# FORCulator: a micromagnetic tool for simulating first-order reversal curve diagrams

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## Summary

1. We describe a method for simulating first-order reversal curve (FORC) diagrams of interacting single-domain particles.

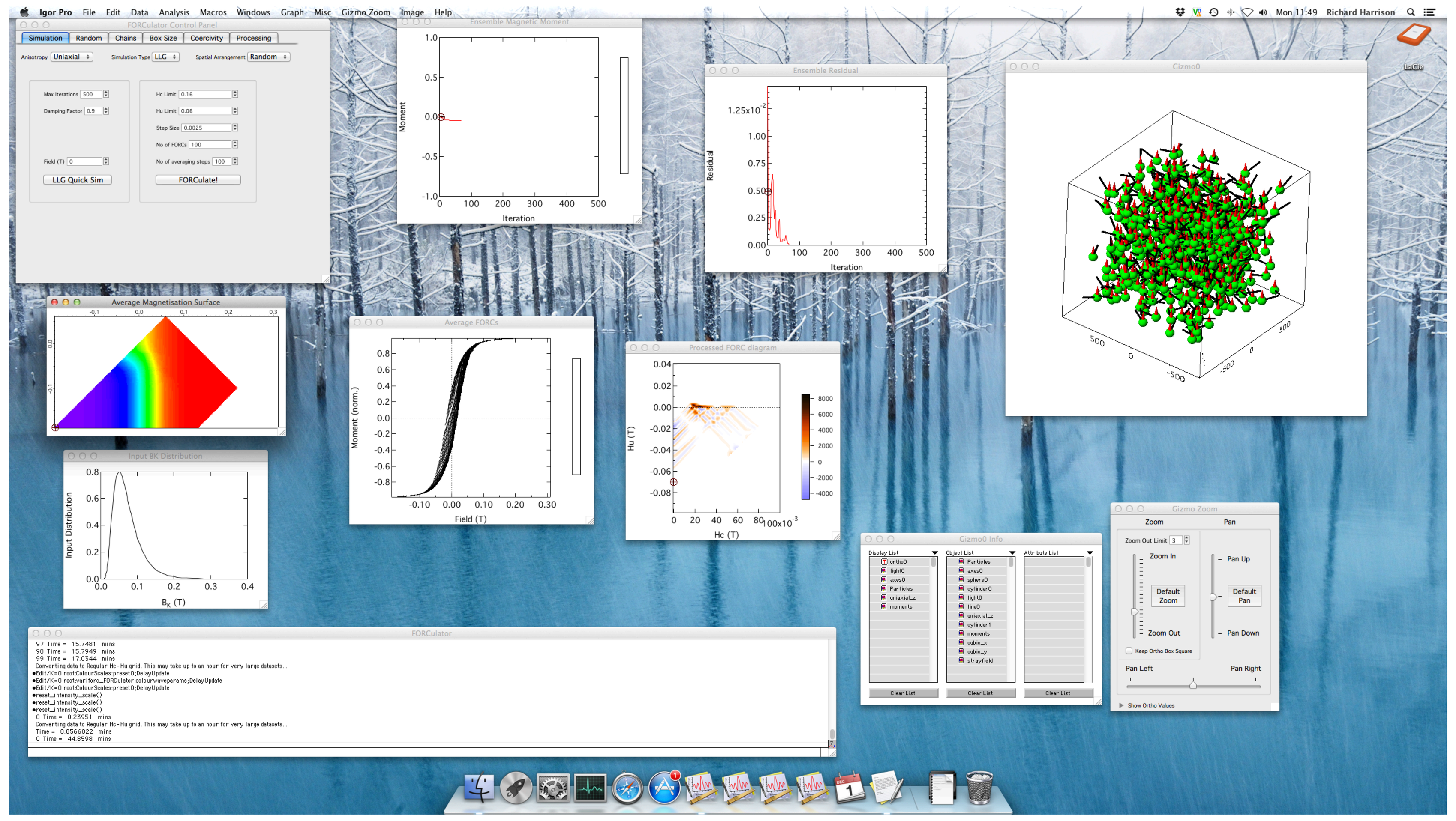
2. Magnetostatic interactions are calculated in real space, allowing simulations to be performed for particle ensembles with arbitrary geometry.

3. The equilibrium magnetization is calculated using an approximate iterated solution to the Landau-Lifshitz-Gilbert equation. Multithreading is employed to allow multiple curves to be computed simultaneously, enabling FORC diagrams to be simulated in reasonable time using a standard desktop computer.

4. Statistical averaging and post processing lead to simulated FORC diagrams that are comparable to their experimental counterparts.

5. The method is applied to several geometries of relevance to rock and environmental magnetism: densely packed random clusters and partially collapsed chains.

6. The method forms the basis of *FORCulator*, a freely available software tool with graphical user interface that will enable FORC simulations to become a routine part of rock magnetic studies.



## FORCulator

1. Anisotropy: Uniaxial or Cubic. Other options will be made available in future versions.

2. Simulation Type: Quasi-static Stoner-Wohlfarth approach (uniaxial only) or LLG. LLG uses an approximate iterated solution to the Landau-Lifshitz-Gilbert equation to obtain the equilibrium state at each field. Use LLG for all but the most weakly interacting uniaxial systems.

3. Spatial Arrangement: Random packing or chains. Other options will be made available in future versions.

4. Coercivity distribution: Log-normal distribution of switching fields. General user defined coercivity distribution will be included in next version.

5. No of FORCs: Set the range of FORC space and field step size to match your experimental measurements.

6. No of averaging steps: To get smooth diagrams, the particle ensemble is regenerated based on the specified parameters. Resulting FORC diagrams are averaged.

7. Smoothing: The calculated diagrams are processed in the same way that your experimental diagrams are processed, enabling direct comparison.

Visit the FORCulator Website: https://wserv4.esc.cam.ac.uk/nanopaleomag/

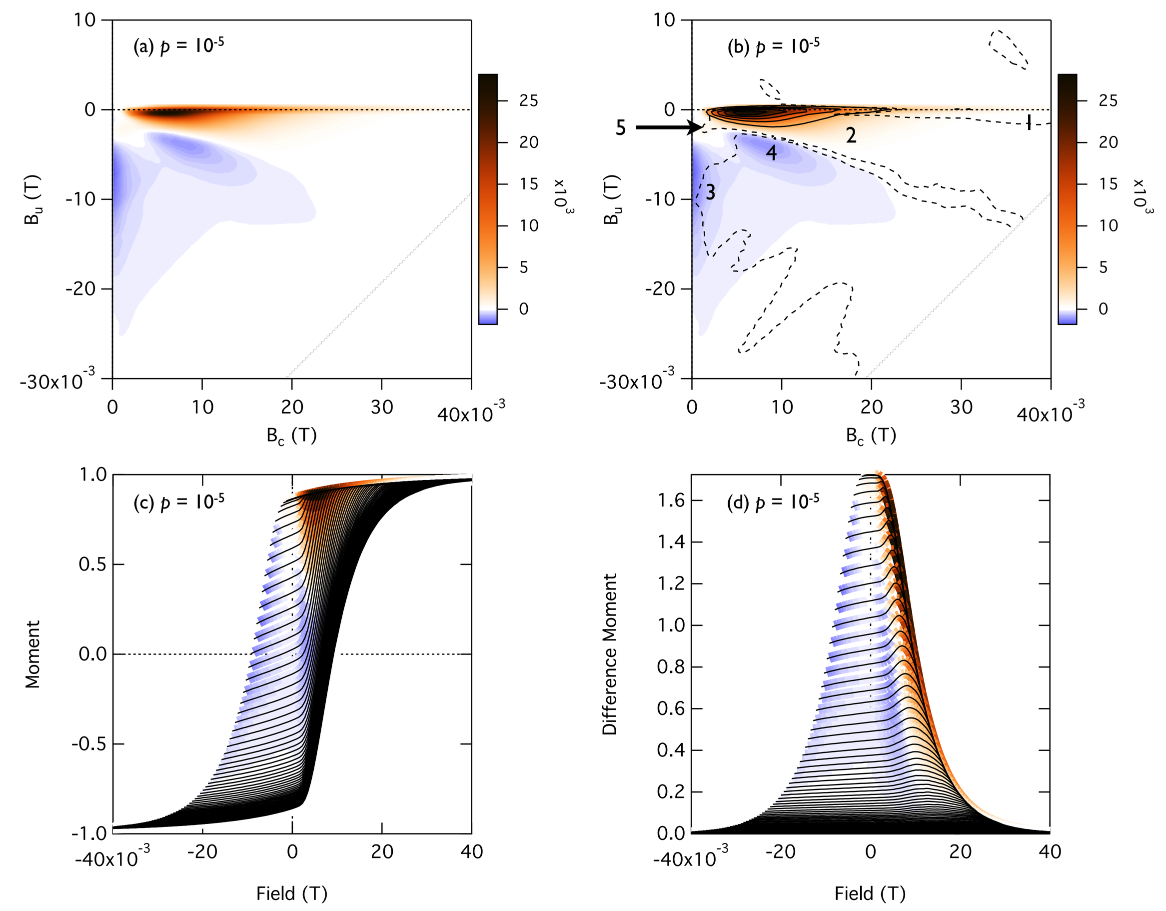
## Non-interacting particles with cubic anisotropy (111 easy axes)

1. Non-interacting cubic particles share some of the FORC characteristics of non-interacting uniaxial particles:

   i. A ridge of intensity close to the $B_u = 0$ axis ('1').
   ii. Positive and negative background signals for $B_u < 0$ ('2' and '3')
   iii. No signal for $B_u > 0$.

2. Some key distinguishing features are present, however:

   i. The peak of the FORC distribution is displaced slightly (< 0.5 mT) to negative $B_u$ values.
   ii. A new negative signal ('4') appears above the remanence diagonal.
   iii. A small region of weak, but statistically significant, positive signal ('5') appears.



## Densely packed random clusters

1. Strongly interacting uniaxial clusters show 'teardrop' and 'wishbone' structures.

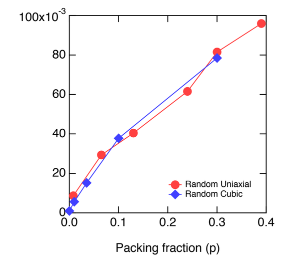
2. Integrated horizontal profiles match input switching field distribution for uniaxial particles.

3. Integrated horizontal profiles DO NOT match input switching field distribution for cubic particles.

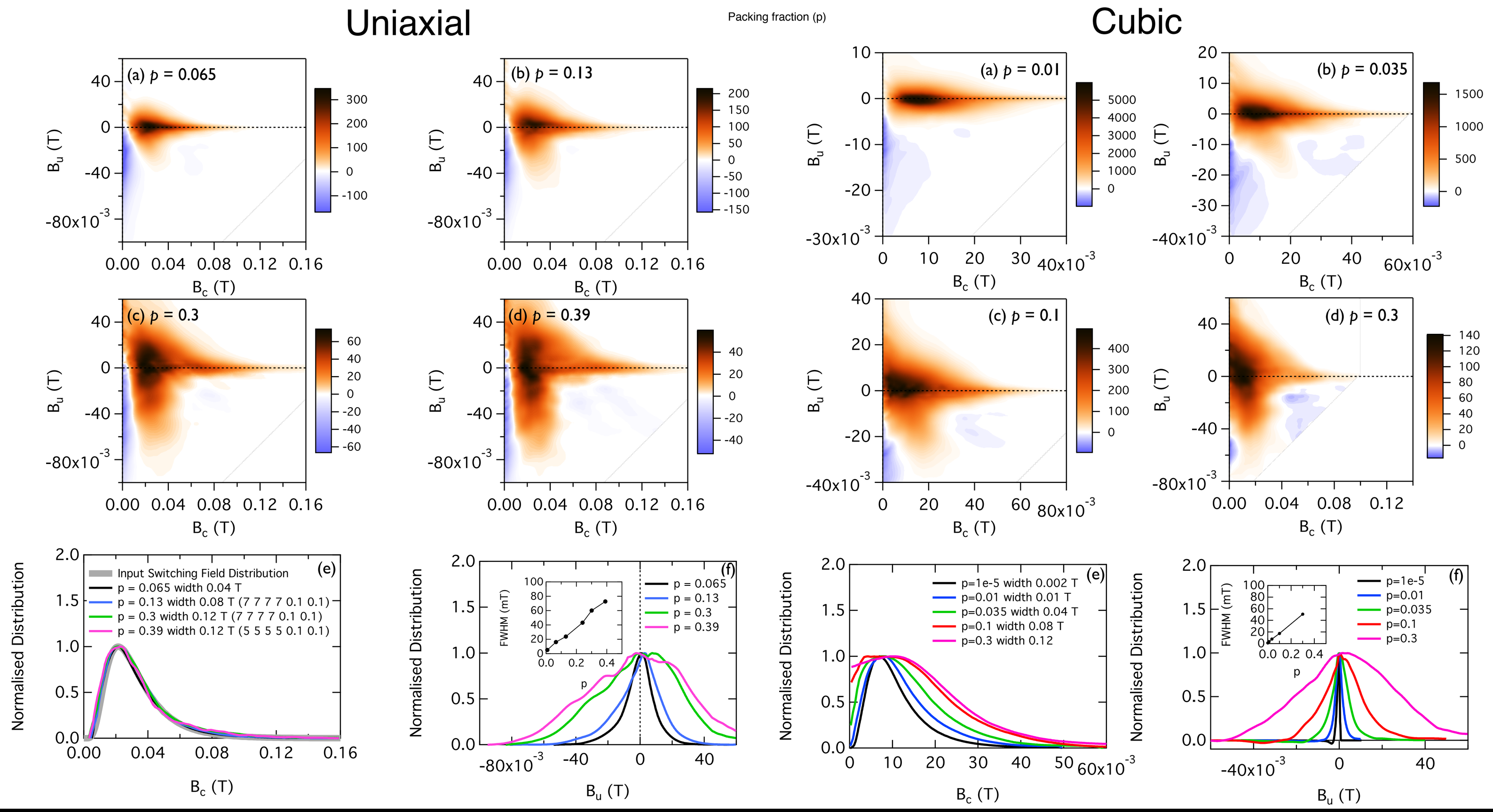
4. Vertical profiles show a systematic broadening with packing fraction.

5. Horizontal and vertical profiles are provide a good estimate of the physical parameters of the ensemble for uniaxial particles.

6. Calculated FORC diagrams for strongly interacting SD clusters are similar to FORC diagrams for non-interacting PSD. A good analogue?



Uniaxial Cubic



## Chains of particles: effect of chain collapse

1. Chains created using a constrained, self-avoiding random walk.

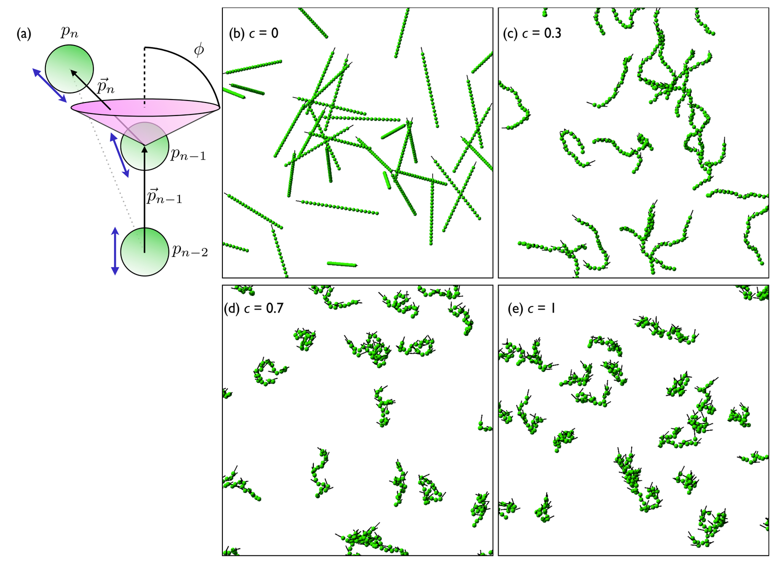
2. Collapse factor *c* varies continuously from 0 (straight chains) to 1 (collapsed chains).

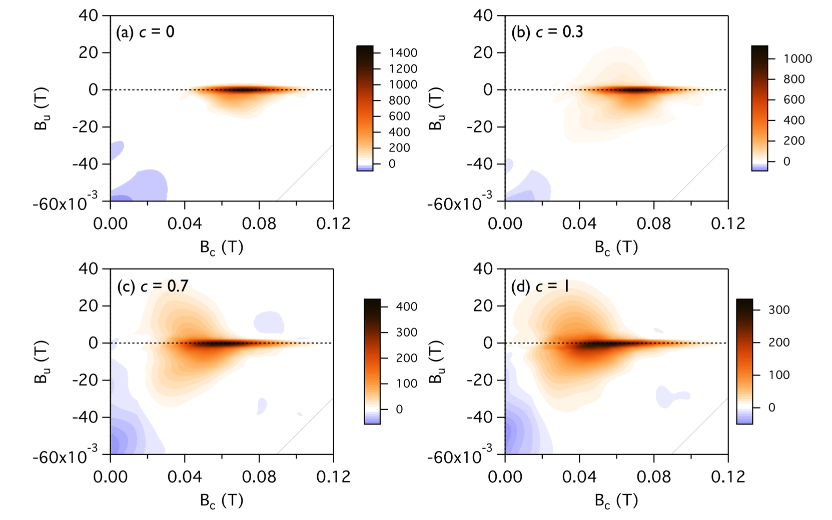
3. Uniaxial easy axes are tangential to the chain axis.

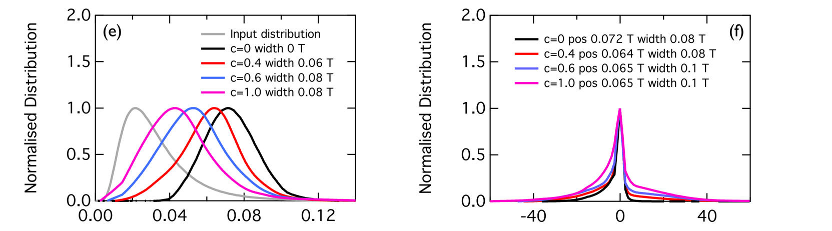
4. Overall coercivity of chains is a strong function of collapse factor.

5. 'Wings' develop and increase in intesnity with collapse factor.

6. Collapsed chain ≠ Random Cluster!







## Chains of particles: effect of interparticle spacing

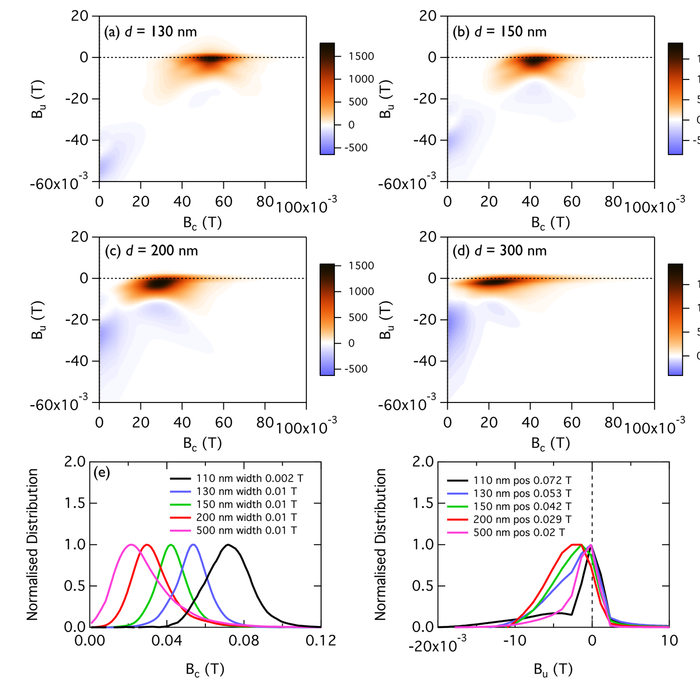
1. Constant chain collapse factor ($c = 0.2$), increasing interparticle separation.

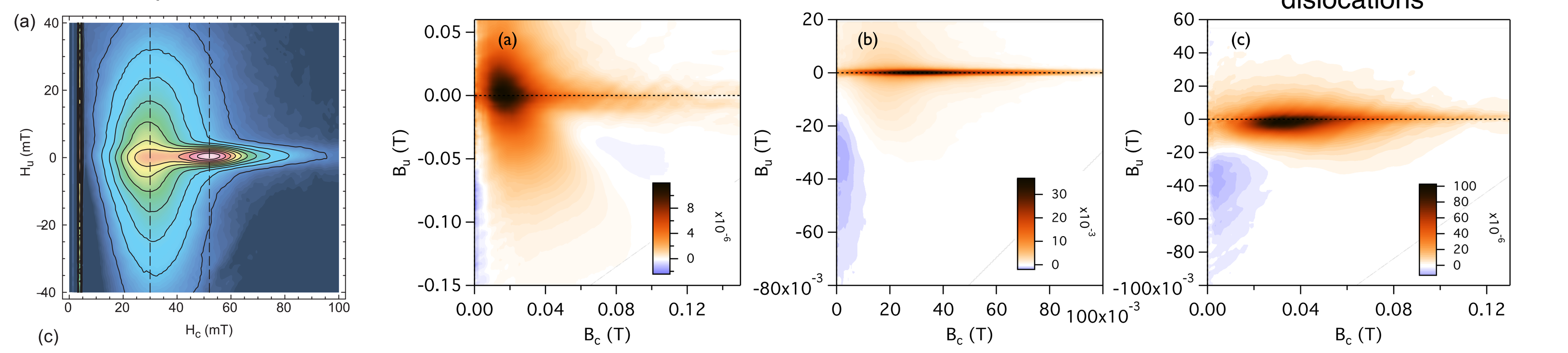
2. Overall coercivity of chains is a strong function of interparticle spacing.

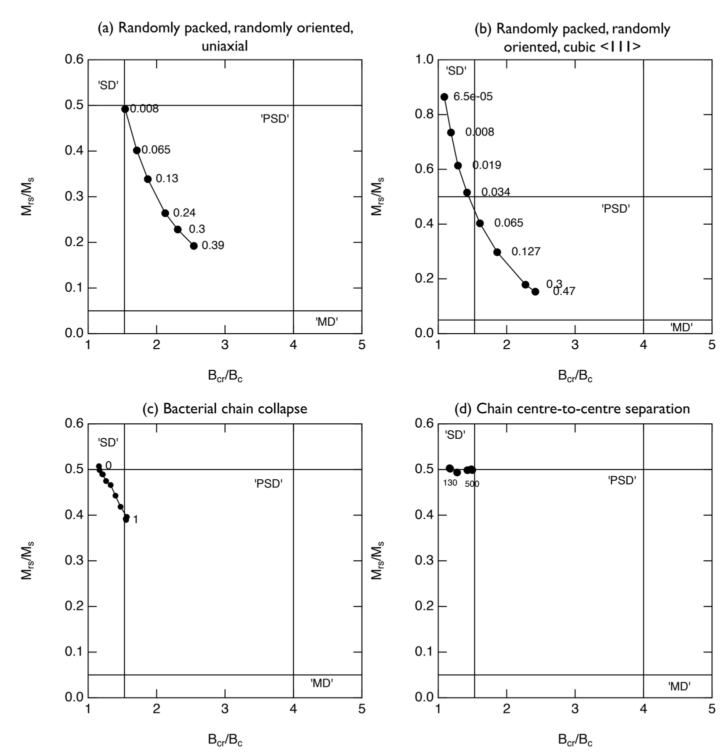
3. Boomerang structure and negative offset for intermediate particle spacings. Indicates positive mean-field interaction along chain axis.

4. Reduces to non-interacting case for spacings more than 5 times the particle diameter.

Chen et al. (2007) Collapsed chains | Fire obsidian (PSD) | Lake sediment with collapsed chains | Oxidised olivine with magnetite chains on dislocations







## Conclusions

1. Geometry-specific FORC signatures provide physical parameterization of the particle ensemble.

2. Strongly interacting SD clusters have similar high-field behaviour to non-interacting PSD particles.

3. Chain collapse leads to distinct FORC signature that can be recognised in natural samples.