Crystal-scale magnetic anomalies revealed by scanning magnetic microscopy

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Workshop 8: "Improving Exploration with Petrophysics: The Application of Magnetic Remanence and Other Rock Physical Properties to Geophysical Targeting"

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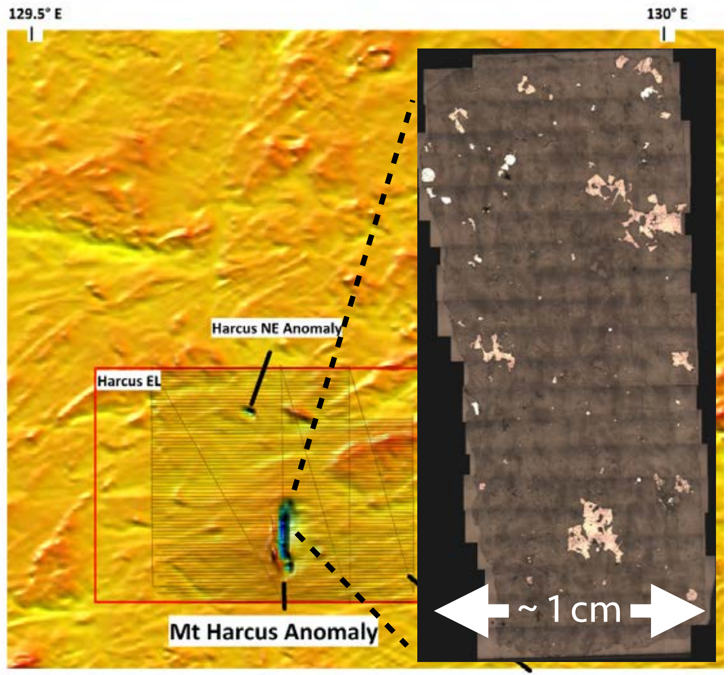
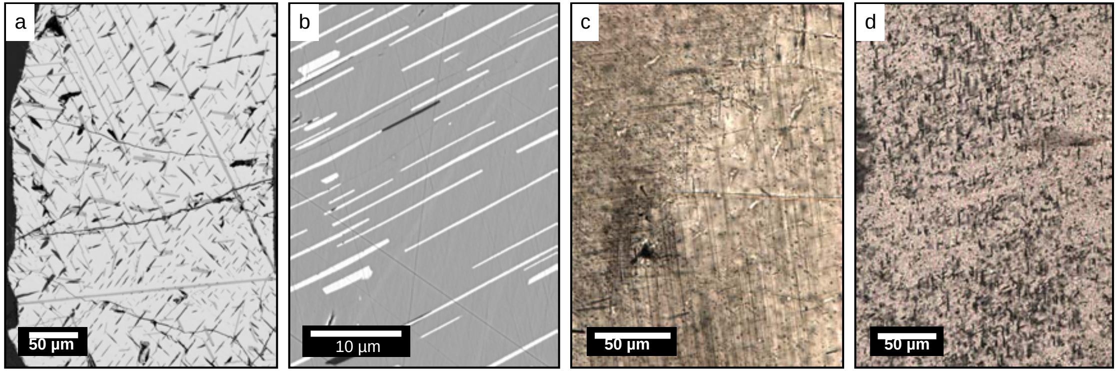
- Scanning magnetic microscopy doesn’t directly address “Geophysical Targeting”
- In some ways, is opposite of exploration: location of sources can be known, and goal is absolute measurement of magnetic intensity & direction
- Field is still learning to apply processing techniques from the exploration community (input welcome)

Outline

- Motivation for micron-scale “aeromagnetic surveys”
- Scanning magnetic microscopes (SMMs): how it works
- Features of our implementation of SMM
- Initial results and possible experiments

Sources of remanent & induced signals can be complicated





Coarse-grained **oxy-exsolved magnetite** (+ spinel)

Ilmenite-hosted **exsolved magnetite** (+ spinel)

Acicular magnetite in plagioclase

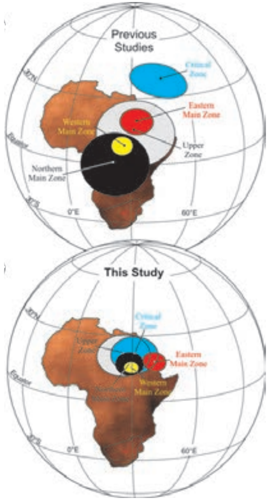
Acicular magnetite in pyroxene

Backscattered SEM

Plane-polarised light

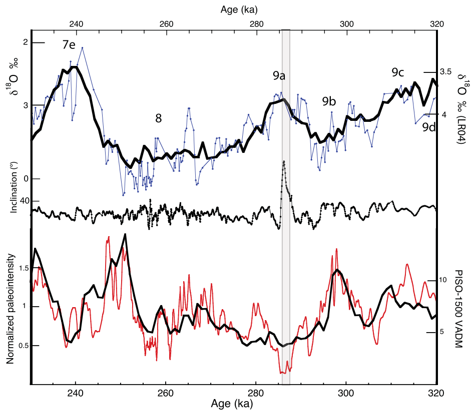
Whole-rock measurements with few mineralogical constraints

Tectonic reconstruction



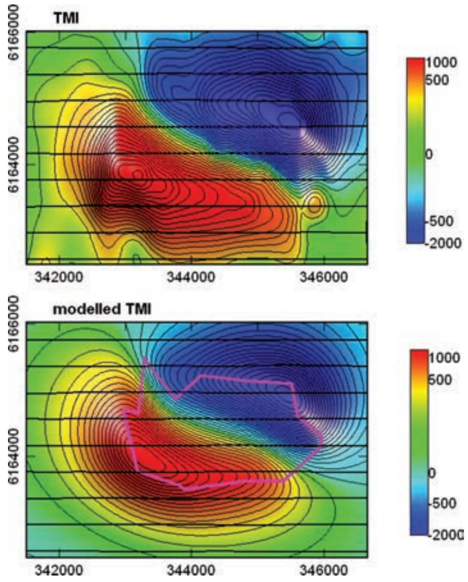
(Letts *et al.*, 2009)

Oceanography & paleointensity



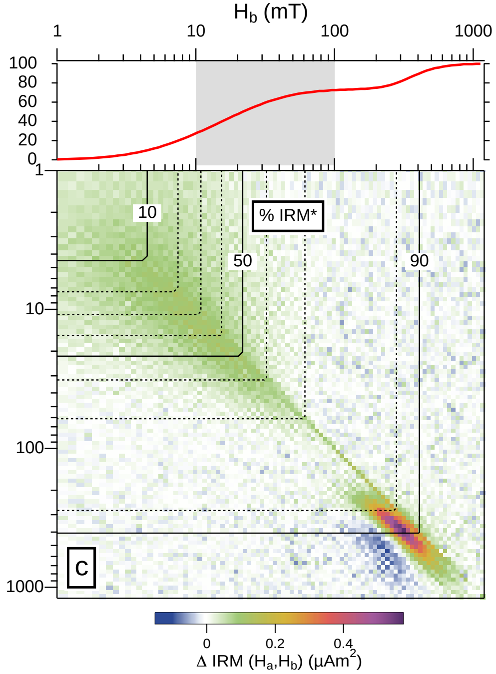
(Channell, 2017)

Forward modelling



(Foss & McKensie, 2011)

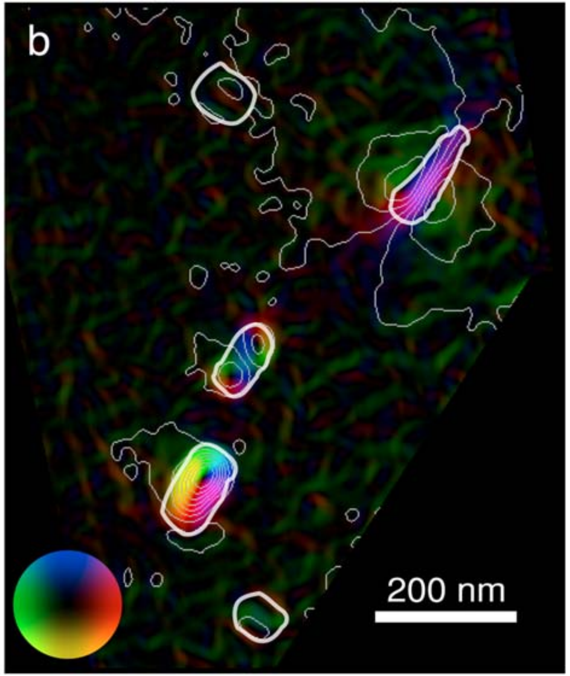
Partial solution: magnetic characterisation

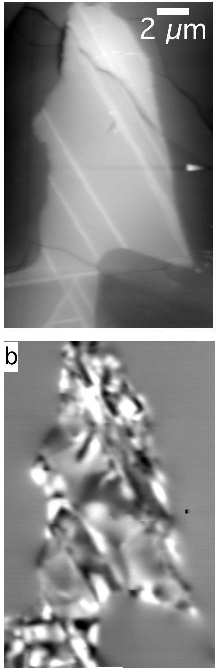


(Church, *et al.*, 2016)

Strict mineralogical constraints: Nanoscale observations and models

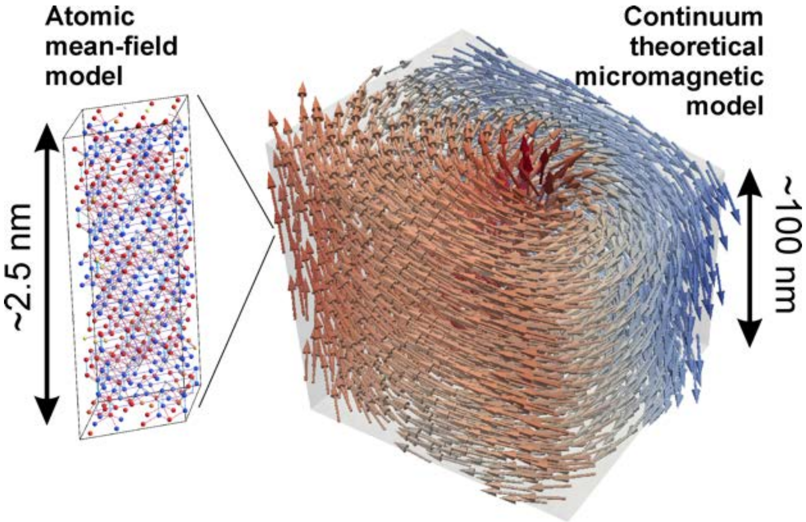
Magnetic imaging (TEM and MFM)





(Lappe *et al.*, 2011)

Modelling at nanometer length scales

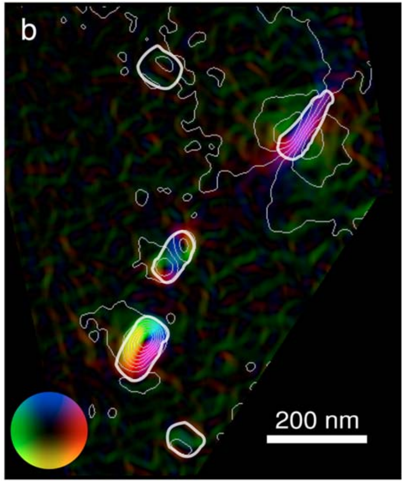


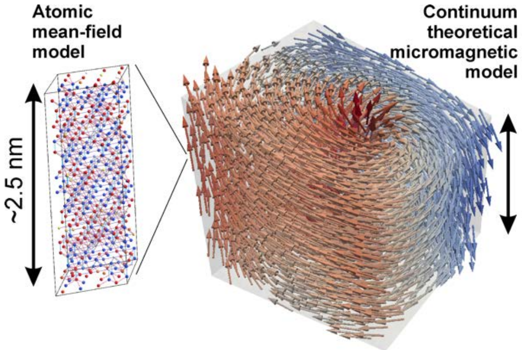
Karl Fabian (NGU)

Nanoscale processes

Bridging the gap

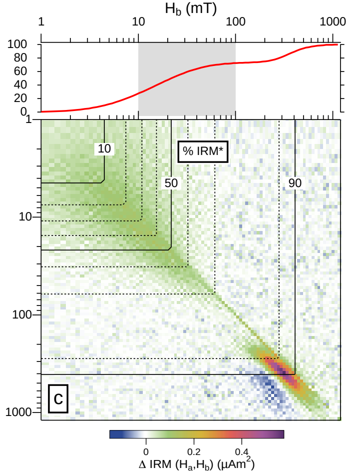
Bulk observations

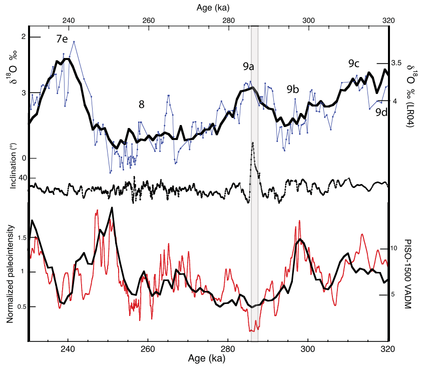


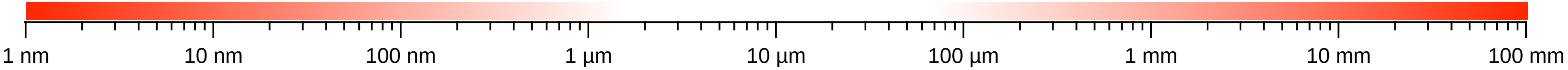


Scanning magnetic microscopy:

measuring fine features while observing large areas

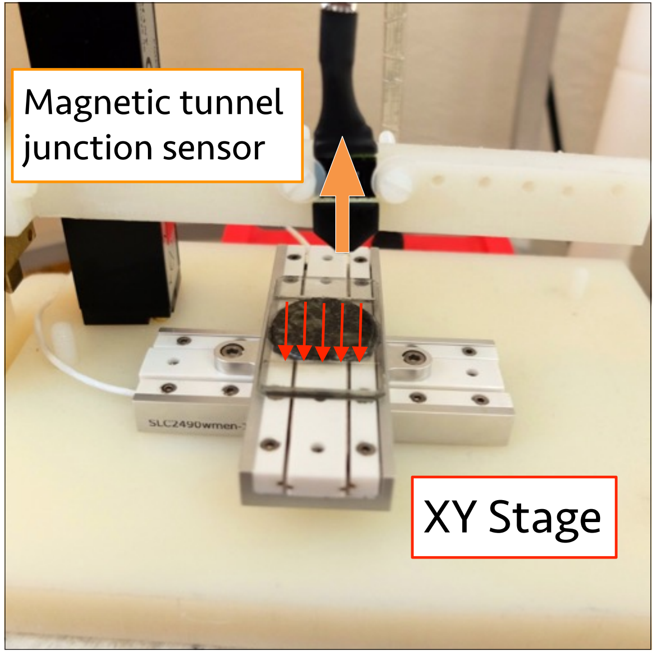




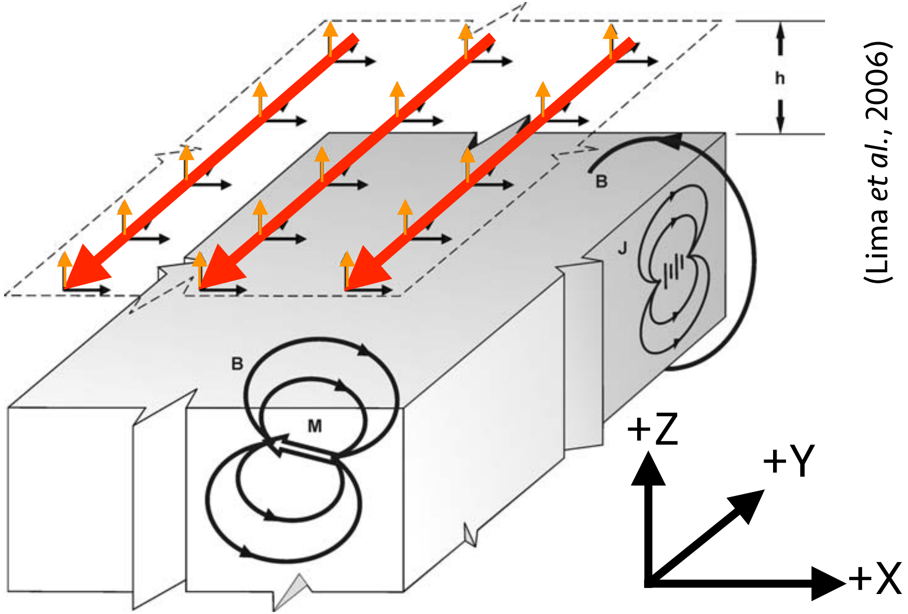


Scanning magnetic microscope

Microscope sample space



Micron-scale analogy with aeromagnetic surveys

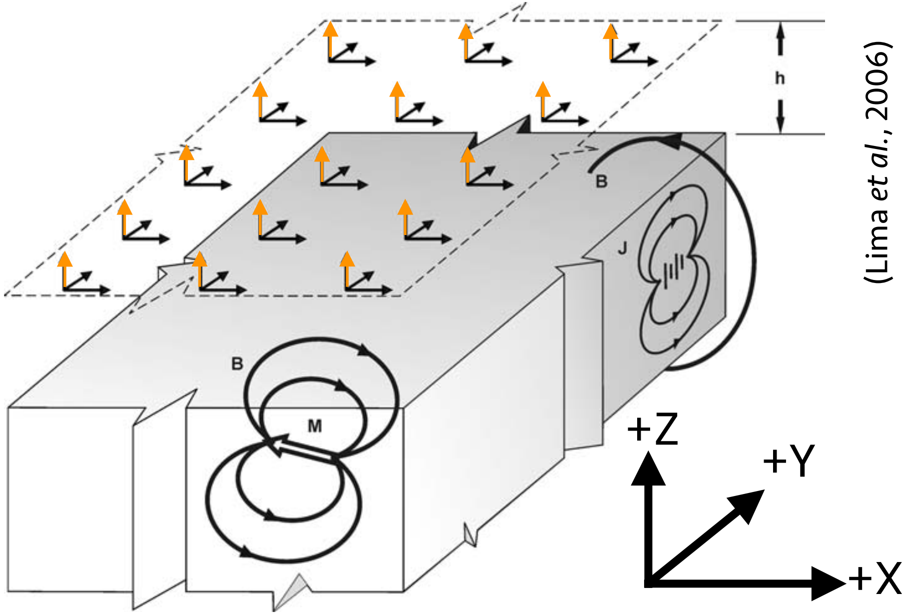


Scan direction

Magnetic field sensing direction

B_z maps & coordinate systems

- Scanning magnetic microscopy uses maps of B_z (cartesian sample coordinates) rather than TMI
- Maps of B_x & B_y can be calculated from $B_z(x,y)$
- Z is positive upwards (opposite to aeromagnetic convention)



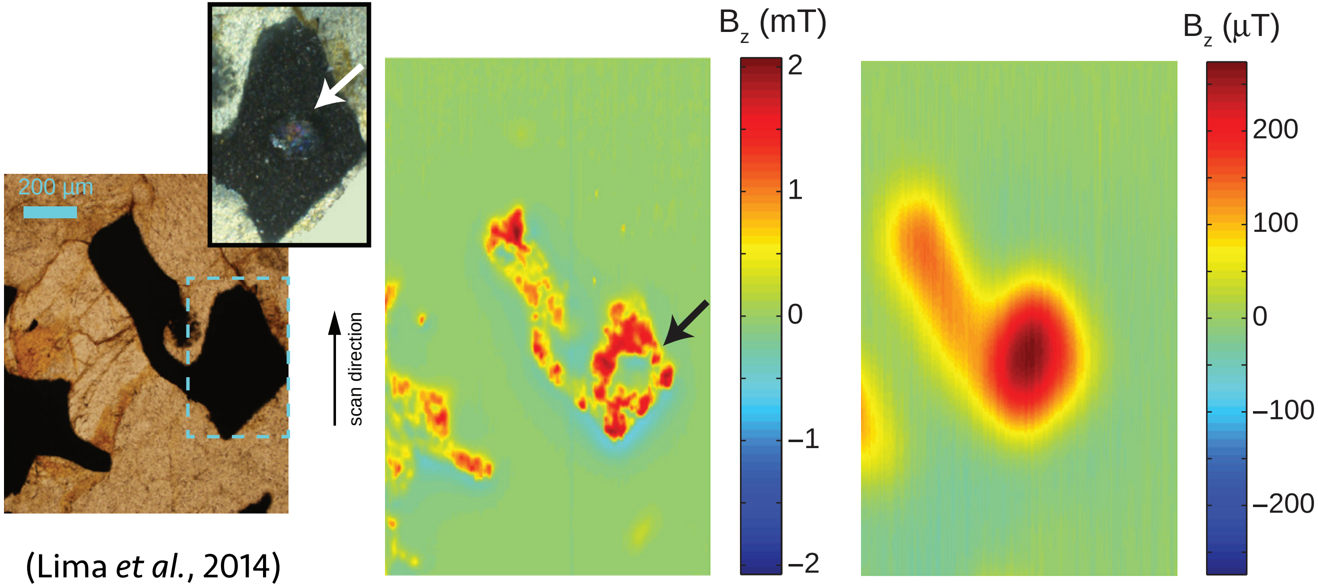
(Lima *et al.*, 2006)

Magnetic field sensing direction

Design features of NTNU microscope

MTJ sensor (similar to hard-drive read head) provides high spatial resolution from close scan height (~100 μm)

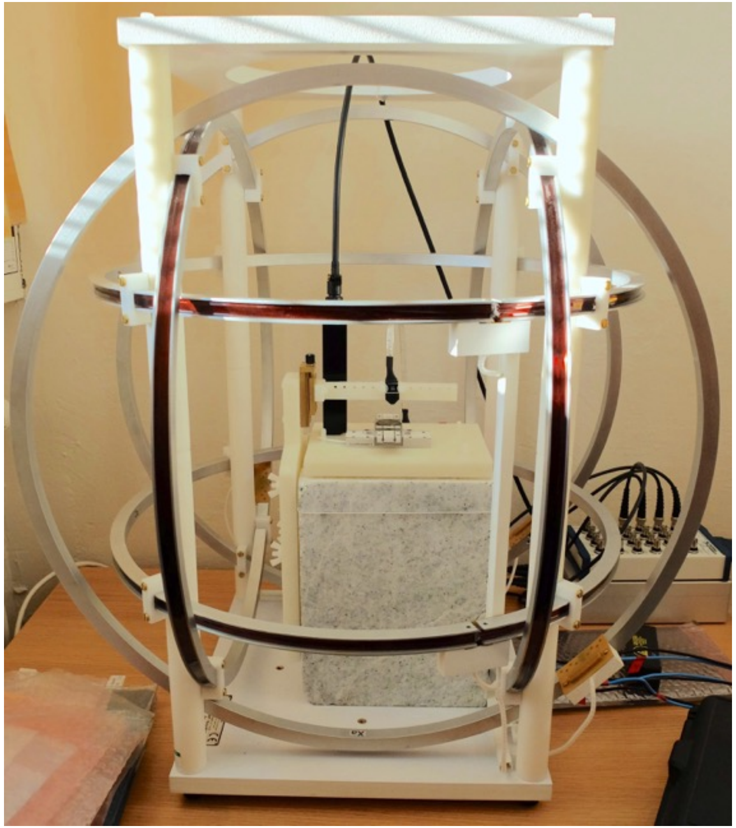
MTJ: Scan height 0—100 μm   SQUID: 200—300 μm



(Lima *et al.*, 2014)

- *SQUIDs have higher sensitivity and S/N but greater "fly height"*
- *Spatial resolution also dependent on desired acquisition time and sensor size*

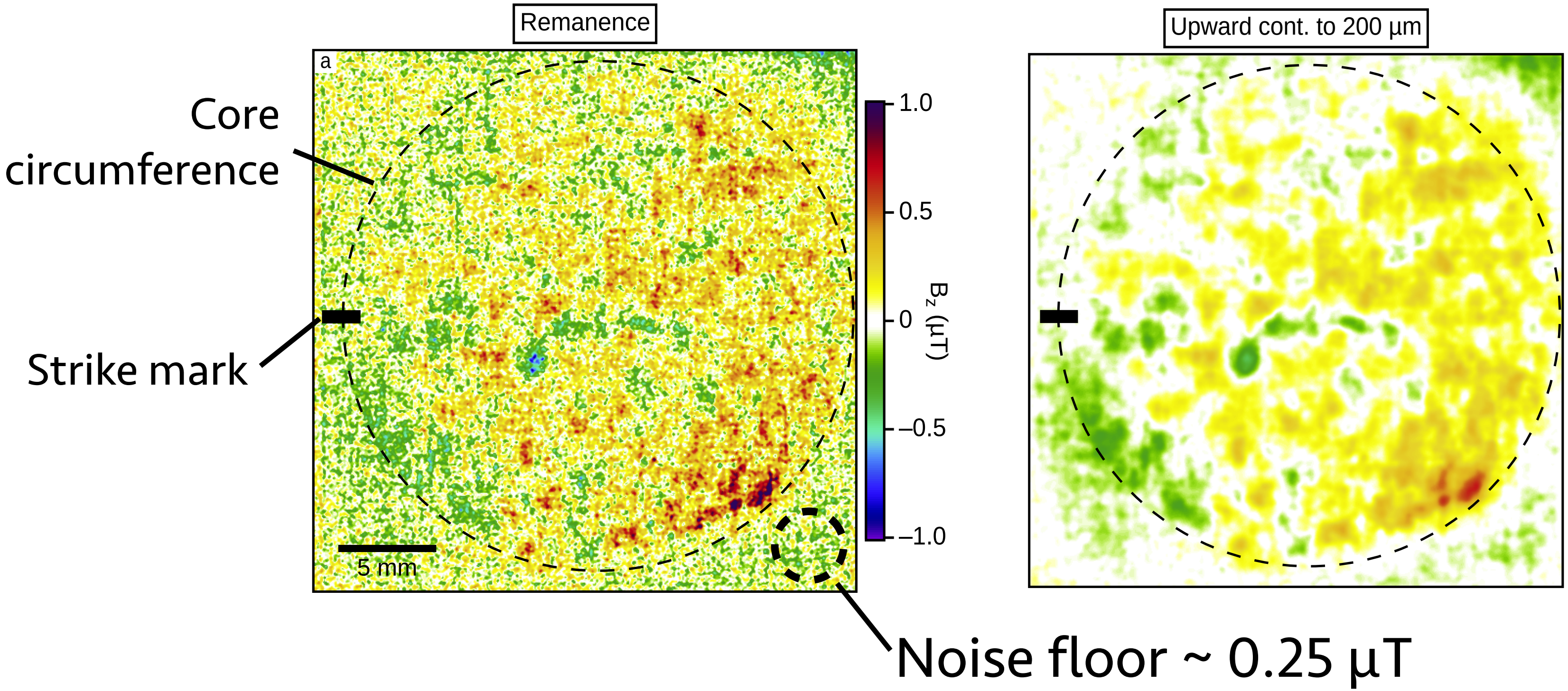
Design features of NTNU microscope



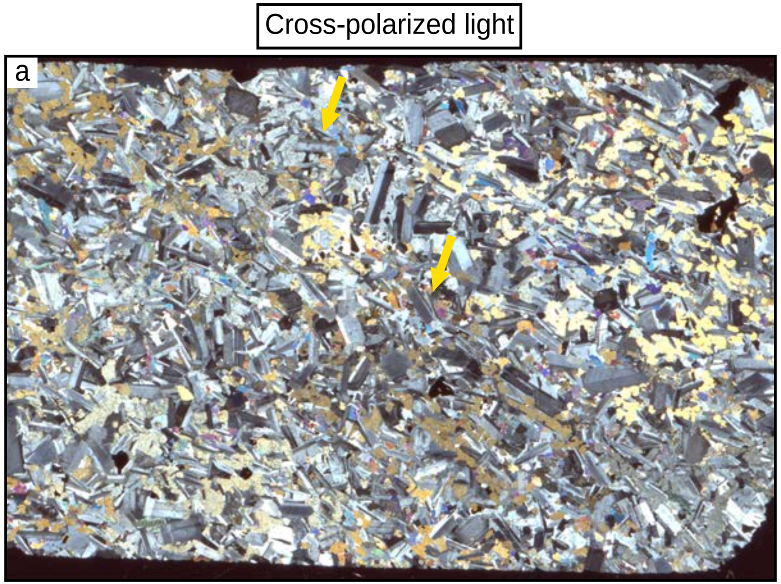
- Helmholtz coils allow active cancelling of ambient field for remanence imaging
- Constant fields in any direction can be applied up to 100 µT to mimic conditions in Earth's field
- Pure induced component calculated by $B_{induced} = B_{in\text{-}field} - B_{rem}$

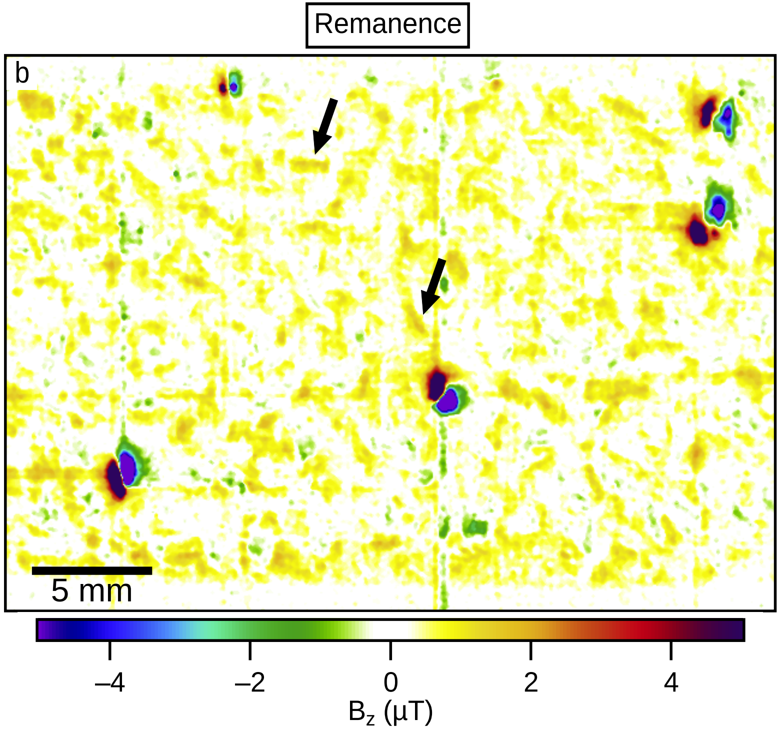
NTNU microscope results: Noise floor

AF demagnetised dunite paleomag core



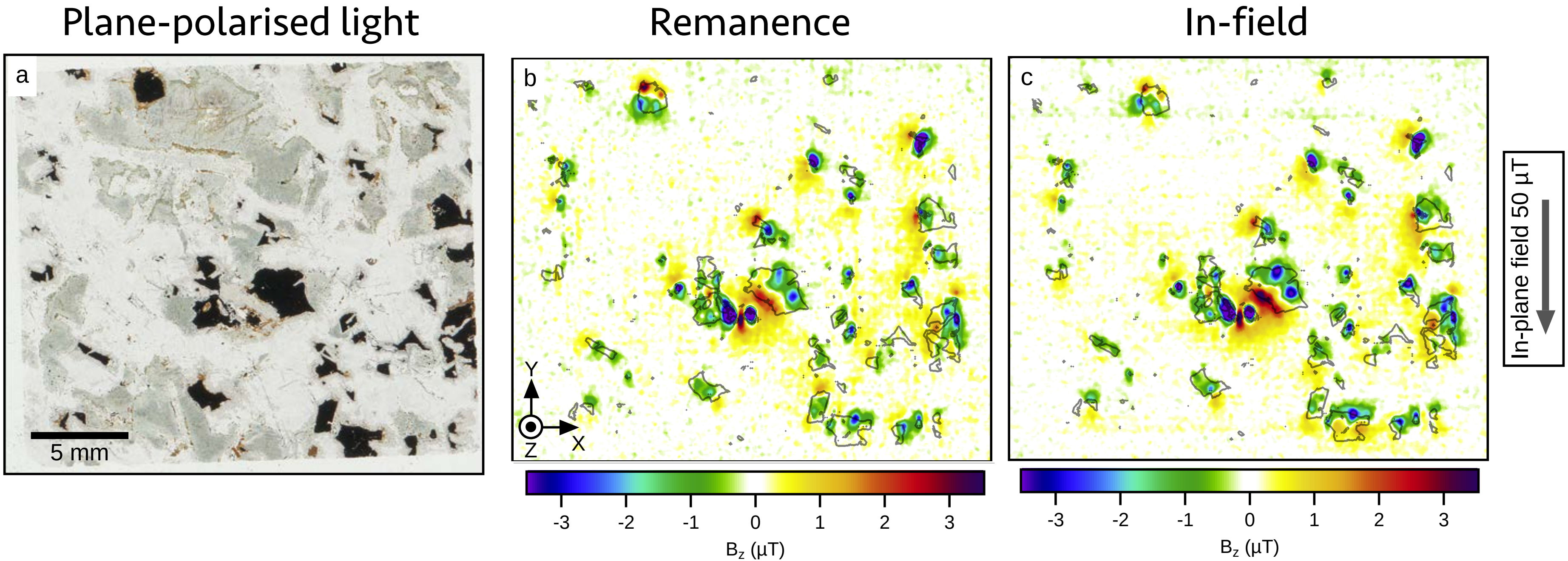
NTNU microscope results: Bushveld gabbro





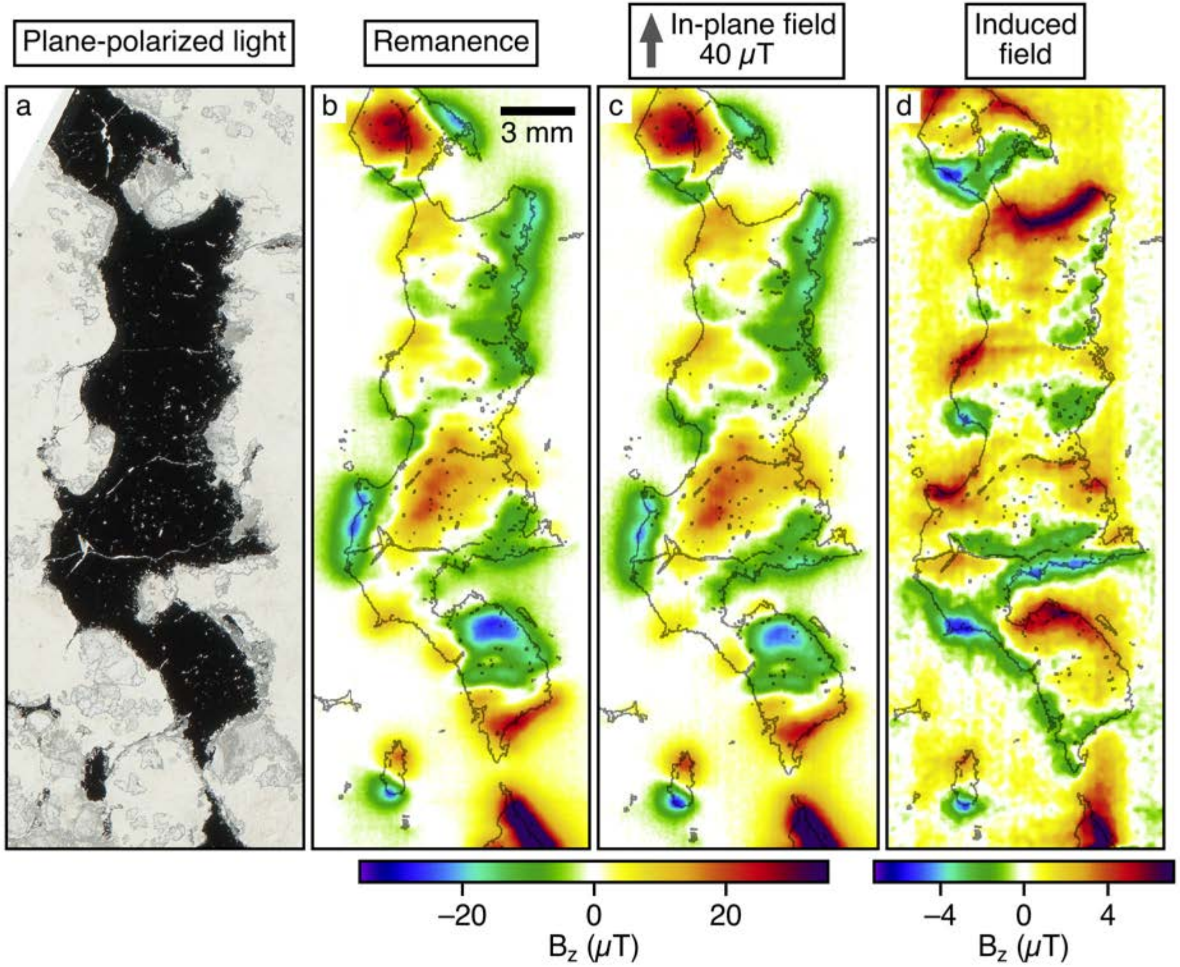
Gabbro from Bushveld layered intrusion, containing discrete magnetite and magnetite-bearing plagioclase (Church *et al.*, in prep)

NTNU microscope results: In-field imaging



Eclogite-facies metagabbro, Western Gneiss Region, Norway
(McEnroe *et al.*, in prep)

Calculating induced field from B_{rem} & $B_{in\text{-}field}$



In-field measurement contains both remanent component and field resulting from induced magnetisation

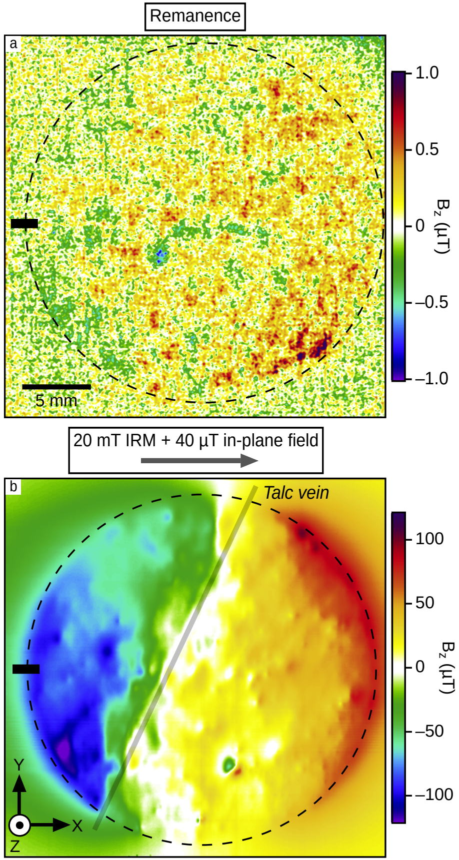
$\therefore B_{induced} = B_{in\text{-}field} - B_{rem}$

Metamorphosed serpentinite, Modum, Norway (Pastore *et al.* 2017)

Experiments made possible by use of discrete samples

Constraints for inversions include:

- Ability to remagnetise in a known direction
- Ability to demagnetise sample, scanning between steps
- Ability to measure total moment of sample
- Knowledge of location of magnetic sources (by using thin sections or CT scans of thick sections)



Conclusions

- SMMs operate on a useful length scale to observe behaviour of complex magnetic systems
- SMM is similar to aeromagnetic surveying, but additional constraints can be applied for inversion
- The NTNU microscope can resolve signal from different phases of coarse-grained rock
- Measuring in 0-field and in applied field allows the calculation of induced signal, and possible inversion using susceptibility