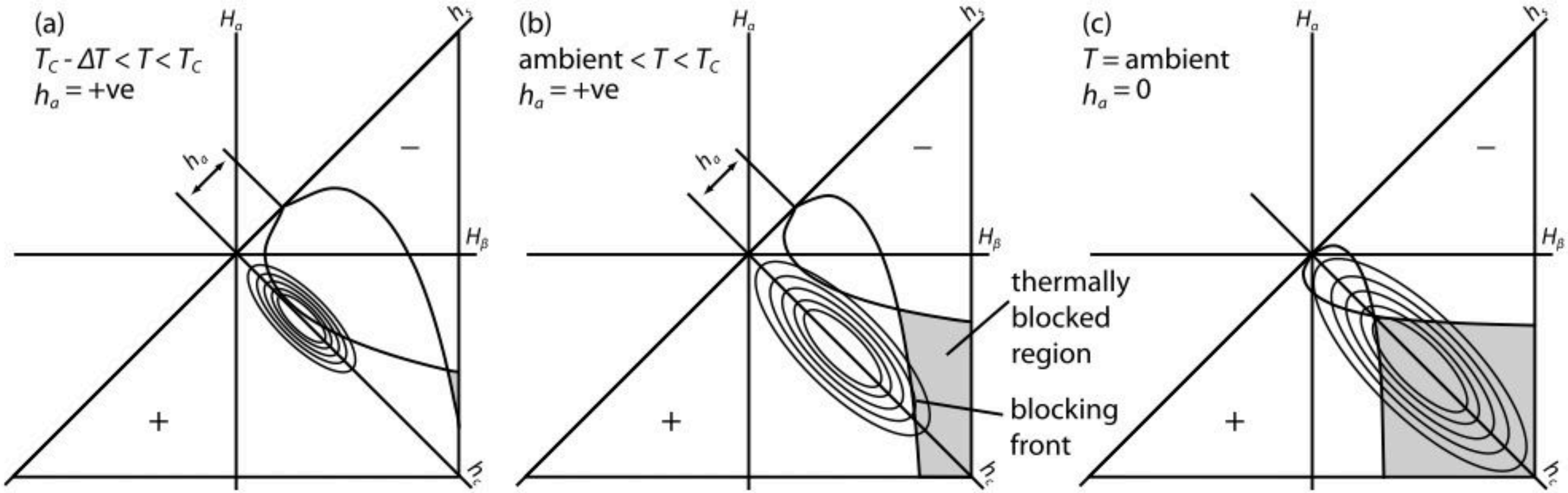


Central Ridge Extraction (FORCinel method)



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

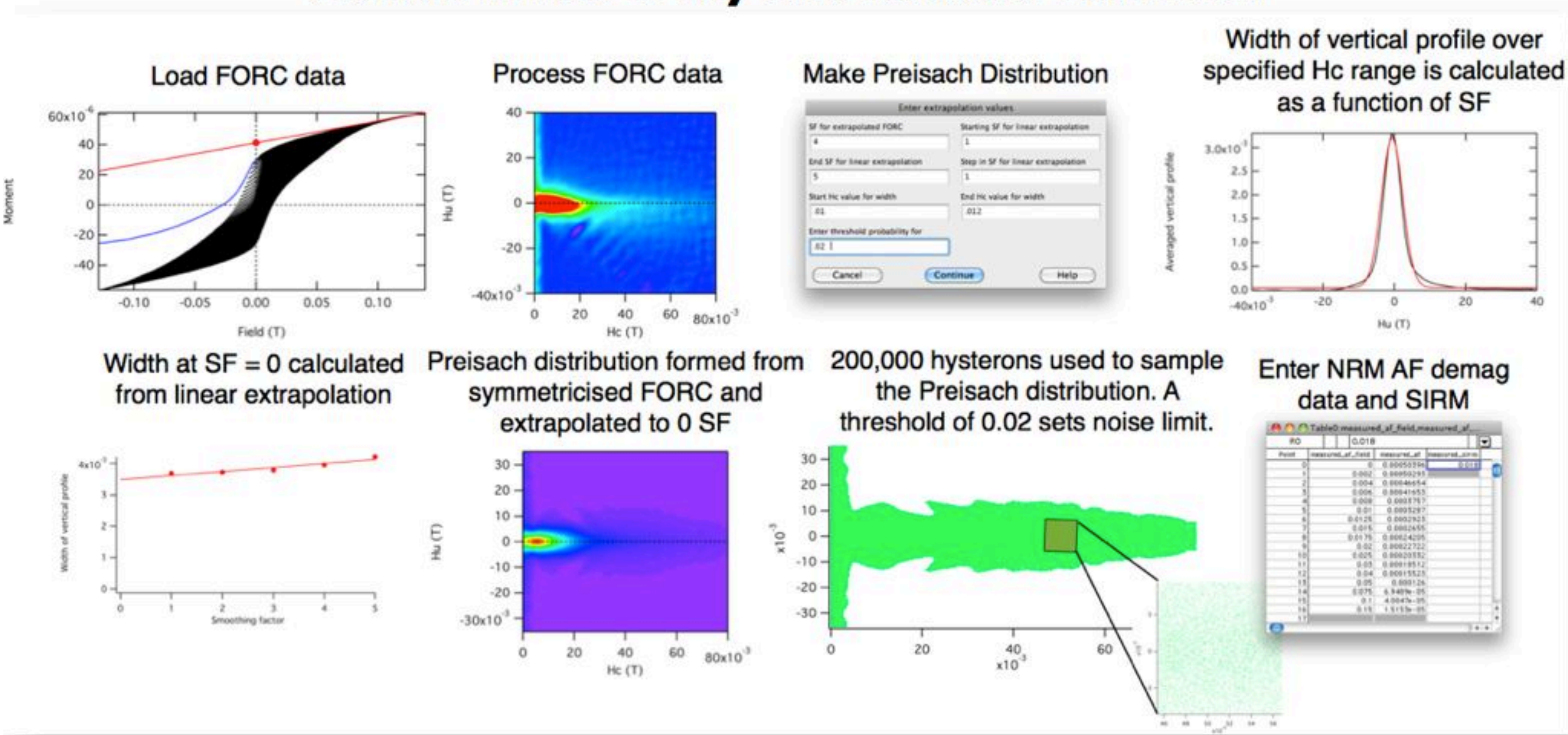


Muxworthy, A.R., and D. Heslop (2011) A Preisach method for estimating absolute paleofield intensity under the constraint of using only isothermal measurements: 1. Theoretical framework. J. Geophys. Res. 116, B04102, doi:10.1029/2010JB007843.

Quantitative modelling of thermal remanence using FORC diagrams

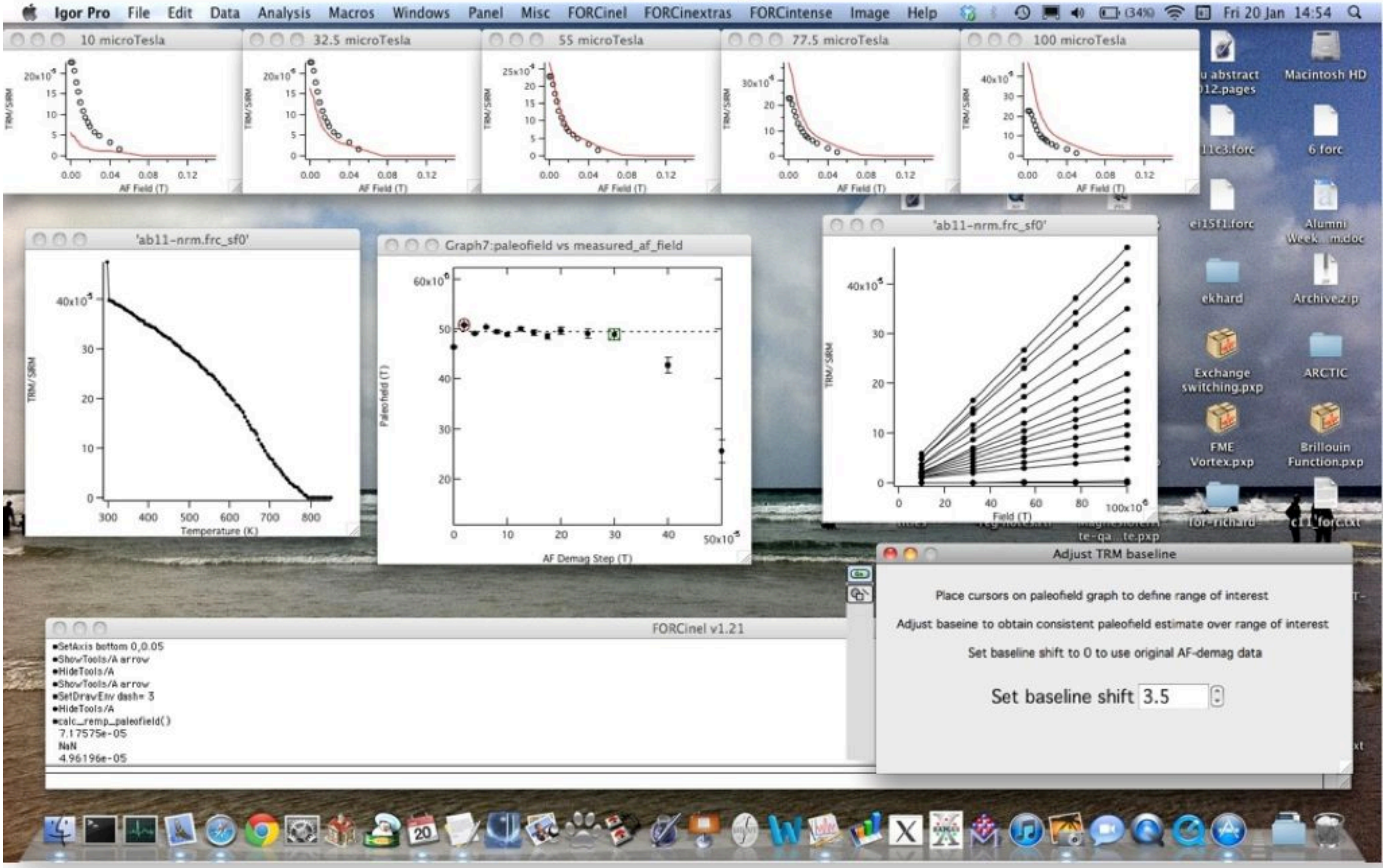
First steps: FORCintense

Adrian Muxworthy and Richard Harrison



AR Muxworthy and D Heslop (2011) A Preisach method for estimating absolute paleofield intensity under the constraint of using only isothermal measurements: 1. Theoretical framework. Journal of Geophysical Research, 116, B04102, doi: 10.1029/2010JB007843.

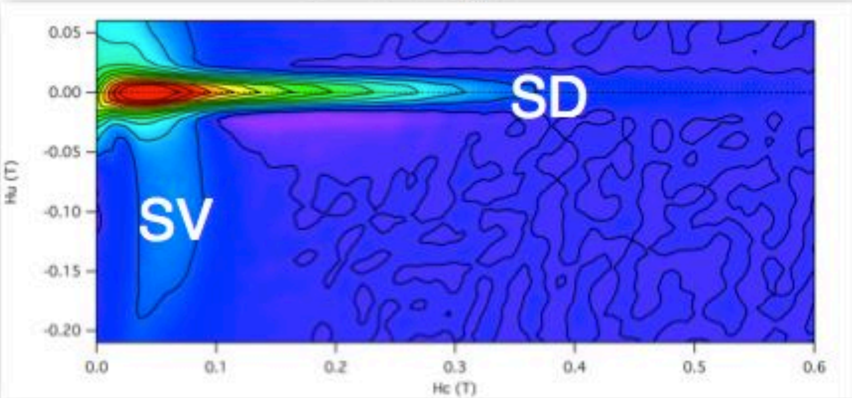
Quantitative modelling of thermal remanence using FORC diagrams



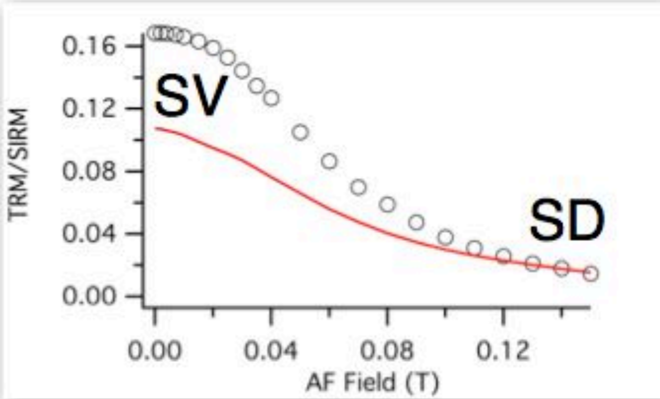
Quantitative modelling of thermal remanence using FORC diagrams

Application to dusty olivine

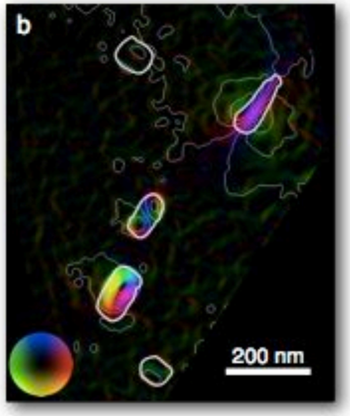
FORC diagram



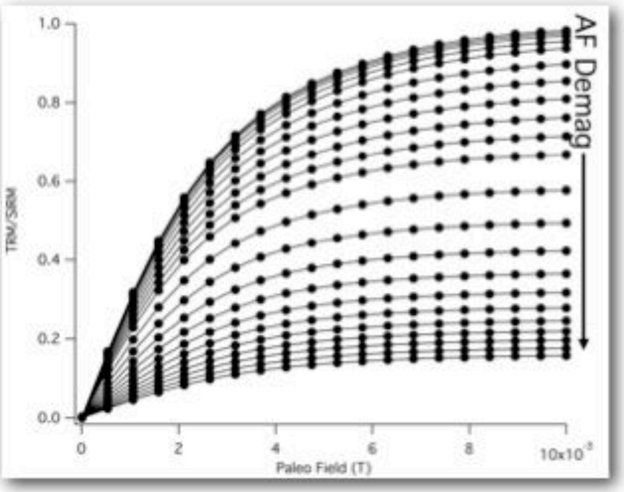
Simulated AF demag at 340 µT (equal to lab field)



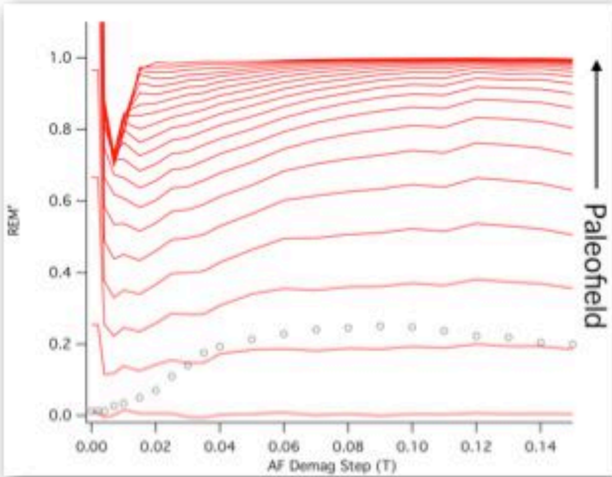
Electron holography



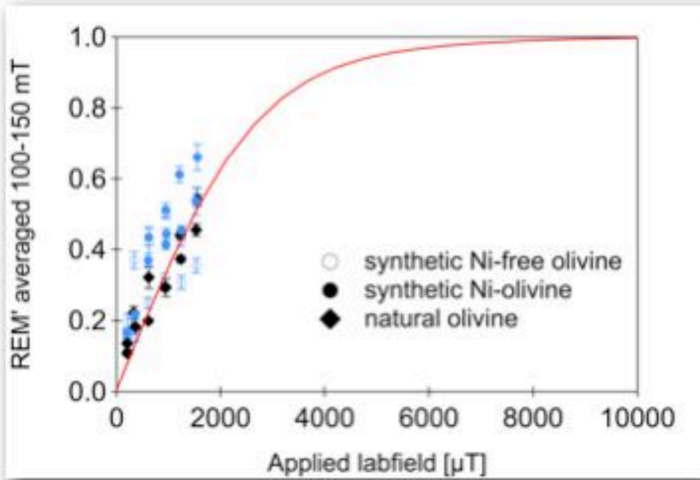
Non-linear TRM acquisition



Calculated vs observed REM'



REM' acquisition curve compared to experimental data



DEMO