Magnetic nanostructures in meteorites: a window on the early solar system

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What can paleomagnetism tell us about the early solar system?

**Differentiated Planetesimals and the Parent Bodies of Chondrites**
B.P. Weiss and L.T. Elkins-Tanton
Annu. Rev. Earth Planet. Sci. 2013. 41:529–60

**Magnetism**

**OBSERVATIONS**
- Allende paleomagnetism

**PREDICTIONS**
- Lifetime
- Asteroid dynamos
- Nebular and T Tauri Sun fields
- Time of acquisition

**Accretion**

**OBSERVATIONS**
- End of accretion
- CV and CR chondrite parent bodies
- L and LL chondrite parent bodies

**PREDICTIONS**
- Start
- Fully undifferentiated bodies
- End
- Partially differentiated chondrite parent bodies
- Start and end
- Fully differentiated bodies

Time after CAI formation (Ma)
Paleomagnetic analysis of individual olivine crystals containing metallic inclusions demonstrates fields of the order 100 µT were present on the parent body. Combining observed blocking temperatures with cooling rate estimates, the results imply that some pallasites formed when liquid FeNi from the core of an impactor was injected as dikes into the shallow mantle of a ~200-kilometer-radius protoplanet.
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
Can we measure remanence at small length scales?

Scanning SQUID microscopy of synthetic dusty olivine

Eduardo Lima, Ben Weiss, Sophie Lappe, Nathan Church, Richard Harrison
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Can we measure remanence at this length scale?

$B_x$ 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).
Can we measure remanence at this length scale?

![Graph showing the relationship between AF Demag Field (mT) and Moment (arb. units).](image)

![Graph showing the relationship between Mx and My or Mz.](image)

![Scale bar for 100 μm.](image)
What do we need to know to interpret the remanence with confidence?

Region of Interest

Which magnetic minerals?
- Positions?
- Separations?
- Volumes?
- Shapes?
- Crystallographic orientations?
- Chemical Compositions?
- Internal microstructures/defects?
- Domain States?
- Coercivities?
- Reversal mechanisms?
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:** $1.92 \times 10^{-8} \ \mu m = 19.2 \ nm$

Slice thickness: 20nm

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

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Electron holography is a TEM technique that allows a two-dimensional projection of magnetic induction to be mapped out with a spatial resolution approaching the nanometre scale.

It provides QUANTITATIVE images of both the magnetic induction inside the material and the stray magnetostatic fields outside the material.
Electron holography: magnetic imaging at the nm scale
Electron holography: magnetic imaging at the nm scale

- Single Domain (SD)
- Double Vortex (DV)
- Single Vortex (SV)
Electron holography: magnetic imaging at the nm scale
Electron holography: magnetic imaging at the nm scale
Domain states and coercivities can be determined. Dynamic information is difficult to obtain via electron holography, but can be obtained using new X-ray methods (see later).
Predicting paleomagnetic stability

Observed volumes combined with coercivities demonstrate high thermal stability of dusty olivine particles - remanence would be acquired immediately on cooling below $T_c$ during chondrule formation and remain stable for 4.6 Ga.
New opportunities for magnetic imaging using X-rays

Electron holography provides unparalleled spatial resolution for the study of nanomagnetic signals in minerals. However there are several key drawbacks:

1. Samples must be thinned to electron transparency - no possibility to measure natural remanence

2. Holography measures magnetic induction rather than magnetisation - images can be difficult/ambiguous to interpret

3. Field of view is limited to ~ 1 µm (although this will change with the advent of double bi-prism microscopes)

4. Measurements are slow and require extensive off-line processing - no possibility to study dynamic processes

All of these issues can be resolved using X-ray methods...
New opportunities for magnetic imaging using X-rays

Illuminating the sample with circularly polarised X-rays tuned to the Fe edge produces absorption that is sensitive to the magnetisation of the sample projected along the X-ray beam direction.

Taking the difference between images collected using left and right circularly polarised X-rays reveals a map of magnetisation (not B) with spatial resolution ~30 nm.

Using stroboscopic methods, dynamic information at the ps-ns timescale can be obtained.
Tazewell Meteorite, Sedgwick Museum of Earth Sciences, University of Cambridge

- **kamacite**
- **tetrataenite**
- **cloudy zone** = tetrataenite + ??
- **clear taenite zone**
- **plessite** = tetrataenite + martensite

50 µm
Tazewell Meteorite, Sedgwick Museum of Earth Sciences, University of Cambridge
2.1. Kinetic evolution equation

For the morphology if the modulus is homogeneous, the applied stress or strain has no effect on the morphology inside the substrate. Due to this homogeneous modulus approximation, the substrate constraint has no effect on the two-phase morphology inside the substrate. As a result, the effect of the substrate constraint on the morphology allows us to isolate the effect of the stress-free surface and constrained interface on the morphological changes. This logical development without the complexity of surface and constrained interface on the morphological changes due to the surface energy driven evolution near the surface region, e.g. the formation of triple junctions between the surfaces.

\[ \frac{\partial X}{\partial t} = \nabla \left[ \frac{DX_0(1-X_0)}{k_B T} \nabla \left( \frac{d_f(X)}{dx} - \alpha \nabla^2 X + \mu_e \right) \right] \]

Computer simulations of spinodal development in the fine, medium and course cloudy zone.

[Image: Computer simulations of spinodal development in the fine, medium and course cloudy zone]
STXM Measurements

Red/blue = magnetisation parallel/antiparallel to X-ray beam (normal to sample plane)
Quantitative analysis of STXM Measurements

Randomly generated tetrataenite islands

Magnetisation assigned to three possible easy axes

Down-sampled to experimental resolution plus noise

Non-random easy axes - CZ formed in a field

Random easy axes - CZ formed in zero field

Results demonstrate that an ultrastable chemical remanence is encoded during formation of the cloudy zone
Chemical Remanent Magnetisation (CRM) is being continuously recorded during slow cooling across the cloudy zone - a time-resolved lateral record of dynamo activity!!
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Outlook

A revolution in paleomagnetism is underway, driven by the ability to perform spatially resolved measurements at micrometre to nanometre length scales. It is becoming possible to extract remanence data from ever more localised regions of interest, where the mineralogy is particularly favourable in terms of paleomagnetic reliability.

An increasing body of evidence suggests that dynamo fields were generated by differentiated meteorite parent bodies, providing many opportunities for paleomagnetism to yield new insight into early solar system processes.

X-ray magnetic imaging is poised to be the next revolution in rock/mineral magnetism, raising the possibility for nanoscale remanence measurements as well as observations of dynamic magnetisation processes.
The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement No. 320750