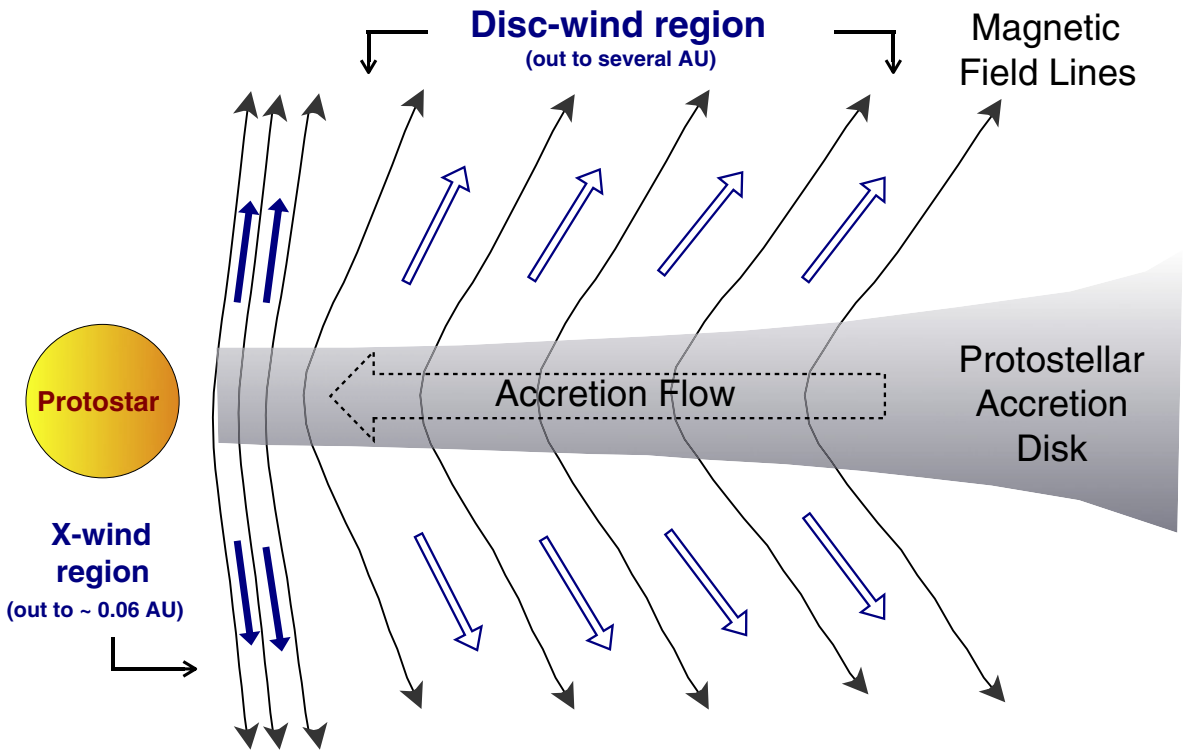
Comparison and calibration of nonheating paleointensity methods: A case study using dusty olivine

Lappe, S.-C. L.L., J. M. Feinberg, A. Muxworthy, and R. J. Harrison (2013), *Geochem. Geophys. Geosyst.*, 14, 2143–2158, doi:10.1002/ ggge.20141.

Chondrule formation

- high temperatures (flash heating)
- different scenarios are associated with different magnetic field intensities
- chondrules may have acquired a pre-accretionary TRM during cooling

→ find a way to reconstruct the field present at chondrule formation by measuring chondritic meteorites



Salmeron, R., and T.R. Ireland (2012) **Formation of chondrules in magnetic winds blowing through the proto-asteroid belt.** *Earth Planet. Sci.*, 327-328, 61-67, doi:10.1016/j.epsl.2012.01.033.

Motivation

Dusty olivine

- found in unequilibrated ordinary chondrites

  Nagahara H. (1981) **Evidence for secondary origin of chondrules**. *Nature*, 292, 135-136.

- high-Mg olivine grains with μm to nm sized Fe-Ni inclusions → dusty appearance

  Rambaldi, E.R., and J.T. Wasson (1982) **Fine, nickel-poor Fe-Ni grains in the olivine of unequilibrated ordinary chondrites.** *Geochim. Cosmochim. Acta*, 46, 929-939, doi: 10.1016/0016-7037(82)90049-7.

  Jones, R.H., and L.R. Danielson (1997) **A chondrule origin for dusty relict olivine in unequilibrated chondrites.** *Meteorit. Planet. Sci.*, 32, 753-760, doi:10.1111/j.1945-5100.1997.tb01565.x.

- formed via sub-solidus reduction of the fayalitic component (Fe_2SiO_4) of the olivine host crystal during the heating event at the chondrule formation

  Boland, J.N., and A. Duba (1981) **Solid-state reduction of iron in olivine - planetary and meteoritic evolution.** *Nature*, 294, 142-144.

Motivation

Dusty olivine

- chondrules cools through the Curie temperature of Fe in the presence of ancient field
  → dusty inclusions acquire TRM

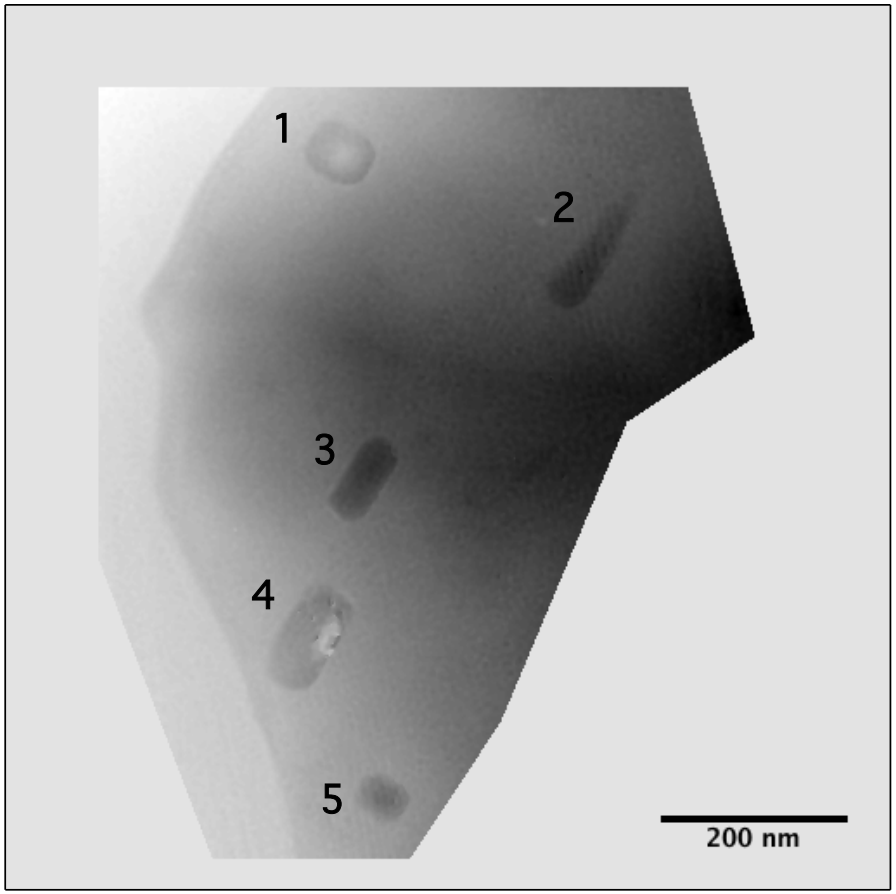
Do they still retain a primary TRM?

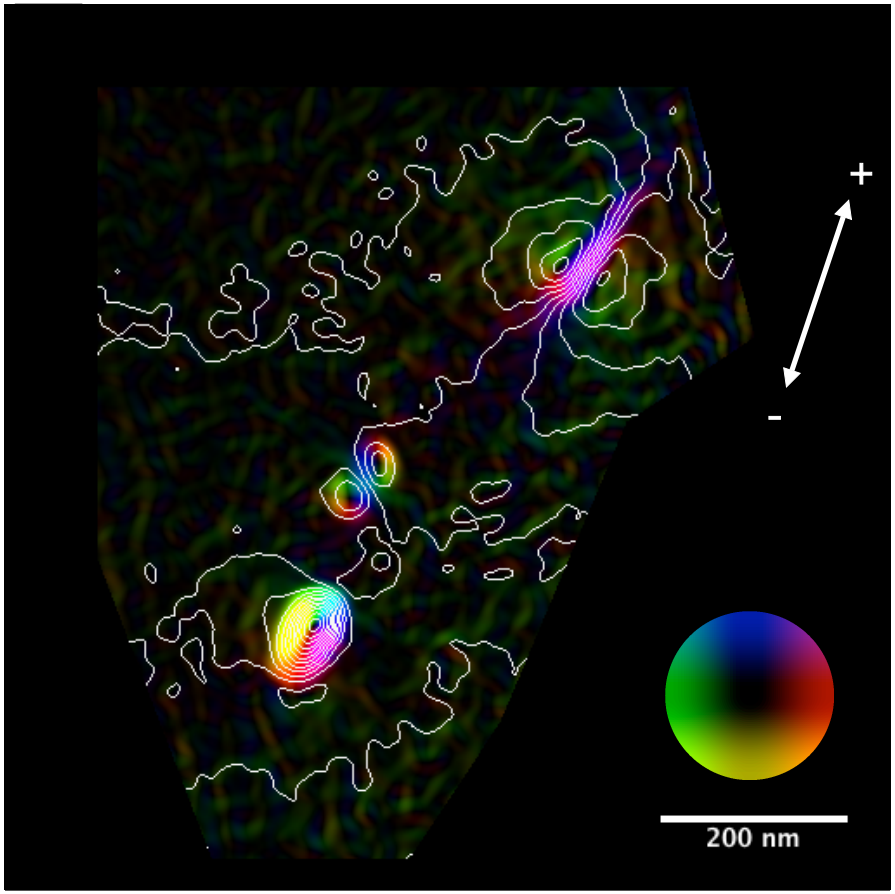
- shielded from thermal and chemical alteration due to surrounding olivine host crystal
- high coercivities, stable remanence behaviour, high mean destructive field
  → faithful carrier of pre-accretionary remanence
  → may retain a record of Early Solar System's magnetic field

Uehara, M., and N. Nakamura (2006) **Experimental constraints on magnetic stability of chondrules and the paleomagnetic significance of dusty olivine.** *Earth Planet. Sci. Lett.* 250, 292-305, doi: 10.10161/j.epsl.2007.07.002.

Motivation

Synthetic dusty olivine





Lappe, S.-C. L. L., N. S. Church, T. Kasama, A. B. da Silva Fanta, G. Bromiley, R. E. Dunin-Borkowski, J. M. Feinberg, S. Russell, and R. J. Harrison (2011), **Mineral magnetism of dusty olivine: A credible recorder of pre-accretionary remanence**, *Geochem. Geophys. Geosyst.*, 12, Q12Z35, doi:10.1029/2011GC003811.

Motivation

Synthetic dusty olivine

- Non-interacting single domain uniaxial particles with high coercivity
- Simple and well understood mineralogy
- TRM acquired under conditions that can be reproduced in the lab (similar temperature/pressure/oxygen fugacity/cooling rate)
- Sufficient density of remanence carriers to allow sub-mm sampling/ measurement (e.g. using scanning magnetic microscopy)
- Stable with respect to chemical alteration/heating (both in nature and lab)

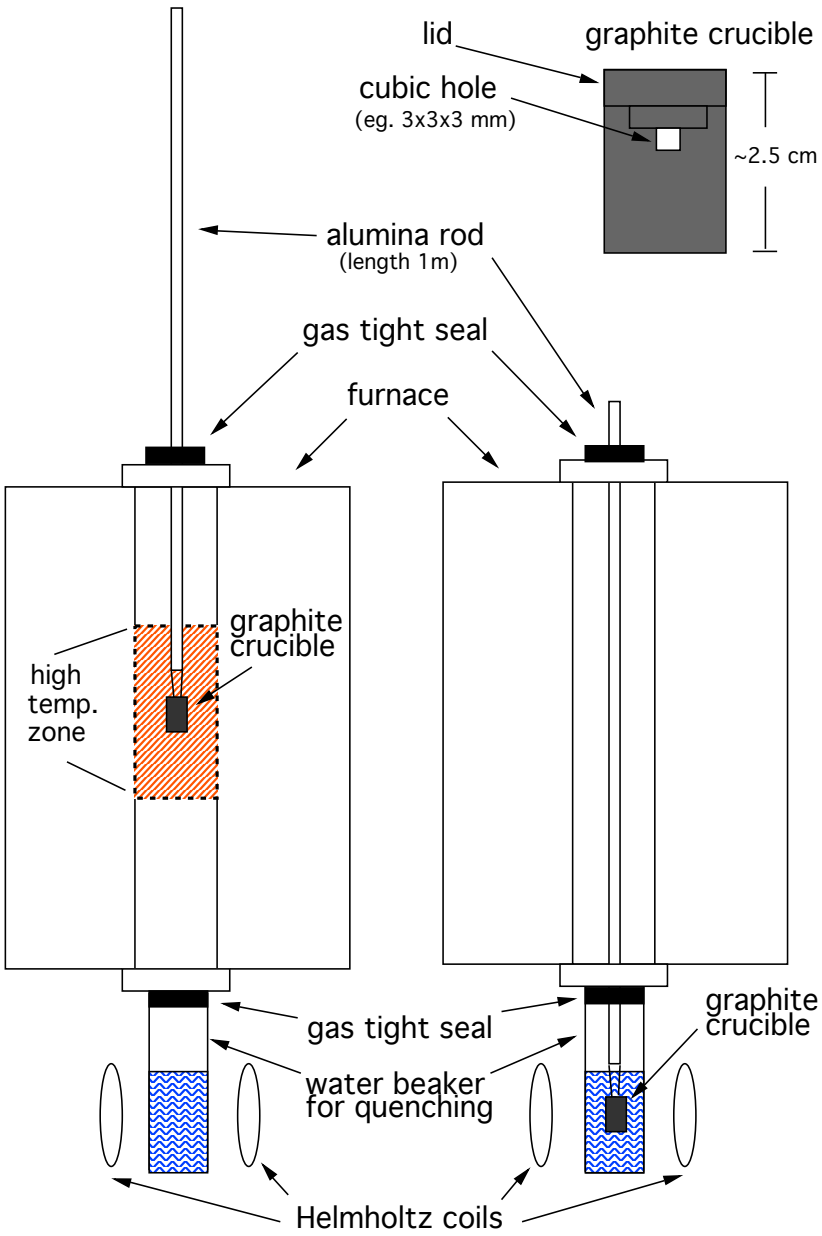
Lappe, S.-C. L. L., N. S. Church, T. Kasama, A. B. da Silva Fanta, G. Bromiley, R. E. Dunin-Borkowski, J. M. Feinberg, S. Russell, and R. J. Harrison (2011), **Mineral magnetism of dusty olivine: A credible recorder of pre-accretionary remanence**, *Geochem. Geophys. Geosyst.*, 12, Q12Z35, doi:10.1029/2011GC003811.

Motivation

Goal: Extract accurate information about the magnetic field intensity, present at the time of chondrule formation, from meteoritic samples

→ establish and calibrate a non-heating method of paleointensity determination

Sample synthesis



3 different starting materials:

- olivine crystals from Icelandic basalt; average comp. 10.2% fayalite; 0.33wt% Ni
- synthetic olivine; 10% fayalite; 0.1wt% Ni
- synthetic olivine; 10% fayalite; Ni-free

fabrication and characterisation of synthetic olivine:

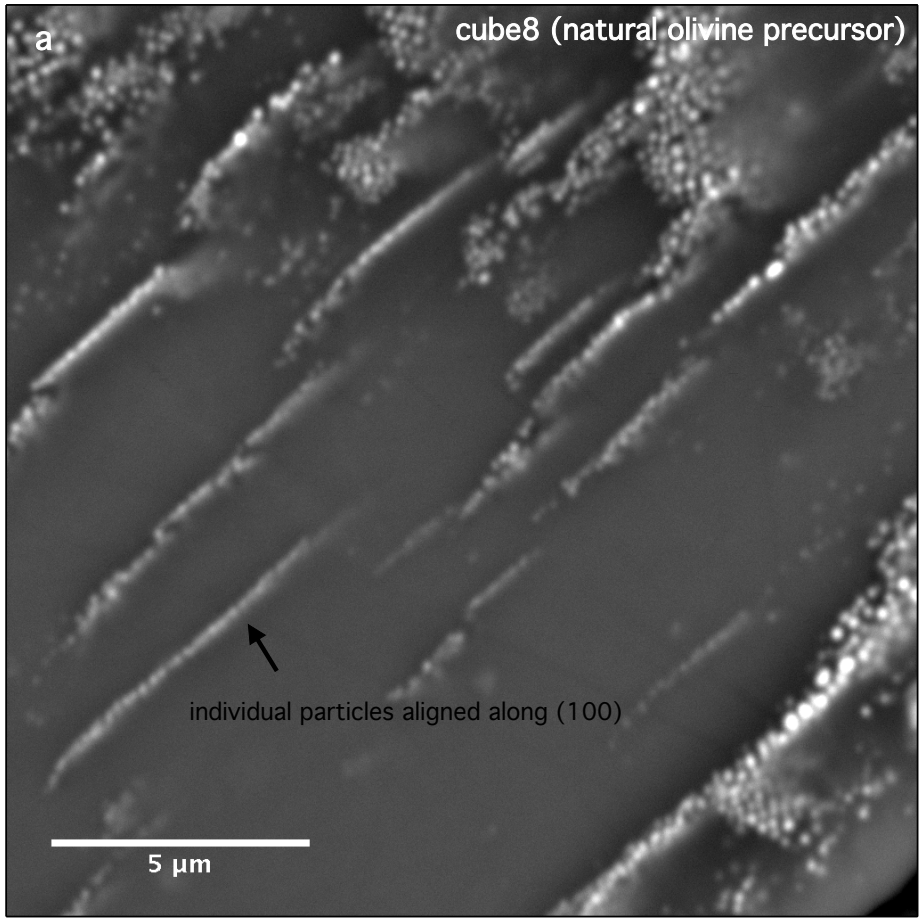
- chemical synthesis from oxides
- X-ray powder diffraction
- SEM
- microprobe

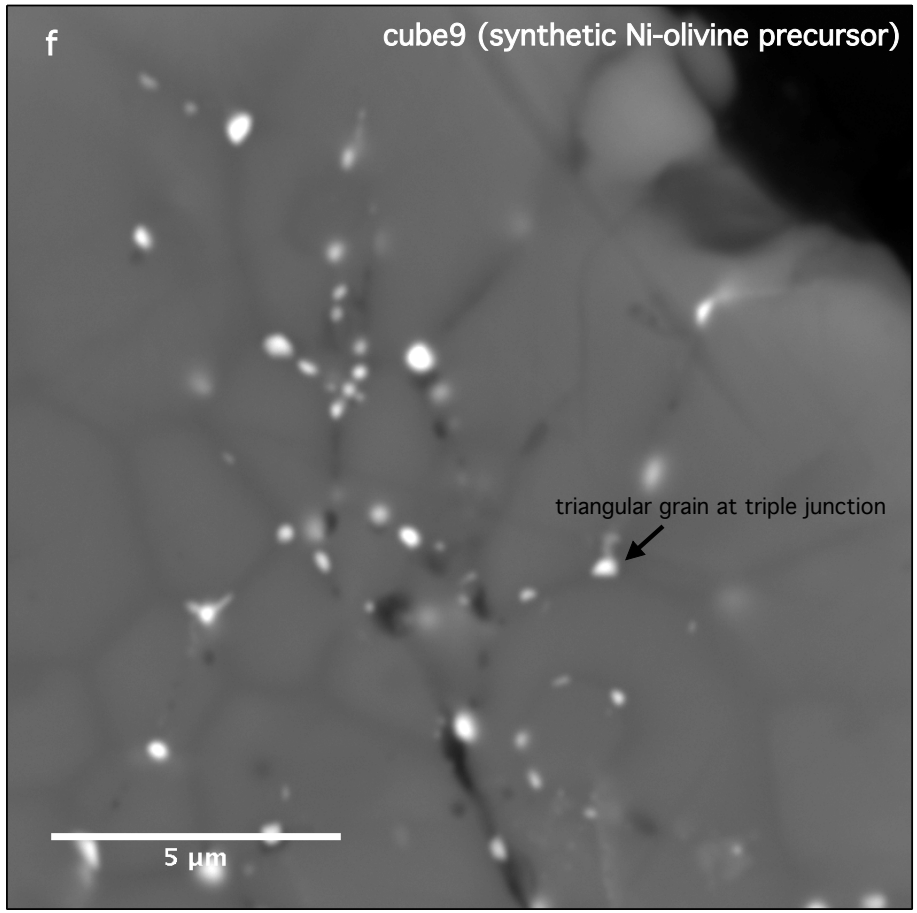
Samples quenched in a known magnetic field:

- design of unique quenching mechanism
- 6 different fields ranging from 0.2 to 1.5 mT, 2-3 samples each

Sample characterisation

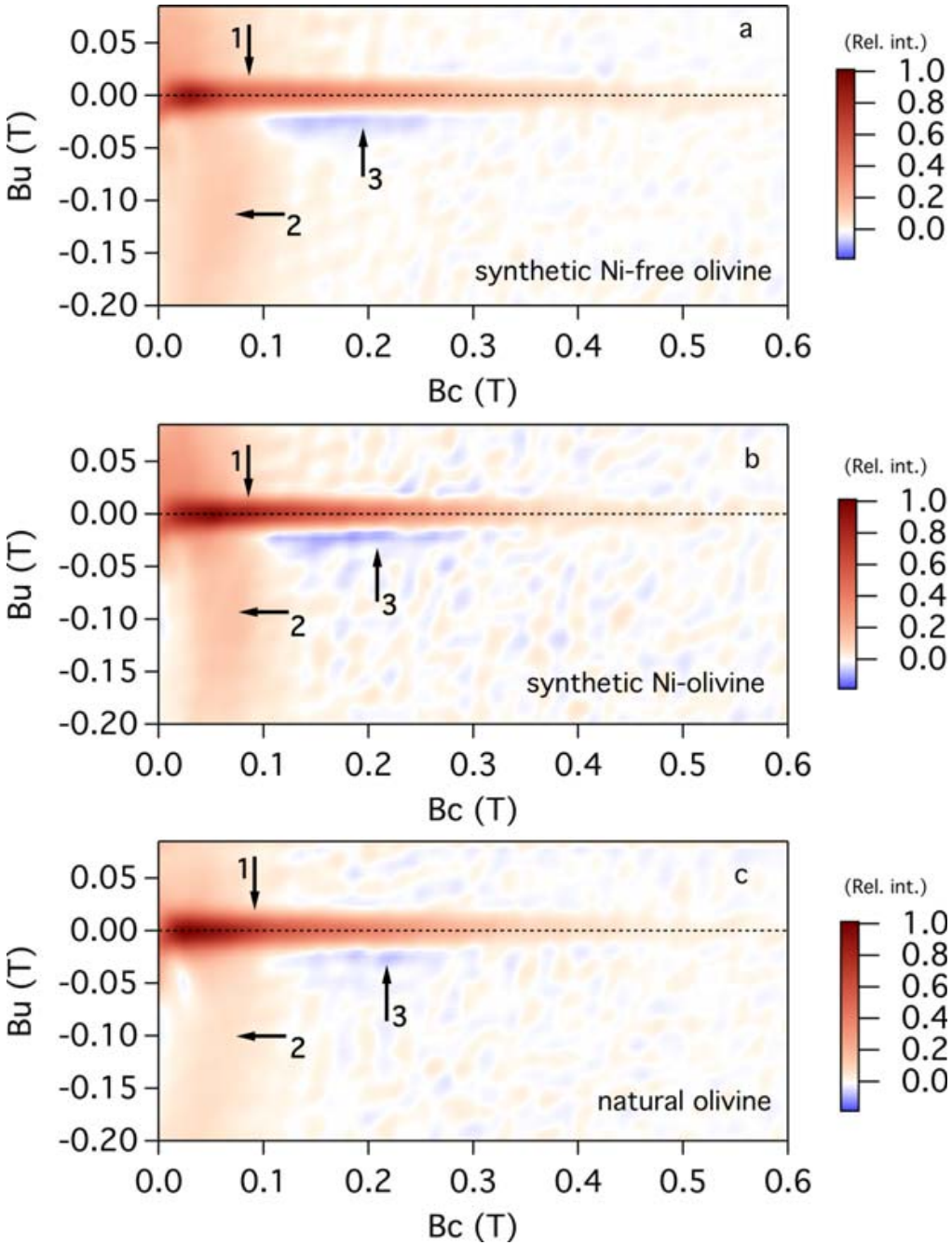
Microscopy





- all samples resemble natural dusty olivines
- samples made from synthetic olivine show less of the very small Fe-inclusions but seem to contain more particles with irregular shapes and more larger inclusions at grain boundaries

First-order reversal curve (FORC) measurements



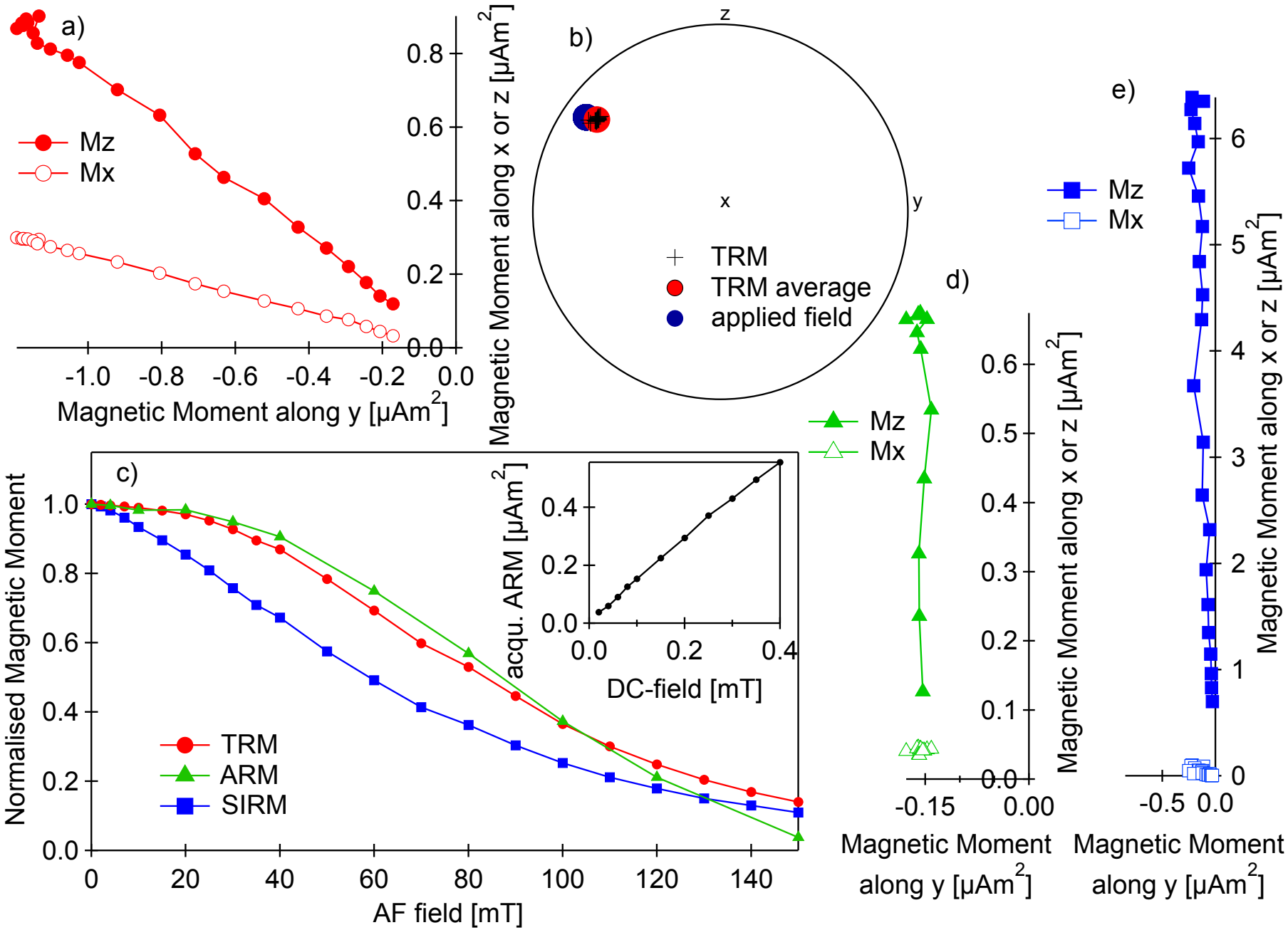
- mix of single domain and vortex states
- coercivity up to 600 mT
- samples made from synthetic olivine generally show higher vortex contribution, i.e. samples made from natural olivine starting material are more SD dominated
- samples made from synthetic olivine also show higher variability in the amount of vortex contribution between different samples
- average vortex annihilation field: 170 mT

Rock-magnetic measurements

- Alternating-field (AF) demagnetisation of thermoremanent magnetisation (TRM)
- Acquisition of anhysteritic remanent magnetisation (ARM); highest bias field: 0.4 mT
- Alternating-field (AF) demagnetisation of anhysteritic remanent magnetisation (ARM)
- Inducement of saturation isothermal remanent magnetisation (SIRM); applied field: 1T
- Alternating-field (AF) demagnetisation of saturation isothermal remanent magnetisation (SIRM)

Rock-magnetic measurements

TRM and IRM demagnetisation, ARM acquisition and demagnetisation

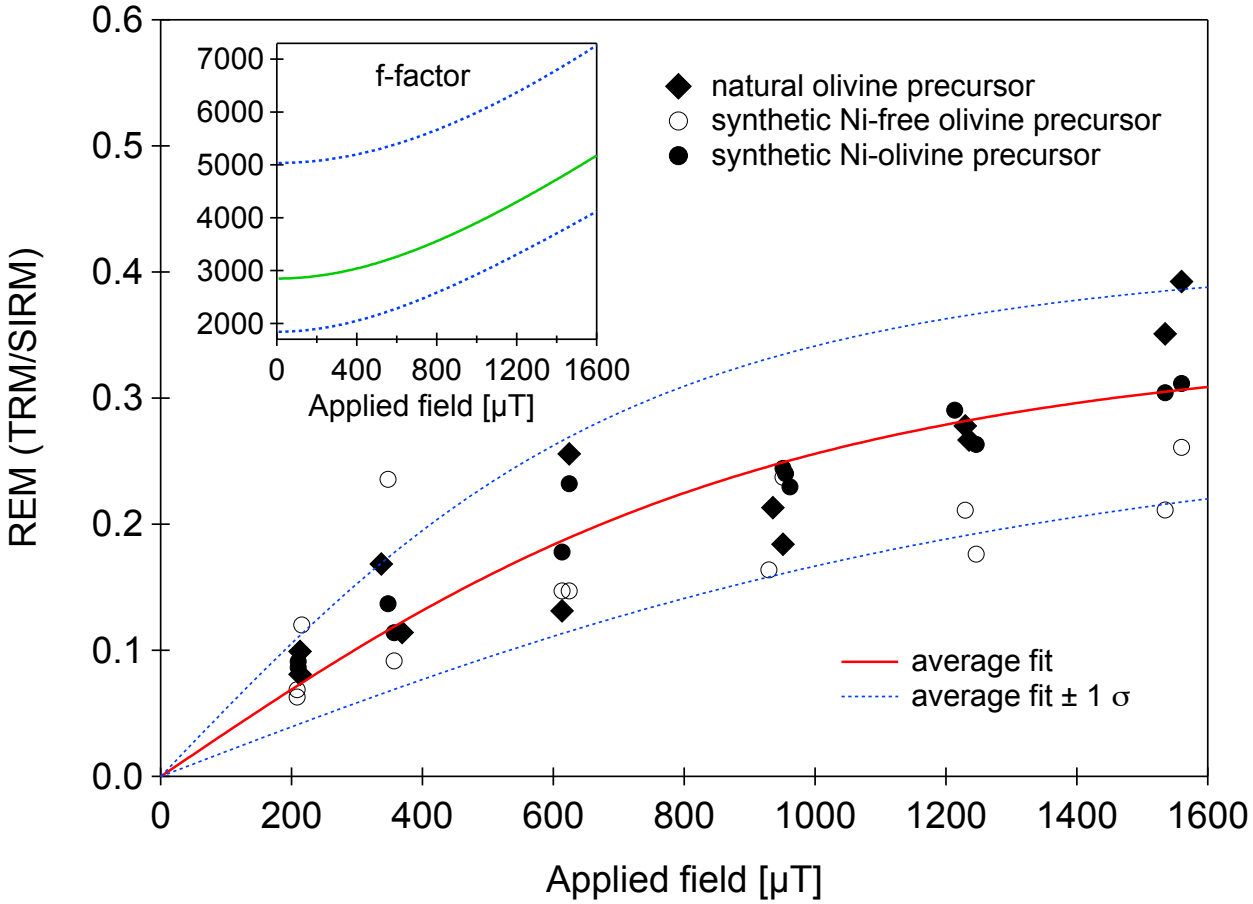


Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: REM

The saturation REM ratio (total TRM/SIRM) shows non-linear behavior as function of applied field, saturating at a value of 0.36. Data were fitted to the theoretical expression for TRM as function of applied field (adapted from Tauxe 2010):

$$REM = \frac{TRM}{SIRM} = 2REM_s \int_0^{90} \tanh\left(\frac{MB\cos\theta}{kT}\right)\cos\theta\sin\theta \mathrm{d}\theta$$



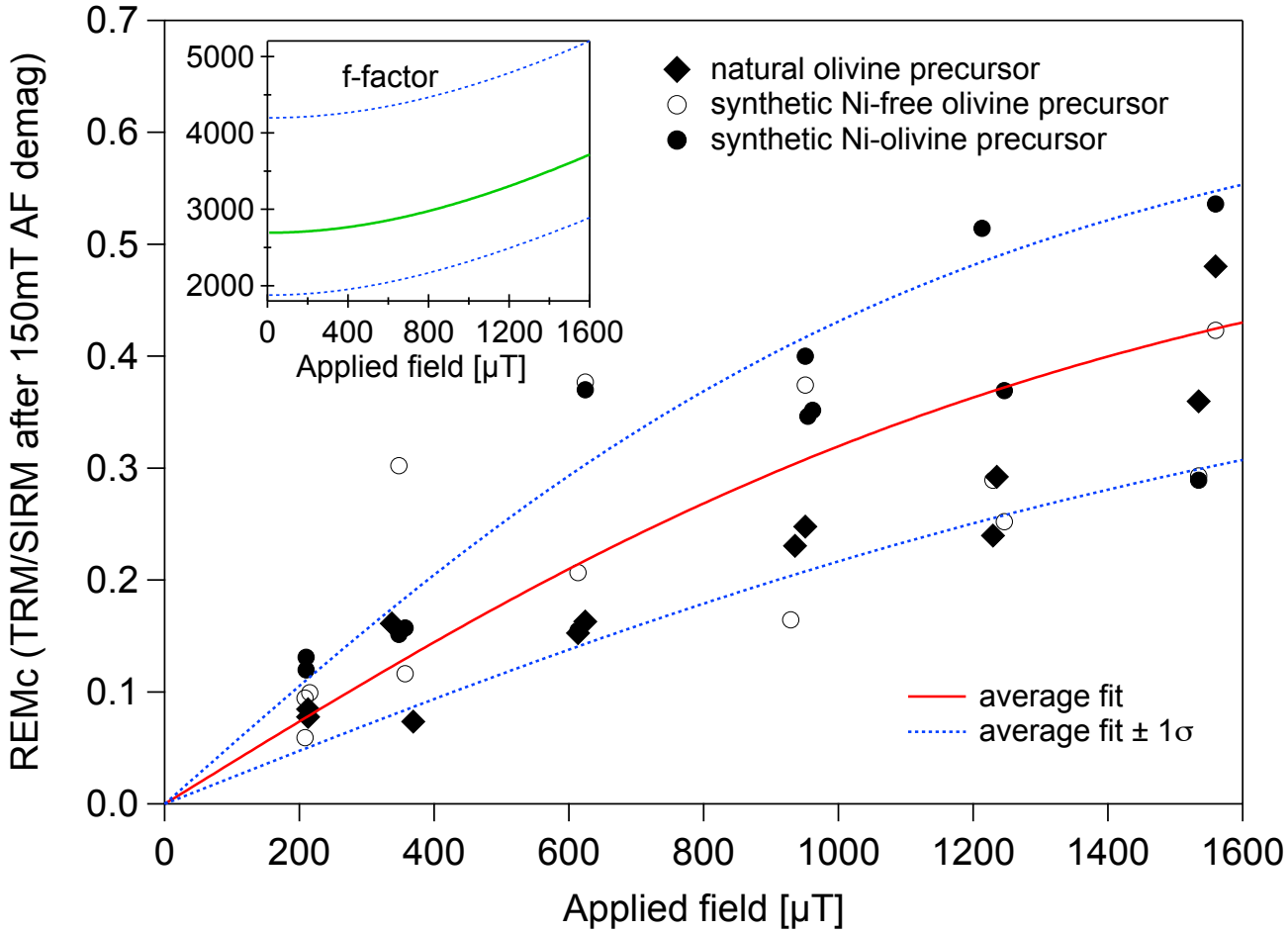
The calibration factor *f* is defined so that the magnetising field B (in μT) is equal to *f**REM. Average *f*-factor for REM: 2850

SIRM > saturation TRM
SV states transform to meta-stable SD states in saturating field → 'over normalization'

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: REMc

REMc = TRM left after demag. to 150 mT / IRM left after demag. to 150 mT



Non-linear behavior, average *f*-factor: 2695, saturation value: 0.6

Over normalization reduced, more of SD component of remanence is isolated

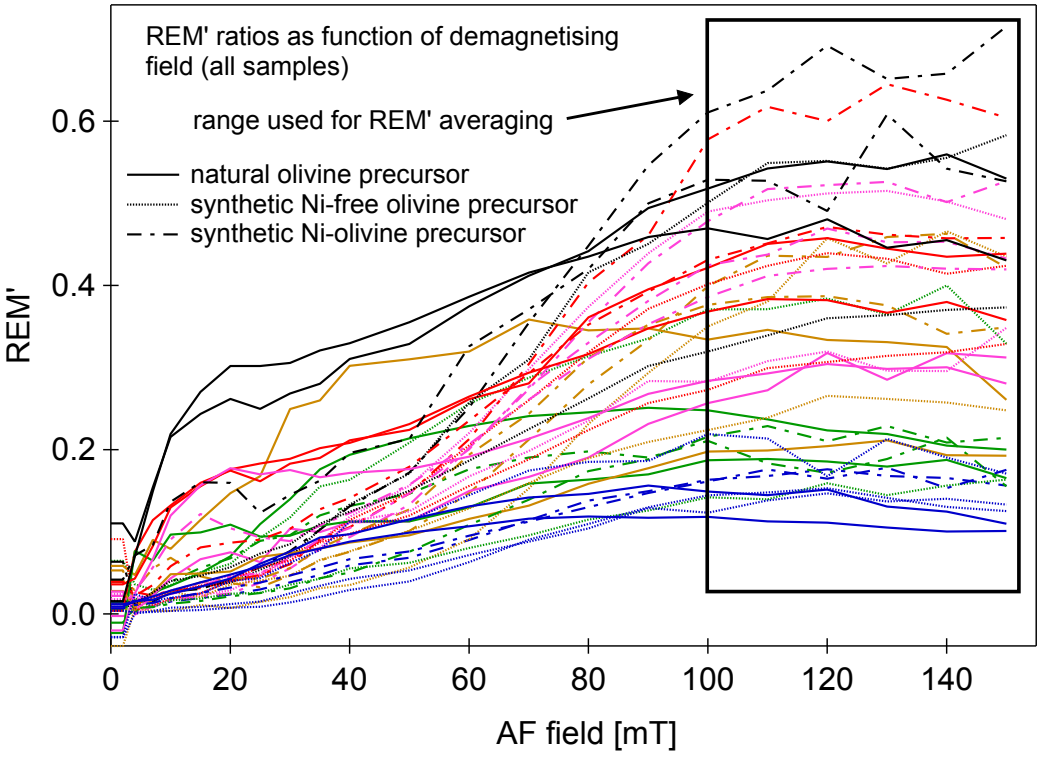
Kletetschka et al. (2003), Gattacceca and Rochette (2004): *f*-factor = 3000

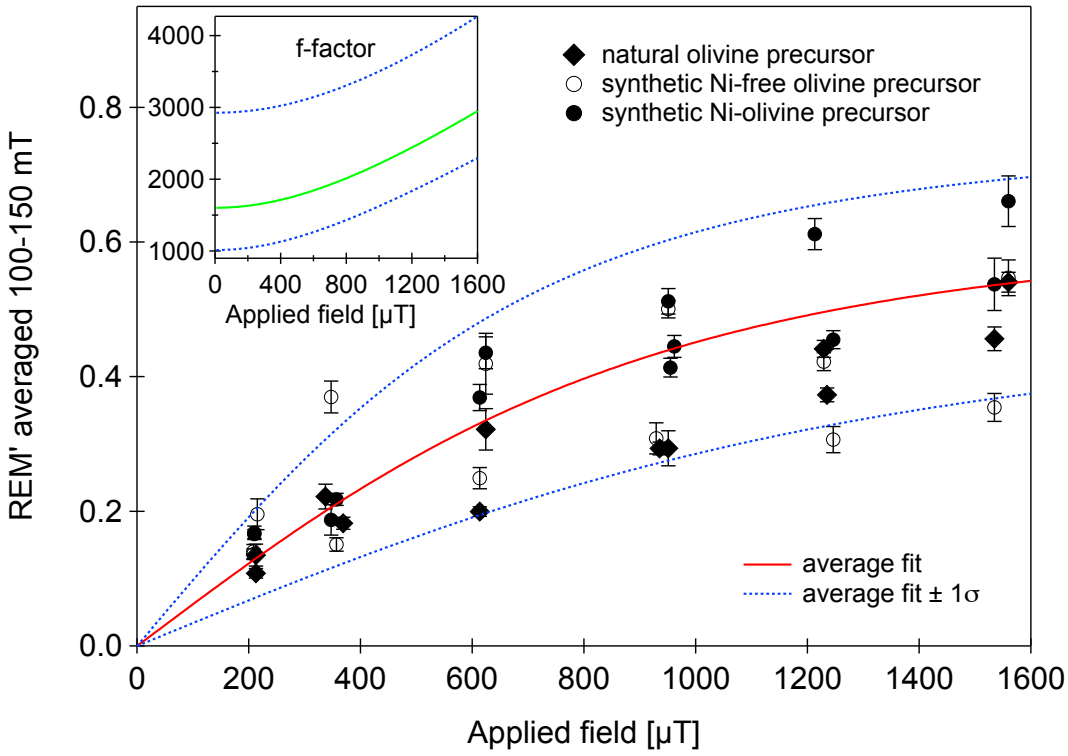
Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: REM'

REM' ratio = slope TRM demagnetisation curve/slope IRM demagnetisation curve

REM' = (dTRM/dAF)/(dIRM/dAF) i.e. REM' = (ΔTRM/ΔIRM)





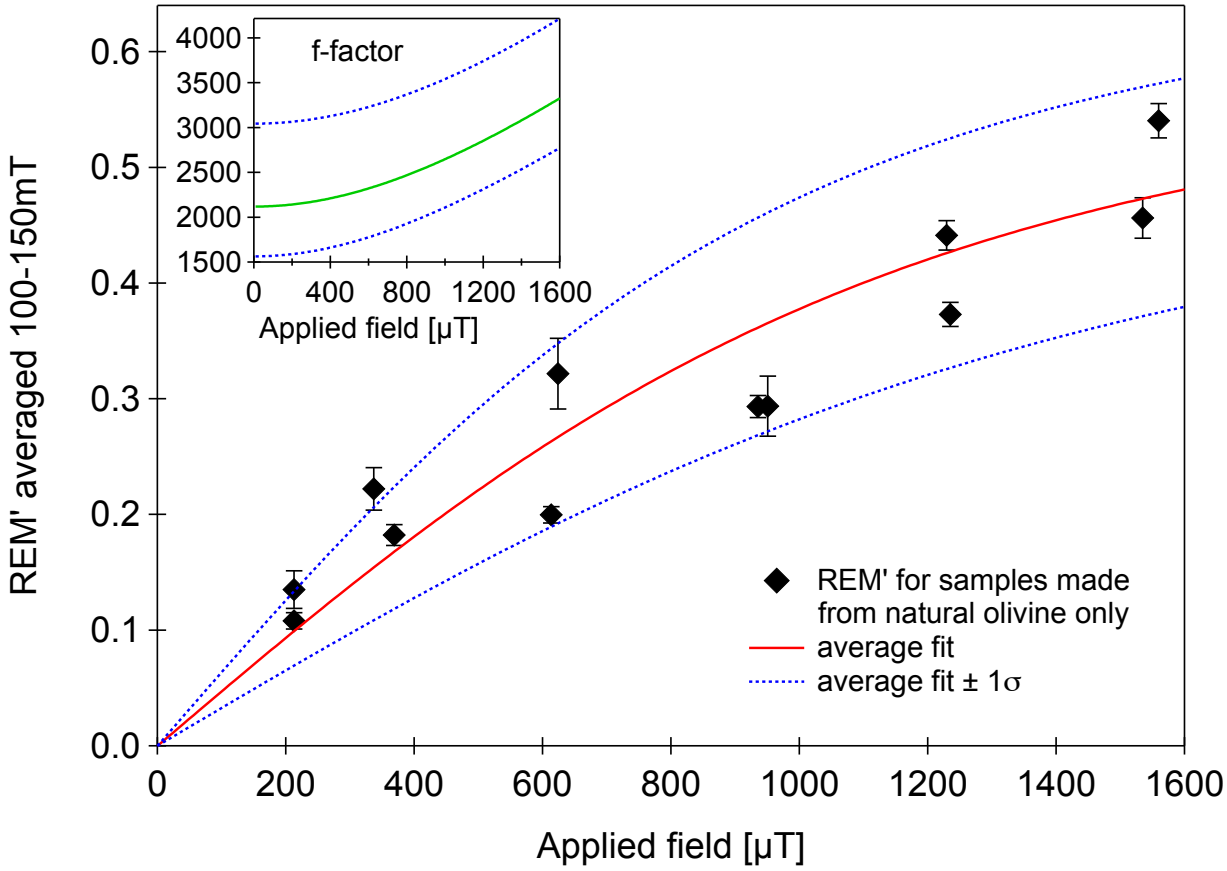
Non-linear behavior, average *f*-factor: 1604, saturation value: 0.6

Over normalization reduced, more of SD component of remanence is isolated

Muxworthy et al. (2011): *f*-factor = 1900

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: REM' natural olivine starting material only



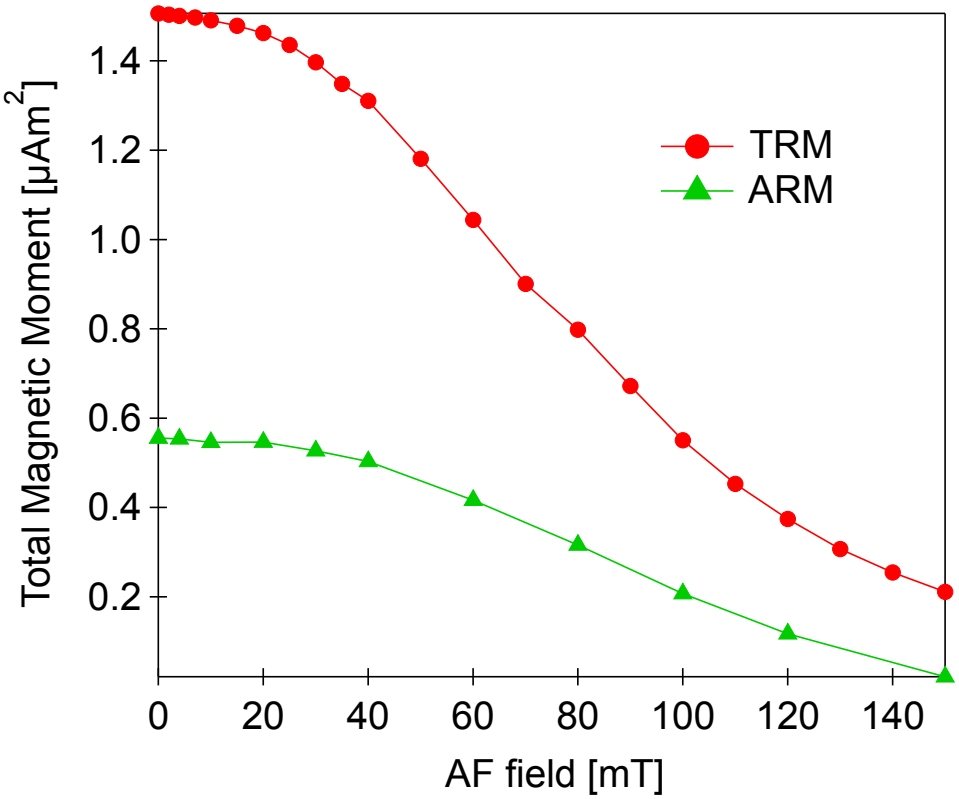
Non-linear behavior, average *f*-factor: 2119, saturation value: 0.60

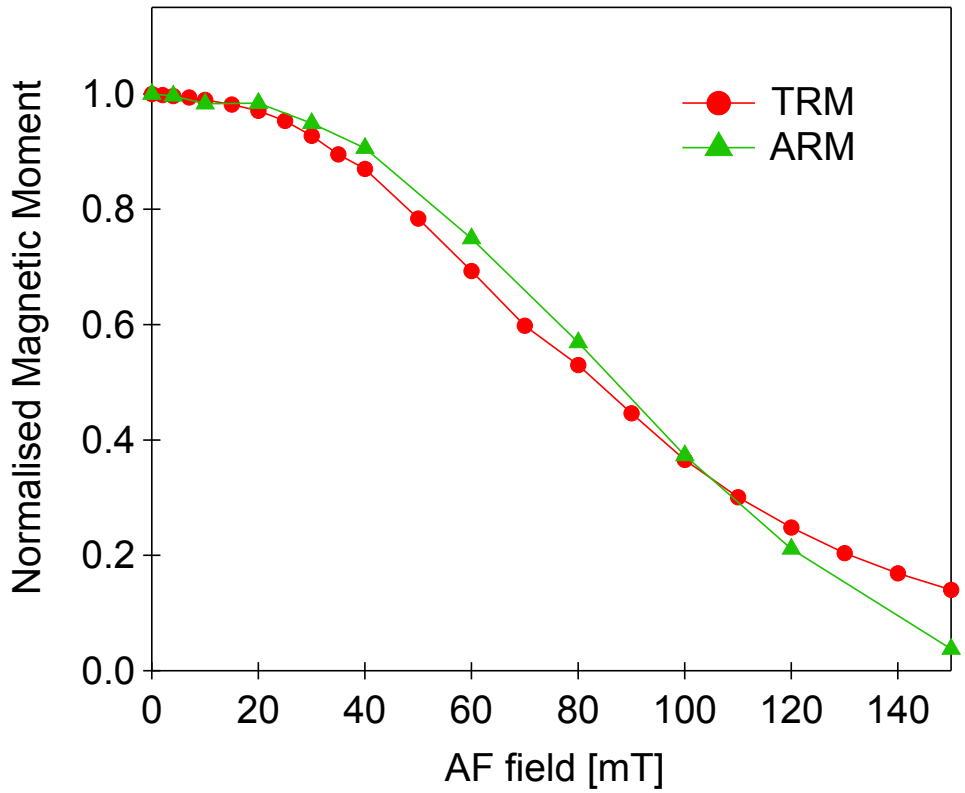
Over normalization reduced, more of SD component of remanence is isolated

Muxworthy et al. (2011): *f*-factor = 1900

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: ARM





AF demagnetisation curve of TRM and ARM are very similar in shape

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: ARM

Relationship between TRM and ARM can be described using the empirical calibration factor f_{ARM}:

$$f_{ARM} = \frac{\chi_{TRM}}{\chi_{ARM}}$$

χTRM, χARM: susceptibility of TRM, ARM acquisition

TRM acquired in field $B_{ancient}$, ARM acquired in field B_{bias} in the lab

f_{ARM} can be calculated:

$$f_{ARM} = \frac{TRM}{ARM}\frac{B_{bias}}{B_{ancient}} \quad \Rightarrow \quad B_{ancient} = \frac{TRM}{ARM}\frac{B_{bias}}{f_{ARM}}$$

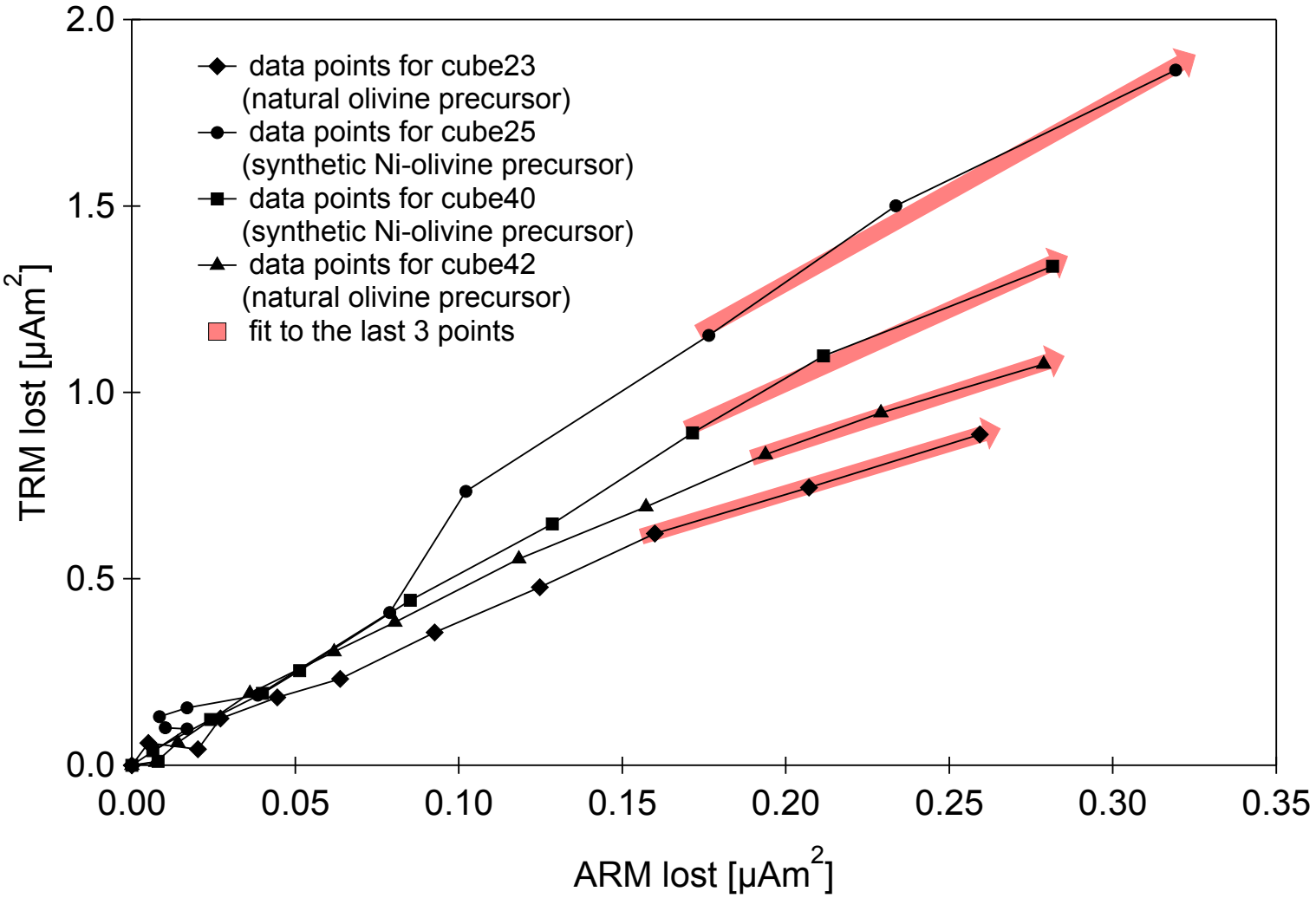
Total remanences TRM, ARM can be substituted by demagnetisation slopes dTRM/dAF and dARM/dAF, giving:

$$B_{ancient} = \frac{dTRM}{dARM}\frac{B_{bias}}{f_{ARM}}$$

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: ARM

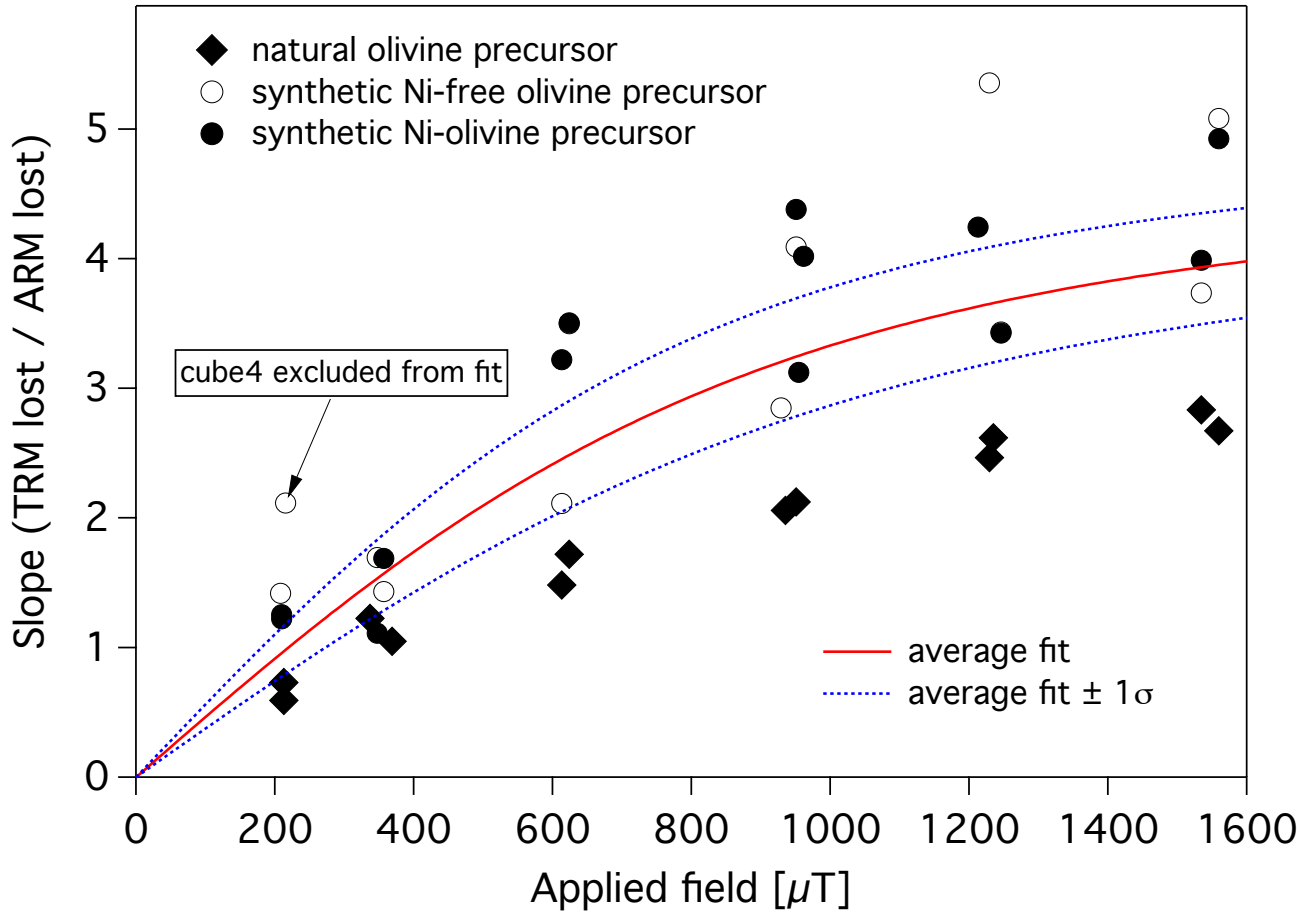
TRM lost at certain point of AF demag vs ARM lost at same demag step



Rock-magnetic measurements

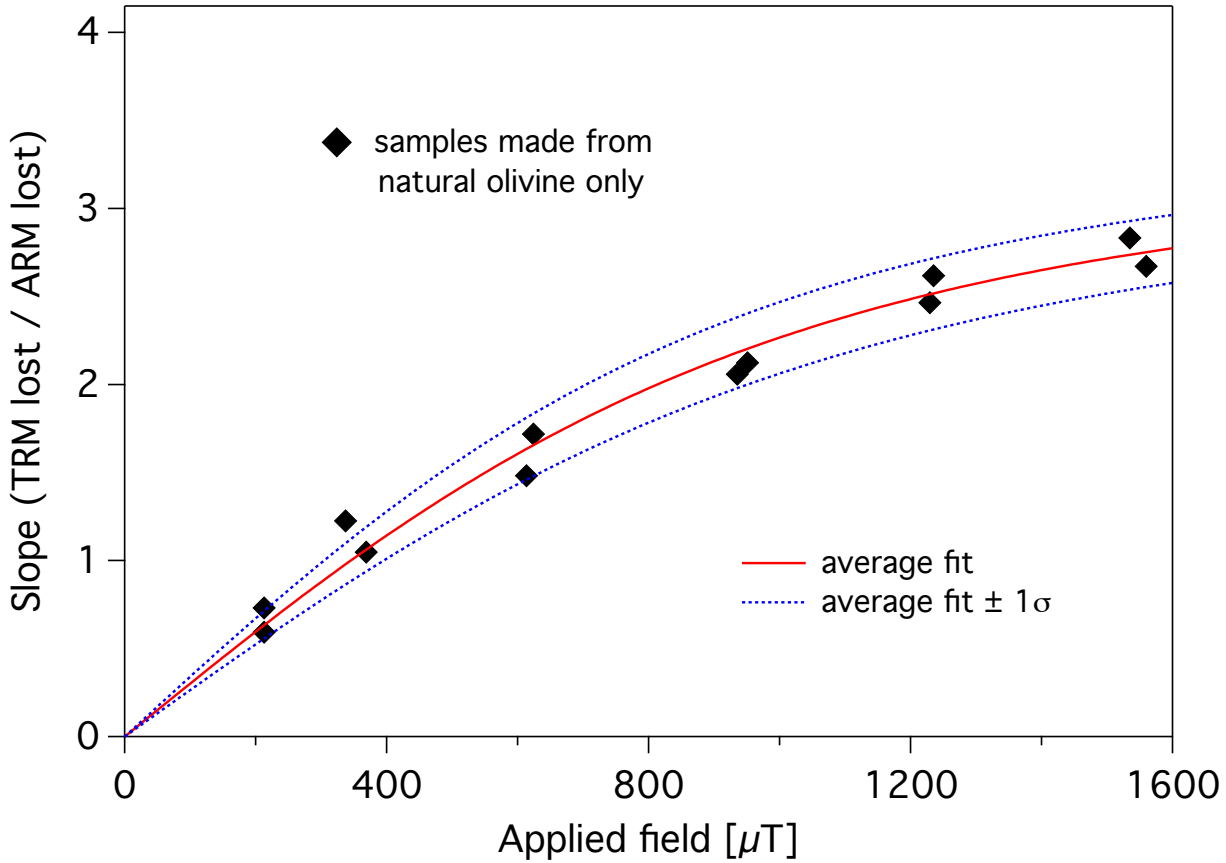
Calibration curve relating applied field to recorded remanence: ARM

Slope of fit to last 3 points vs applied lab field



Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: ARM natural olivine starting material only

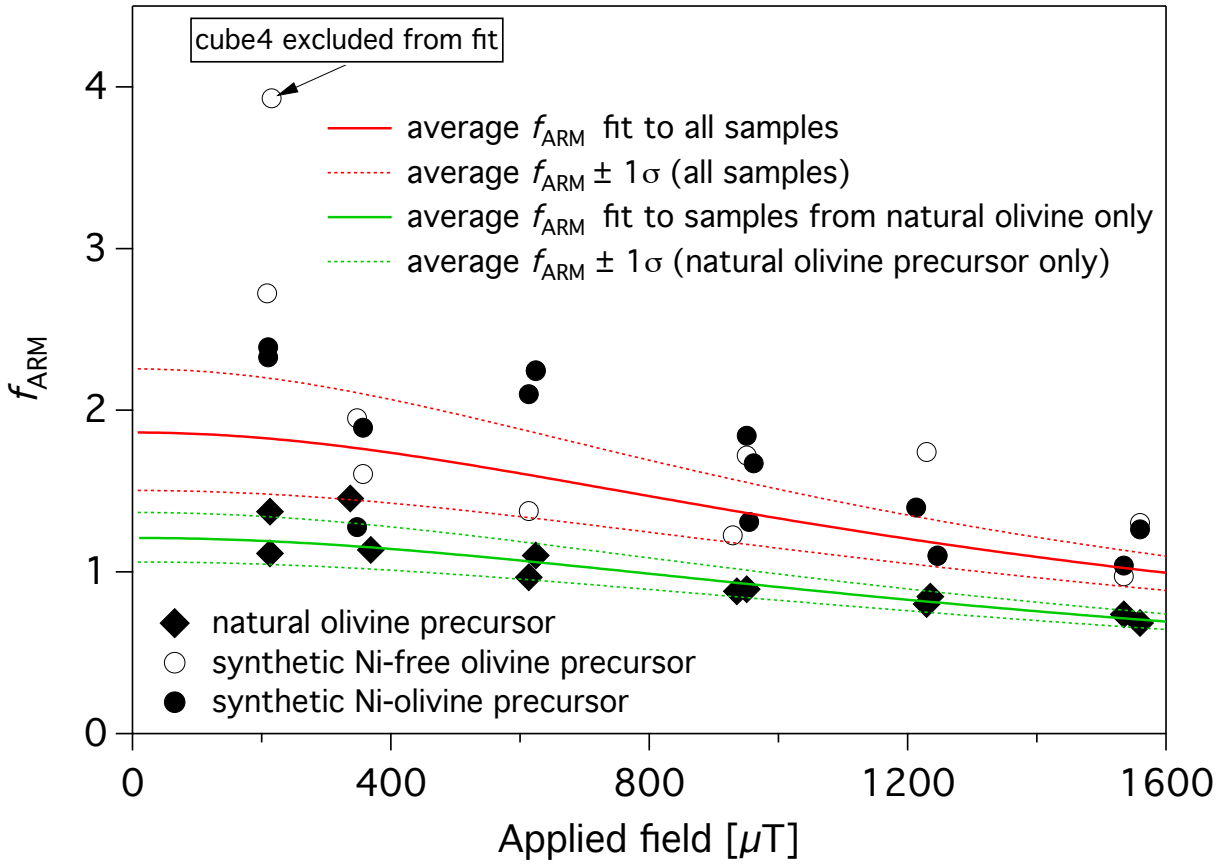


The slope (TRM lost/ARM lost) is specific for the bias field used for the ARM acquisition. Therefore, f_{ARM} is calculated which is valid generally.

f_{ARM} = (slope (TRM lost/ARM lost)*B_{bias})/$B_{ancient}$

Rock-magnetic measurements

Calibration curve relating applied field to recorded remanence: ARM

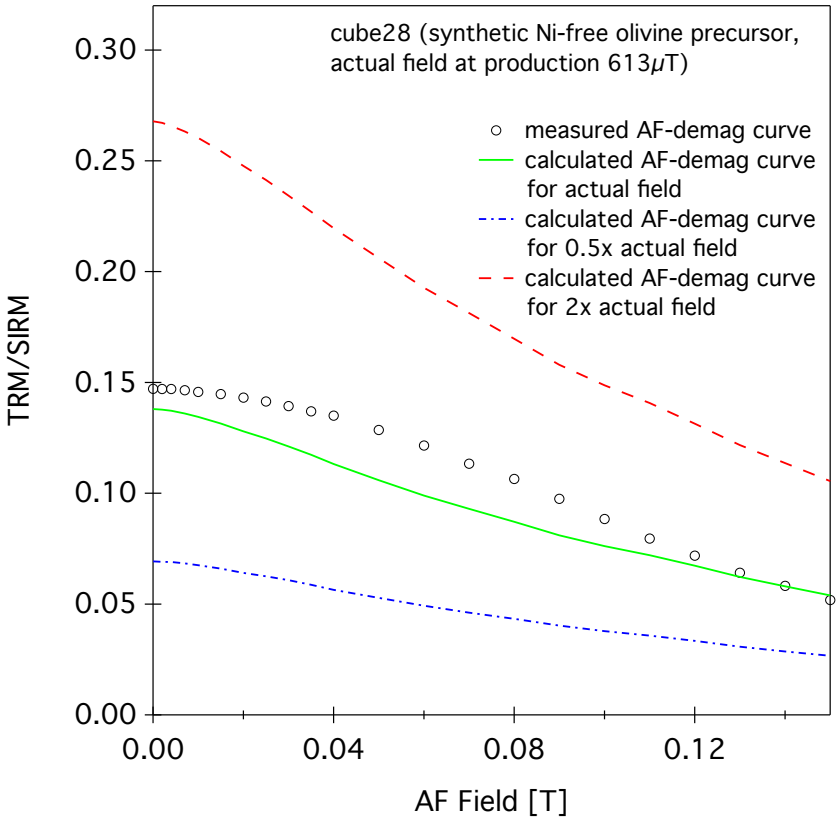


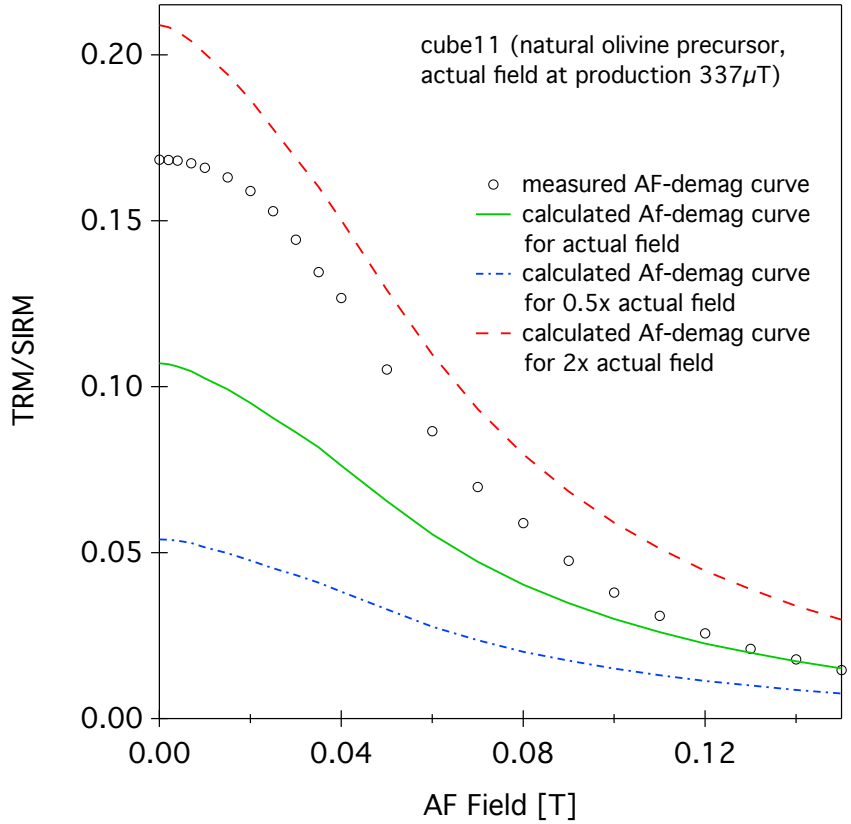
Average f_{ARM} at 0 field for all samples: 1.86

Average f_{ARM} at 0 field for samples made from natural olivine: 1.21

Yu (2010): $f_{ARM} = 2.60 \pm 1.32$

FORC method



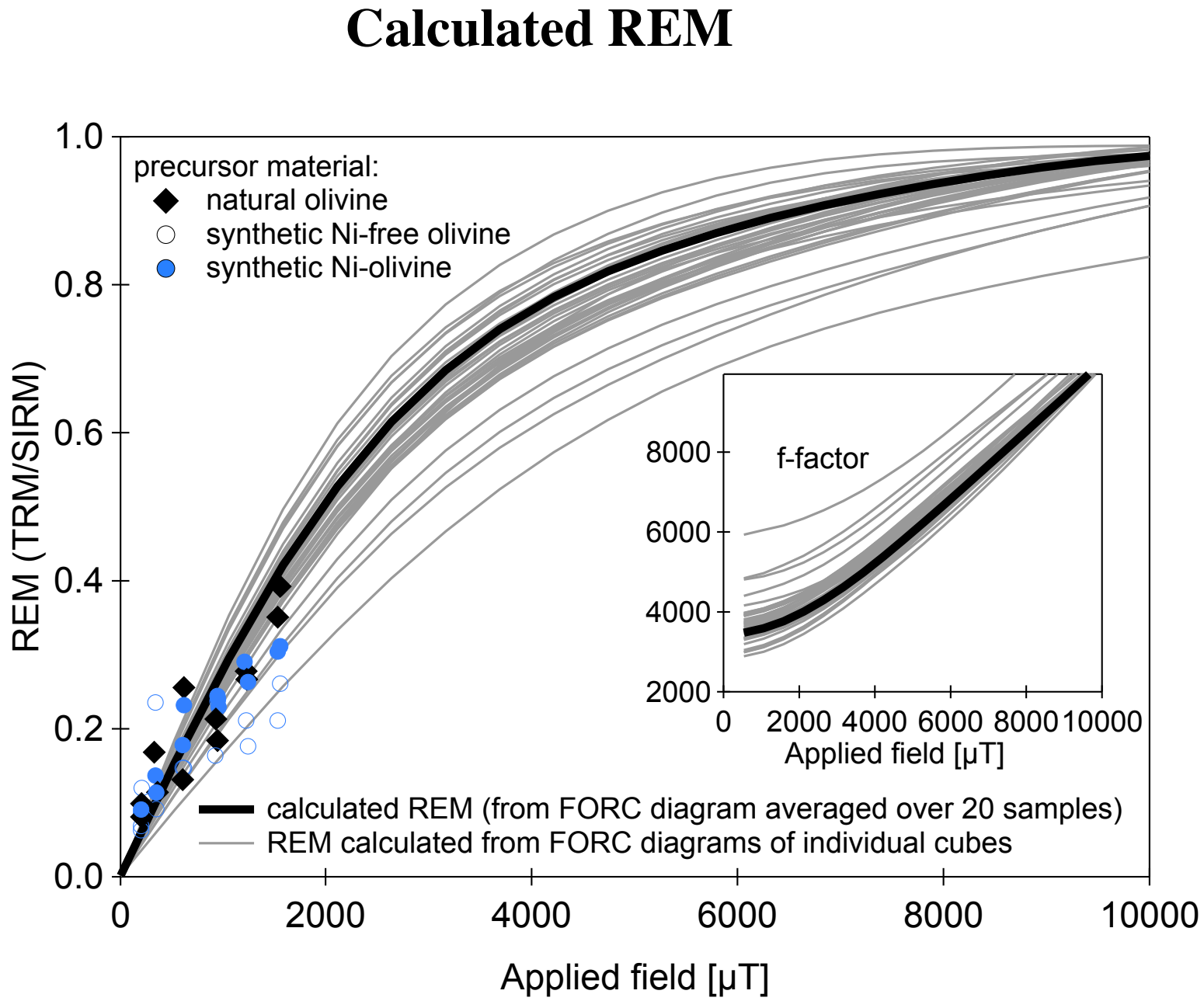


Due to the contribution of vortex states to the FORC signal, the method only works for high demagnetisation fields.

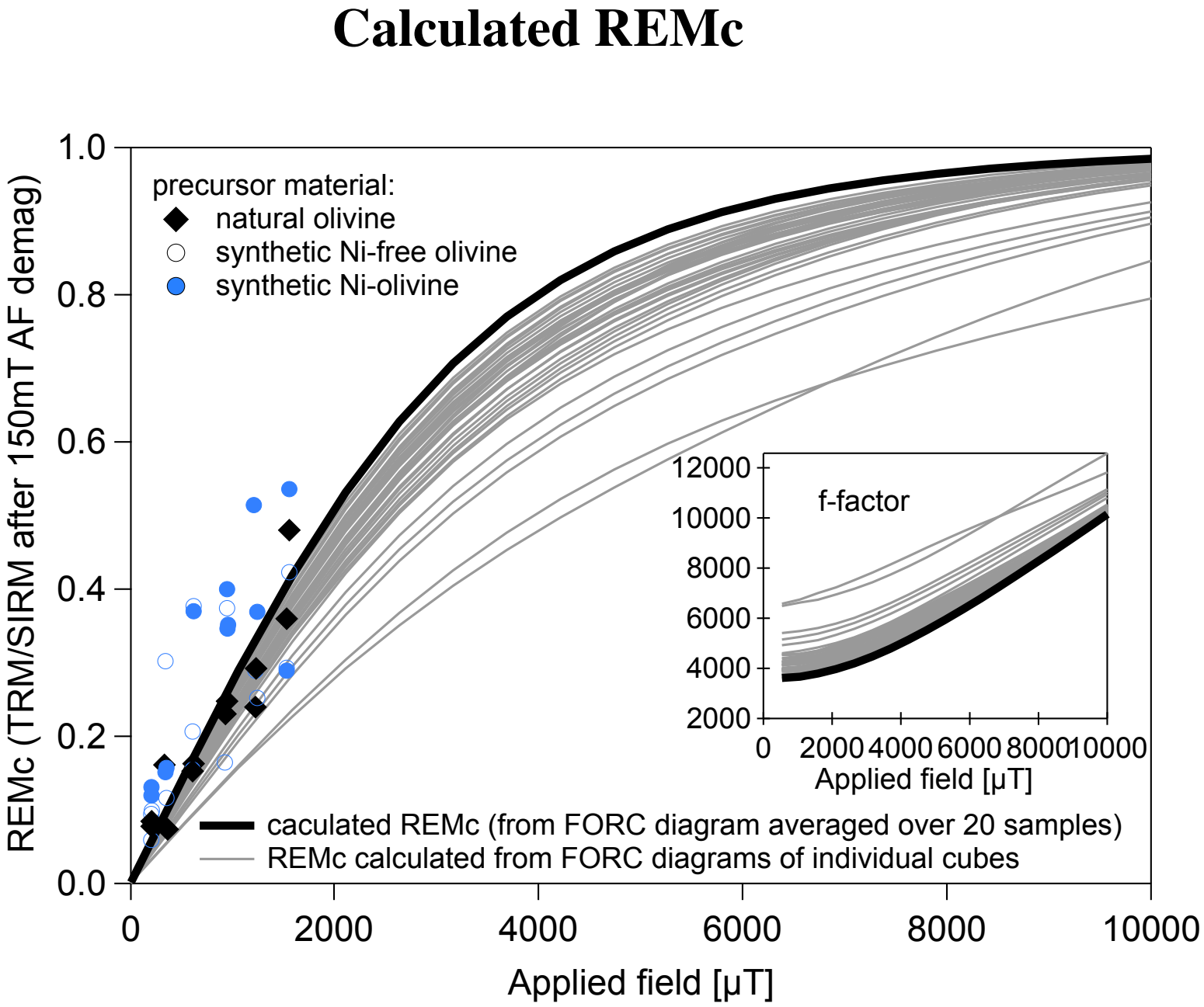
FORC diagrams of samples made from synthetic olivine generally show higher amount of particles in vortex states.

FORC method works best for samples made from natural olivine, which are more SD dominated, at high demagnetisation fields.

FORC method

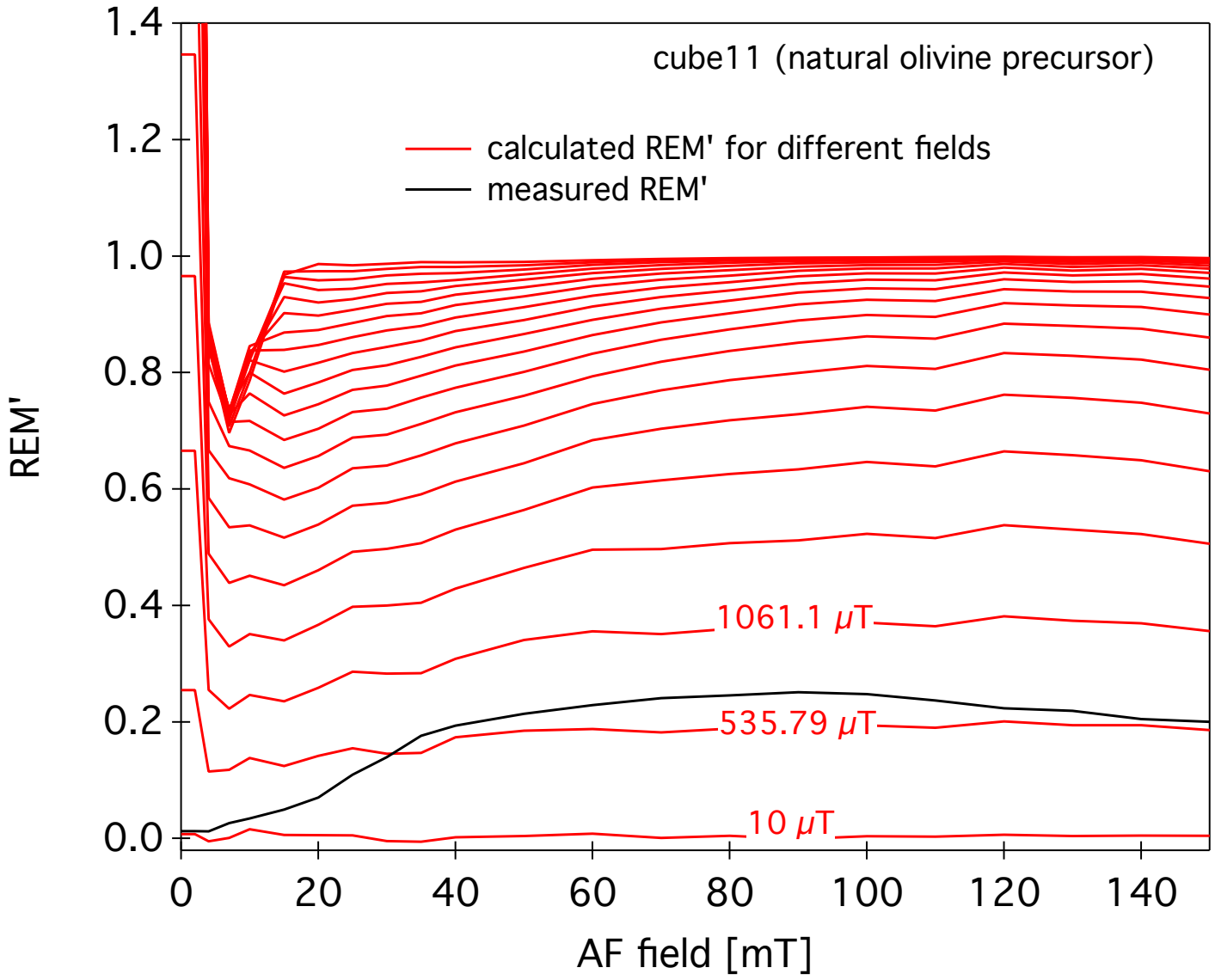

Calculated REM
precursor material:
natural olivine
synthetic Ni-free olivine
synthetic Ni-olivine
REM (TRM/SIRM)
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
Applied field [μT]
f-factor
8000
6000
4000
2000
0
2000 4000 6000 8000 10000
Applied field [μT]
calculated REM (from FORC diagram averaged over 20 samples)
REM calculated from FORC diagrams of individual cubes

FORC method


Calculated REMc
REMc (TRM/SIRM after 150mT AF demag)
1.0
0.8
0.6
0.4
0.2
0.0
precursor material:
natural olivine
synthetic Ni-free olivine
synthetic Ni-olivine
f-factor
12000
10000
8000
6000
4000
2000
0
2000
4000
6000
8000
10000
Applied field [μT]
caculated REMc (from FORC diagram averaged over 20 samples)
REMc calculated from FORC diagrams of individual cubes
0
2000
4000
6000
8000
10000
Applied field [μT]

FORC method

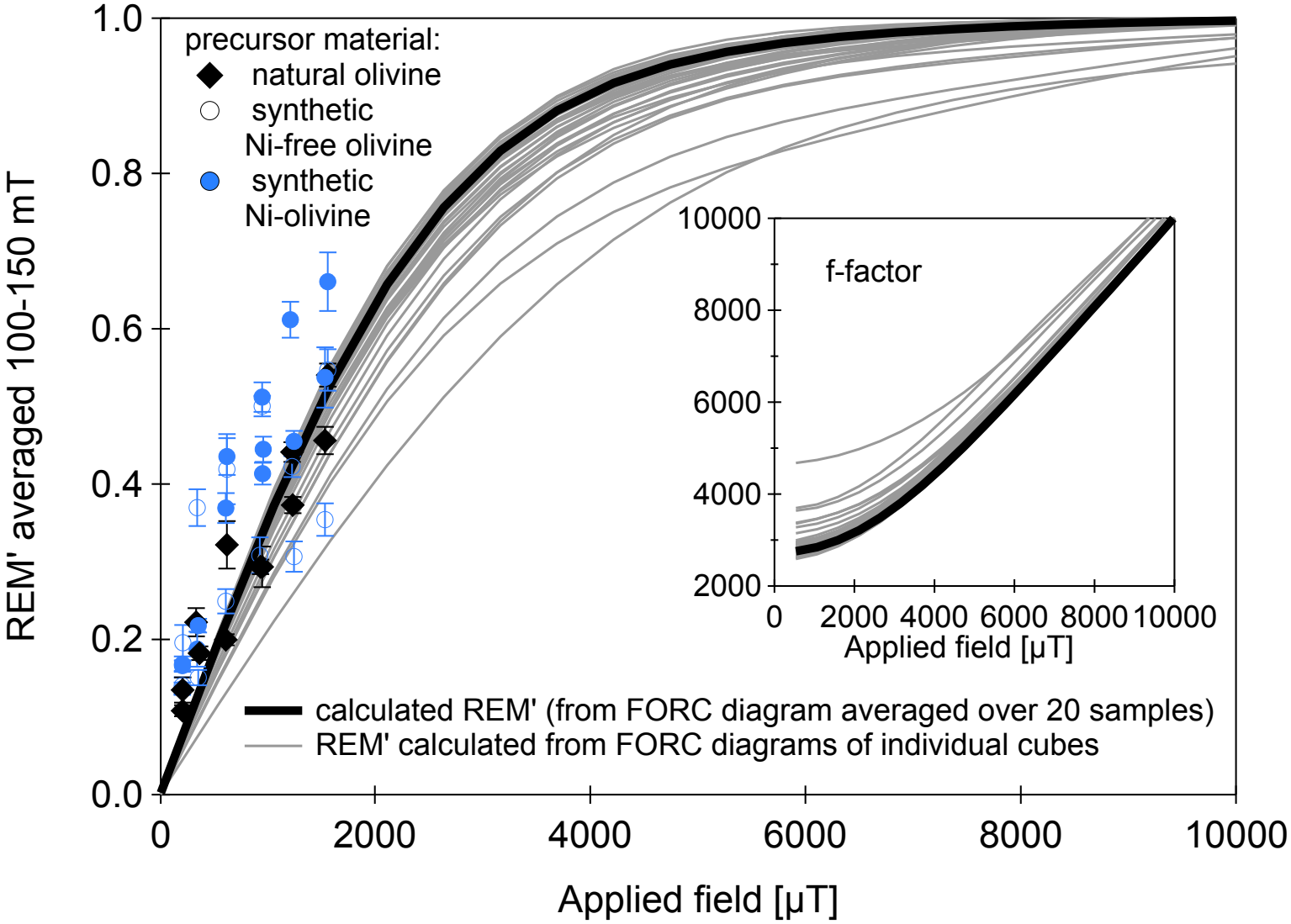
Calculated REM'



Actual field for this sample: 337 μT

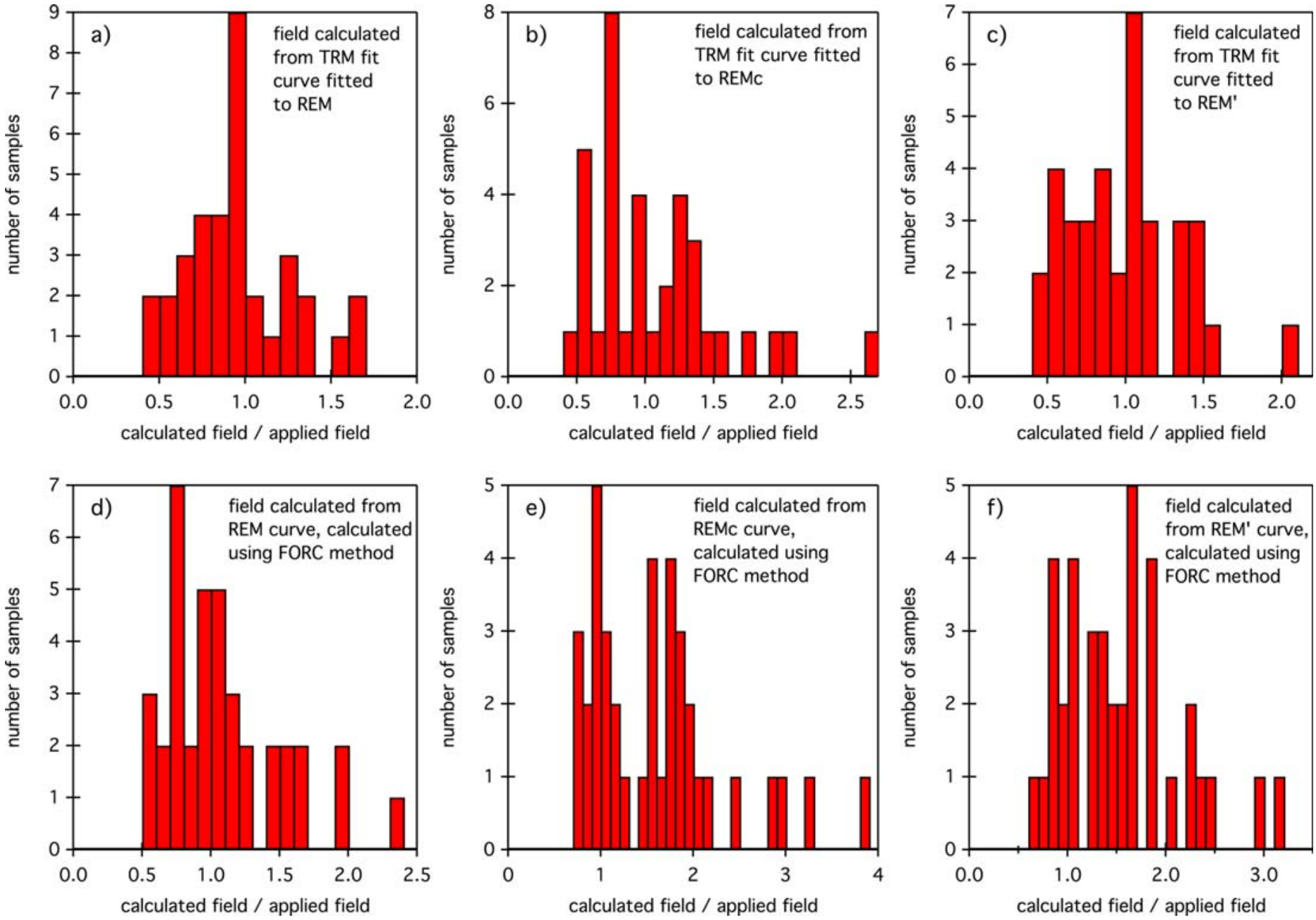
FORC method

Calculated REM’



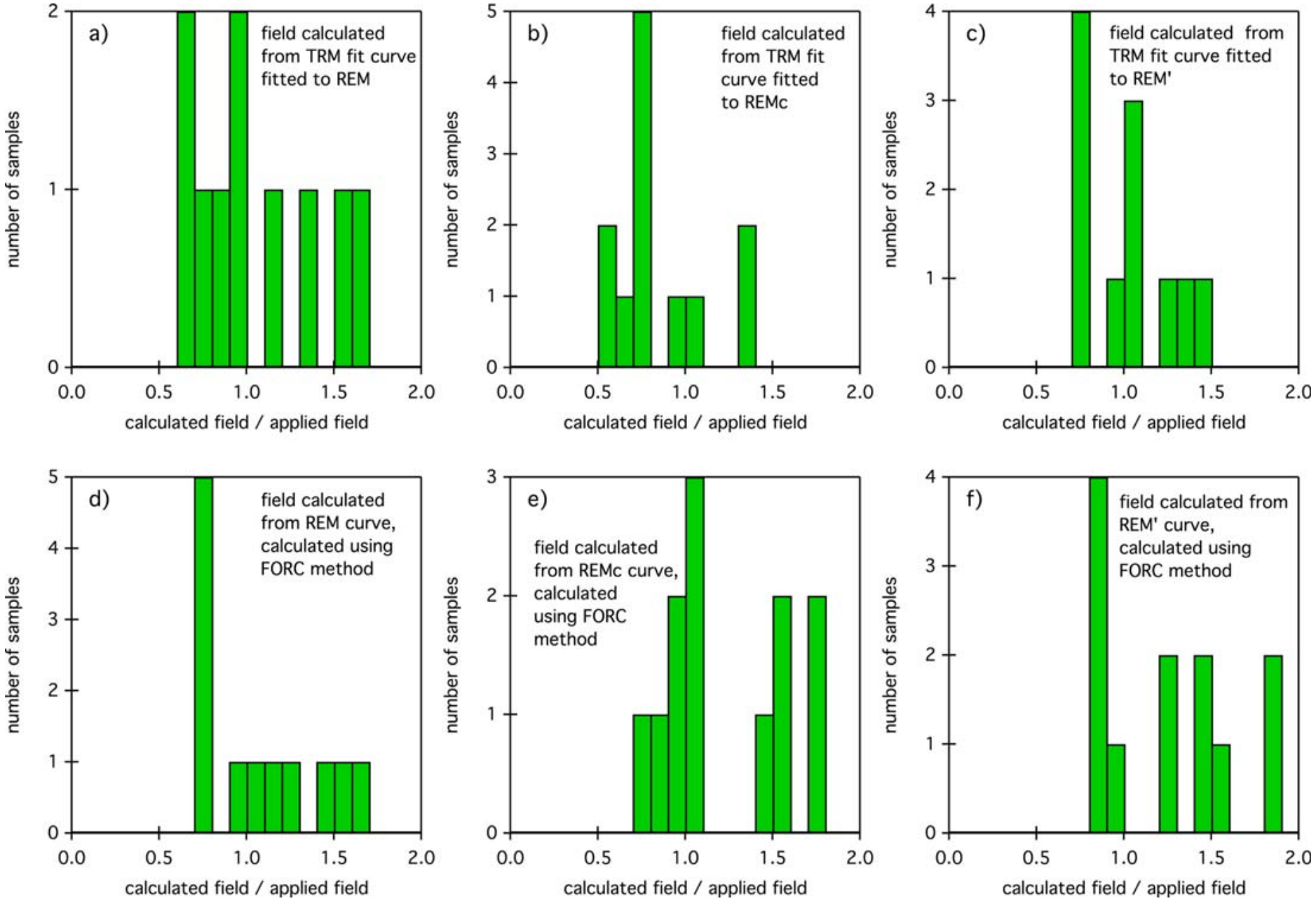
Rock-magnetic measurements

Normalized Paleofield Estimates

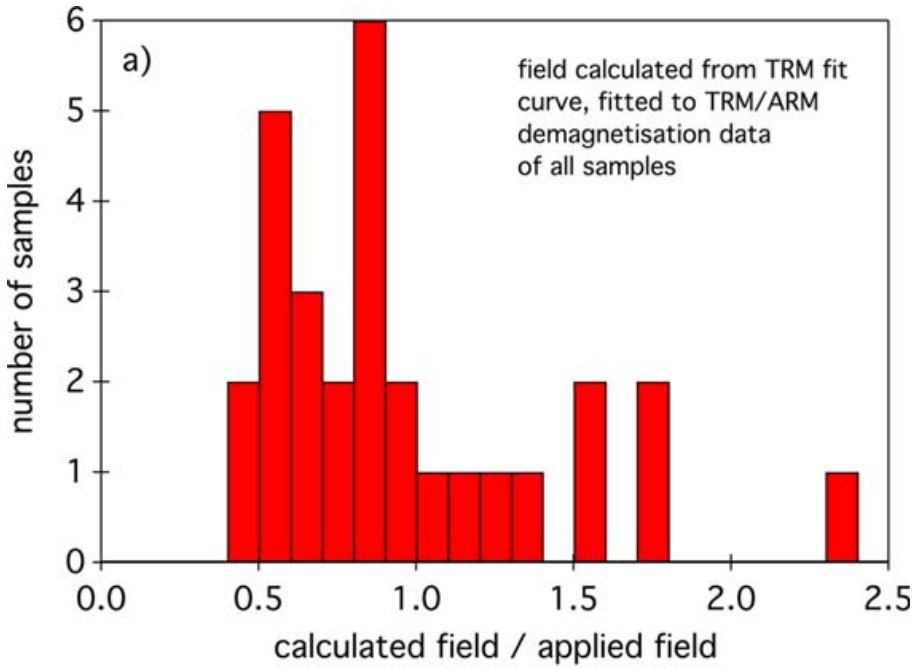


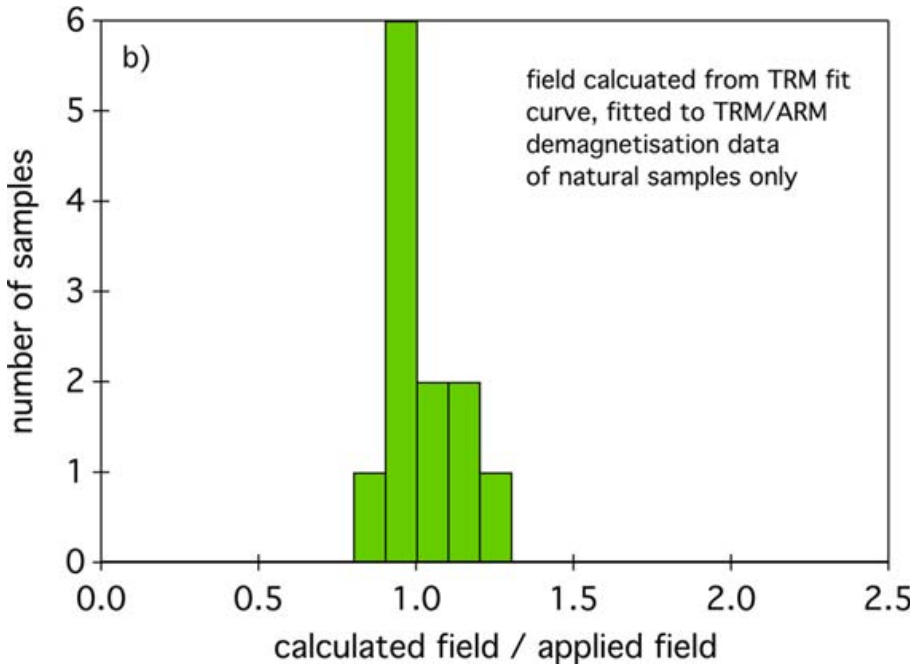
Rock-magnetic measurements

Normalized Paleofield Estimates, natural olivine starting material



Rock-magnetic measurements





Normalized Paleofield Estimates ARM method

For samples made from natural olivine starting material (i.e. samples dominated by SD particles) the recovered field estimates are within ±30% of the actual field values

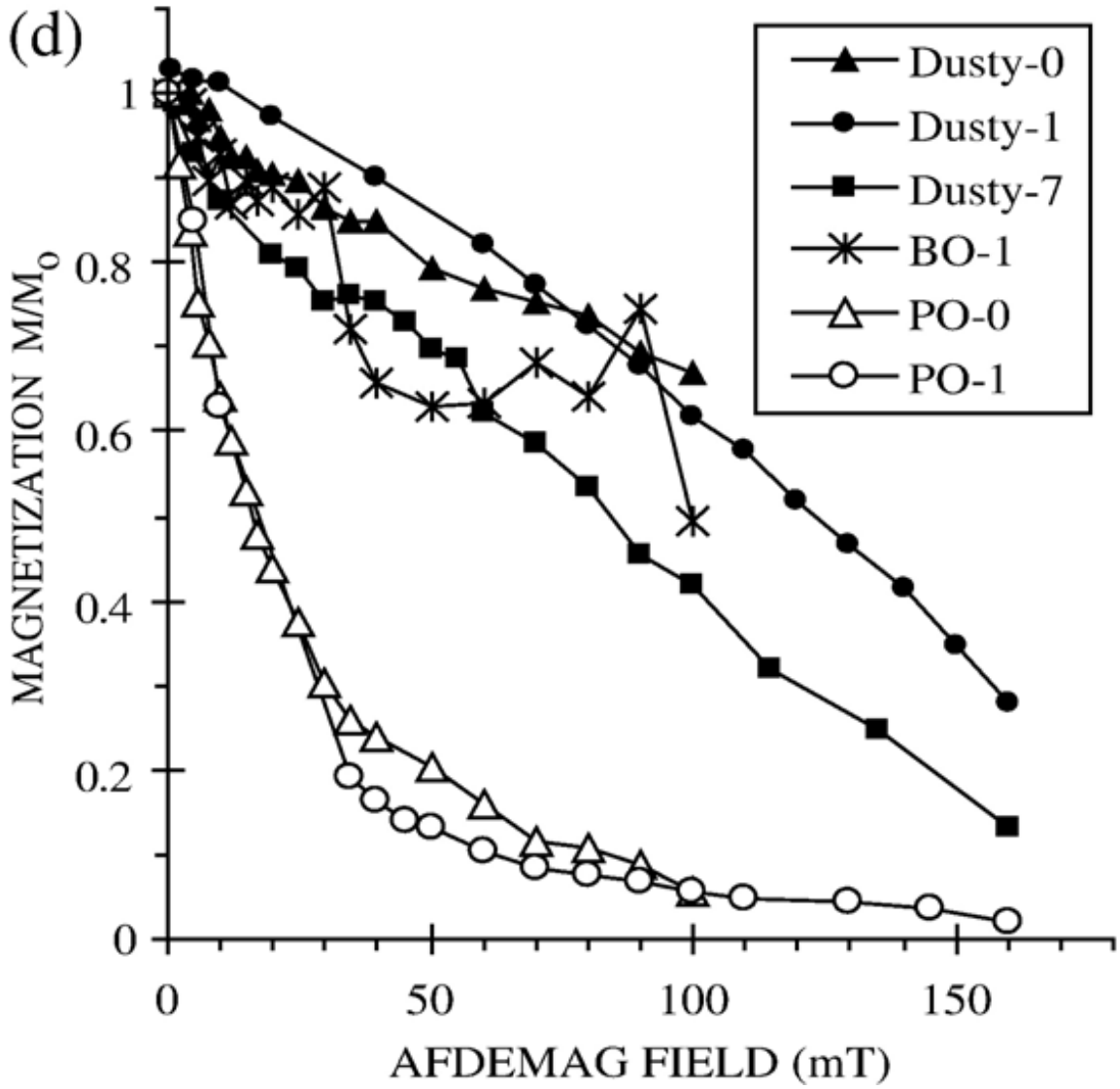
Conclusions

- SIRM > saturation TRM due to transformation of SV to metastable SD states → 'over normalization' of TRM by SIRM in REM method
- Over normalization reduced in REMc and REM' method as more of SD component of remanence is isolated
- Data scatter due to variable amounts of SV versus SD particles
- ARM provides closer analogue to TRM than SIRM → ARM normalization of high-coercivity remanence gives best results
- FORC method works well for SD dominated samples, fails for samples with large amounts of SV remanence carriers

THANK YOU!!

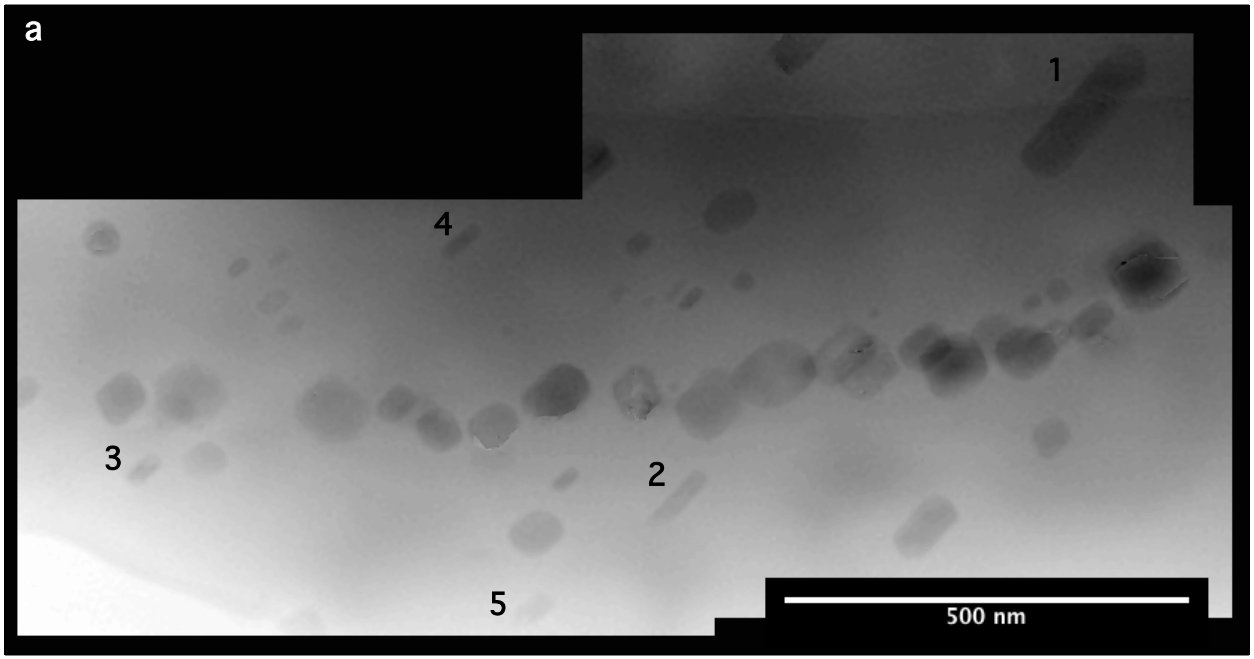
Additional Slides

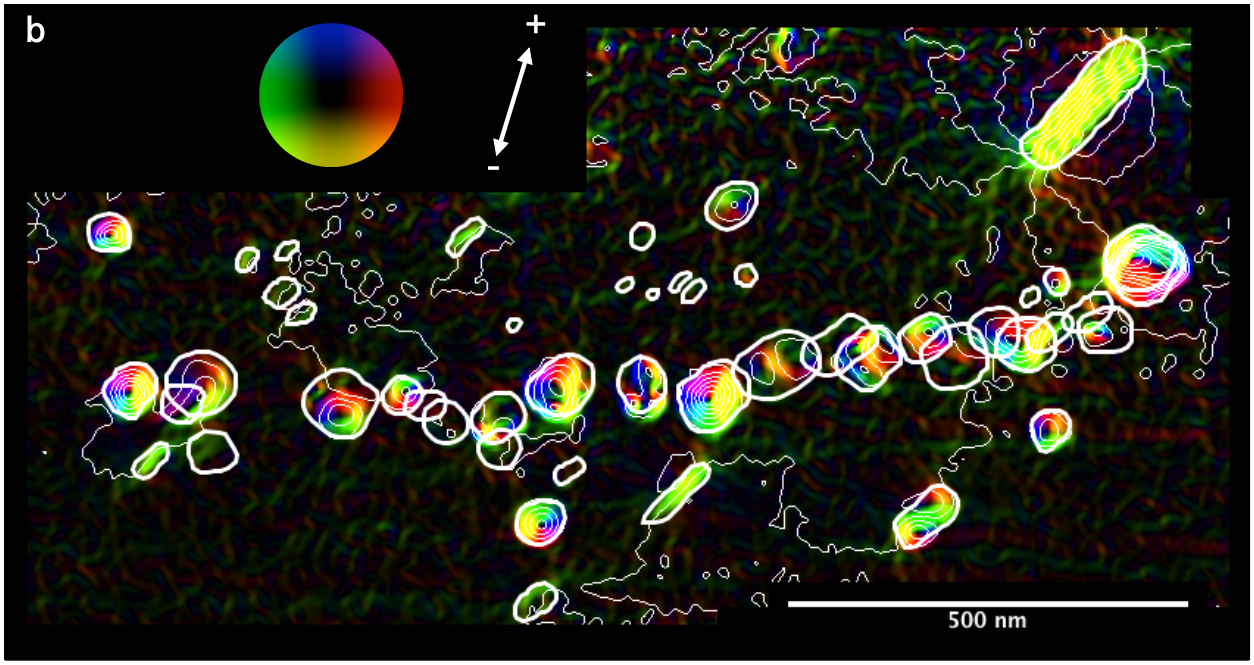
Motivation



Uehara, M., and N. Nakamura (2006) **Experimental constraints on magnetic stability of chondrules and the paleomagnetic significance of dusty olivine.** *Earth Planet. Sci. Lett.* 250, 292-305, doi: 10.10161/j.epsl.2007.07.002.

Motivation



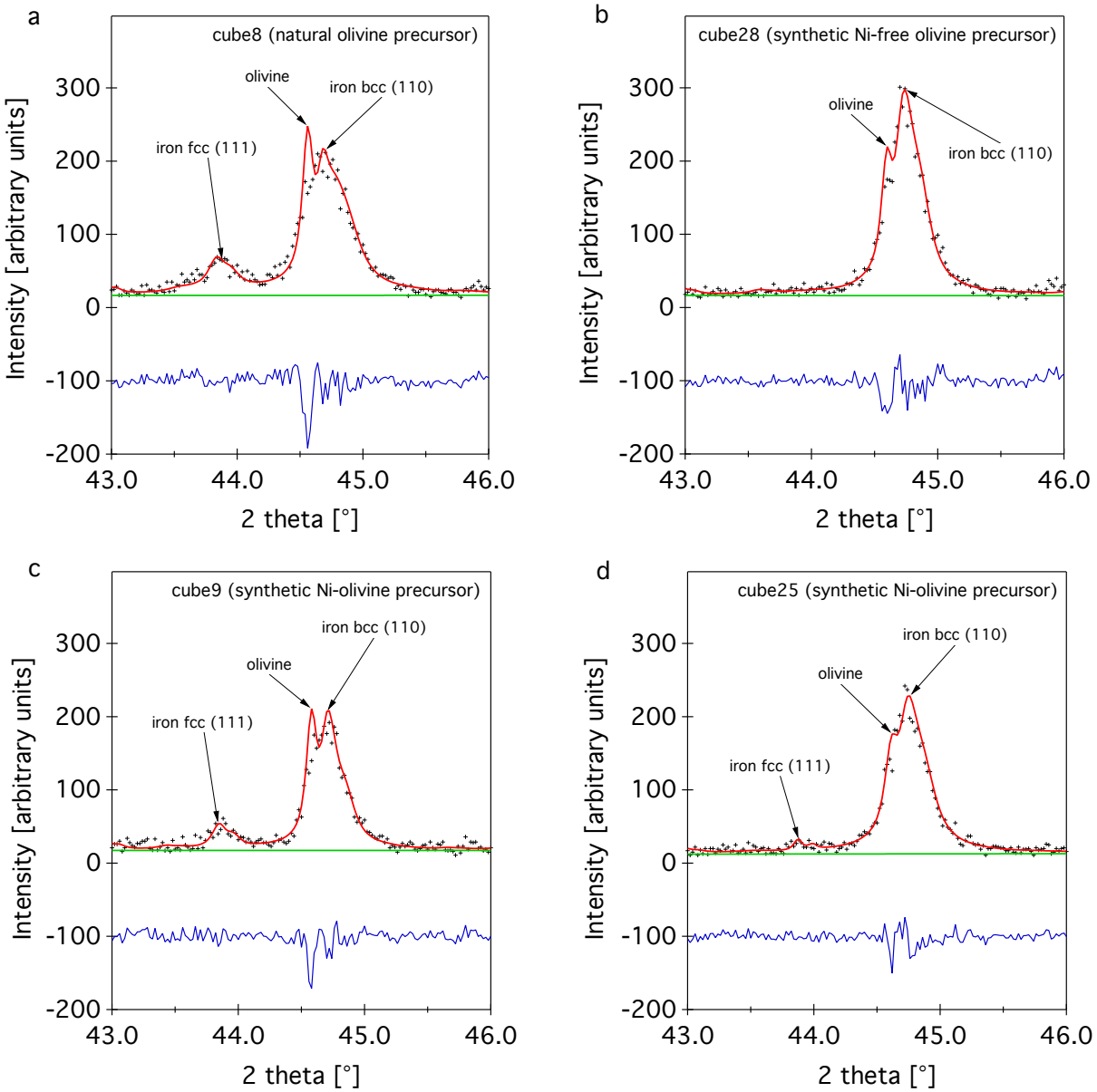


Synthetic dusty olivine

Lappe, S.-C. L. L., N. S. Church, T. Kasama, A. B. da Silva Fanta, G. Bromiley, R. E. Dunin-Borkowski, J. M. Feinberg, S. Russell, and R. J. Harrison (2011), **Mineral magnetism of dusty olivine: A credible recorder of pre-accretionary remanence**, *Geochem. Geophys. Geosyst.*, 12, Q12Z35, doi:10.1029/2011GC003811.

Sample characterisation

X-ray Powder Diffraction



- all samples contain body-centred cubic (bcc) iron
- varying amounts of additional face-centred cubic (fcc) iron

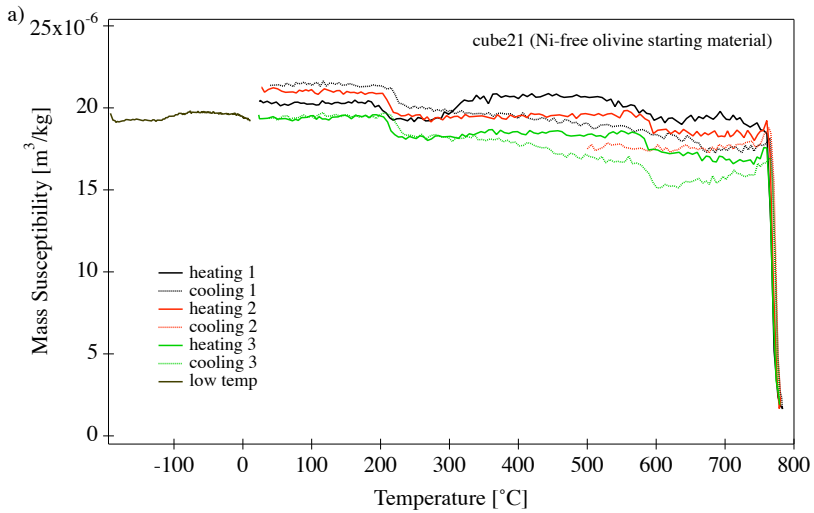
Sample characterisation

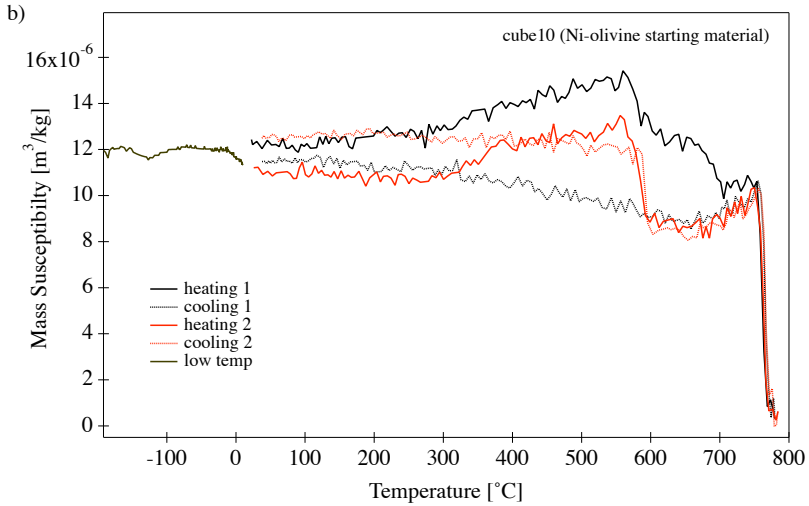
X-ray Powder Diffraction

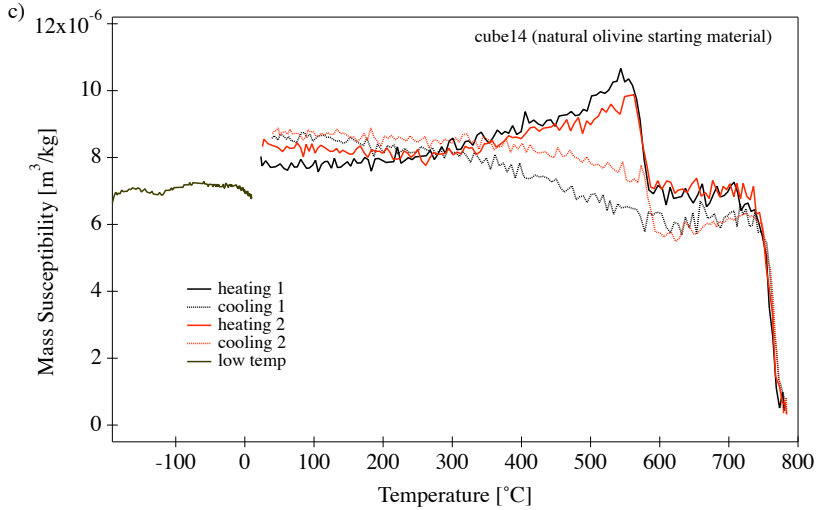
sample ID	starting material	coherently scattering domain size in bcc-iron [nm]	coherently scattering domain size in fcc-iron [nm]
cube8	natural olivine	42 ± 4	76 ± 25
cube28	synthetic Ni-free olivine	61 ± 4	NA
cube9	synthetic Ni-olivine	70 ± 11	116 ± 57
cube25	synthetic Ni-olivine	52 ± 4	NA

- coherently scattering domain sizes = estimate of grain sizes of Fe
- generally larger for samples made from synthetic olivine
- samples made from synthetic olivine show higher variability in coherently scattering domain sizes for different samples

Calibration method	**M[MAm²]**	**REMs**	**average *f* factor**	***f* factor range**
REM	0.0015(5)	0.36(7)	2850 μT	$1843 < f\ (\mu T) < 5038$
REMc	0.0010(2)	0.6(1)	2695 μT	$1877 < f\ (\mu T) < 4198$
REM’	0.0015(5)	0.6(1)	1604 μT	$1015 < f\ (\mu T) < 2926$
REM’ natural olivine only	0.0012(2)	0.60(7)	2119 μT	$1564 < f\ (\mu T) < 3044$
Calibration method	**M[MAm²]**	**dTRM/dARMs**	**average f_{ARM} at 0 field**	**f_{ARM} range at 0 field**
ARM	0.0015(2)	4.6(3)	1.86	$1.50 < f_{ARM} < 2.26$
ARM natural olivine only	0.0014(1)	3.3(1)	1.21	$1.06 < f_{ARM} < 1.37$


a)
cube21 (Ni-free olivine starting material)
25x10-6
20
15
10
5
0
Mass Susceptibility [m3/kg]
heating 1
cooling 1
heating 2
cooling 2
heating 3
cooling 3
low temp
-100
0
100
200
300
400
500
600
700
800
Temperature [°C]


b)
cube10 (Ni-olivine starting material)
16x10-6
14
12
10
8
6
4
2
0
Mass Susceptibilty [m3/kg]
heating 1
cooling 1
heating 2
cooling 2
low temp
-100
0
100
200
300
400
500
600
700
800
Temperature [°C]


c)
cube14 (natural olivine starting material)
12x10-6
10
8
6
4
2
0
Mass Susceptibility [m3/kg]
heating 1
cooling 1
heating 2
cooling 2
low temp
-100
0
100
200
300
400
500
600
700
800
Temperature [°C]