Anisotropy of Magnetic Remanence: Empirical Guidelines Towards an Efficient Acquisition Protocol

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ADVANCED
GEOSCIENCE
INSTRUMENTS
COMPANY

Institute of Geology of the CAS, v. v. i.

1. Theoretical background for AMR

2. Instruments and data acquisition techniques

3. Empirical guidelines demonstrated on test samples

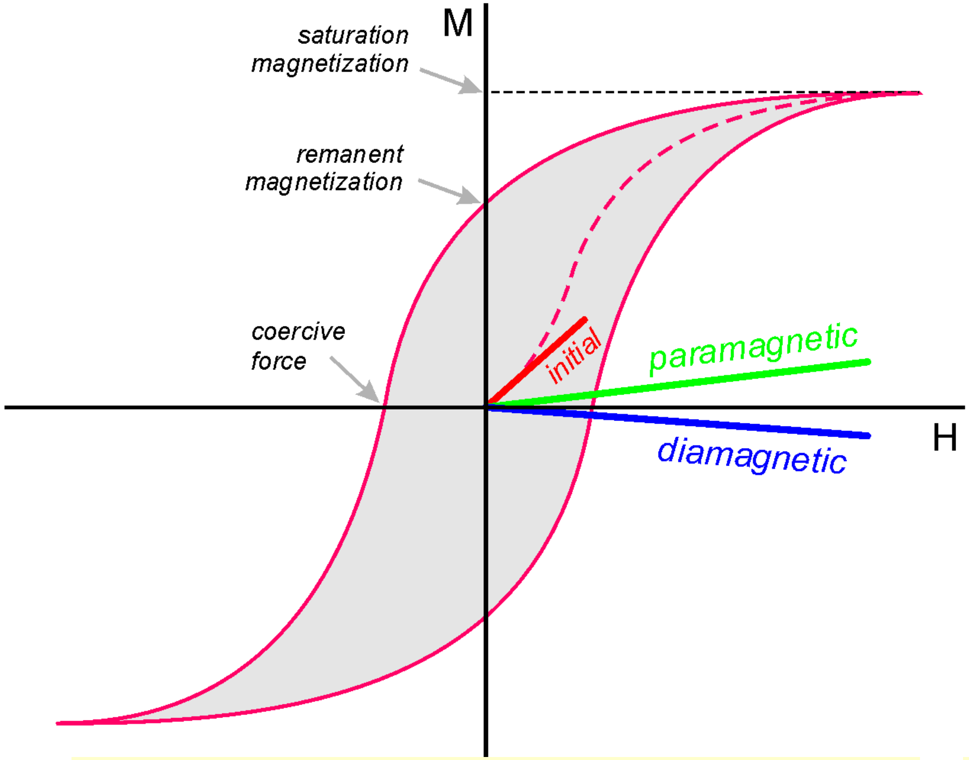
Introduction

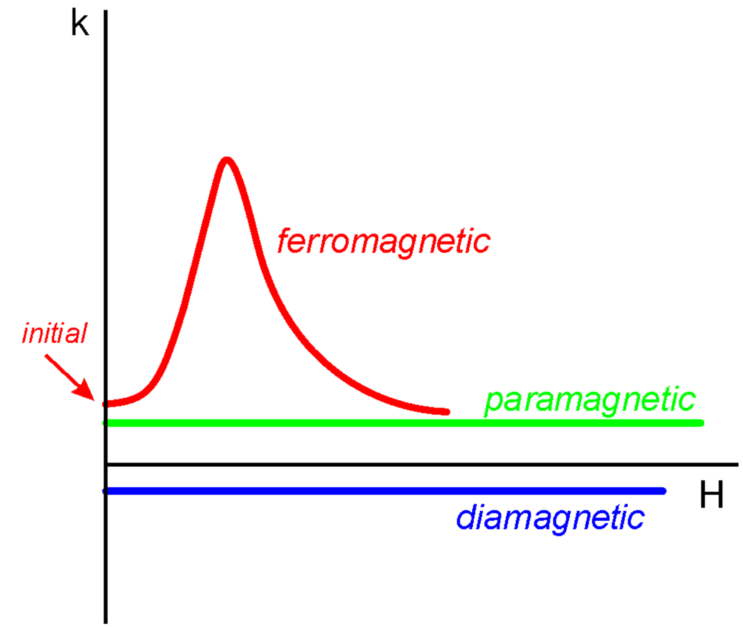
- Rocks and sediments display a magnetic anisotropy when constituent mineral grains have a preferred orientation.
- Magnetic fabric is usually described by the **anisotropy of magnetic susceptibility (AMS)**. As all minerals in a rock or sediment (diamagnetic, paramagnetic, ferromagnetic /sensu lato/) contribute to the susceptibility; the observed anisotropy is the sum of the individual mineral components, their specific susceptibility anisotropy and their preferred alignment.
- The **anisotropy of magnetic remanence (AMR)** is only dependent on the ferromagnetic grains (s.l.) in a rock. Since the number of different ferromagnetic phases is more limited, the source of the AMR is easier to distinguish, and the degree of anisotropy is less sensitive to mineral variation.

Application

- Tool to study rock texture (Petrofabric)
- Compared to the other methods of fabric analysis (U-stage, X-ray texture goniometry, neutron texture goniometry, EBSD), AMS is fast, cheap, high-resolution, non-destructive.
- It can be applied to many samples covering whole outcrops, drill cores, or geological units.
- Application in structural geology and tectonics, volcanology, sedimentology, and paleomagnetism.

Hysteresis loop





$$\mathbf{M} = \mathbf{M_i} + \mathbf{M_r}$$

Induced magnetization ($\mathbf{M_i}$)

Remanent magnetization ($\mathbf{M_r}$)

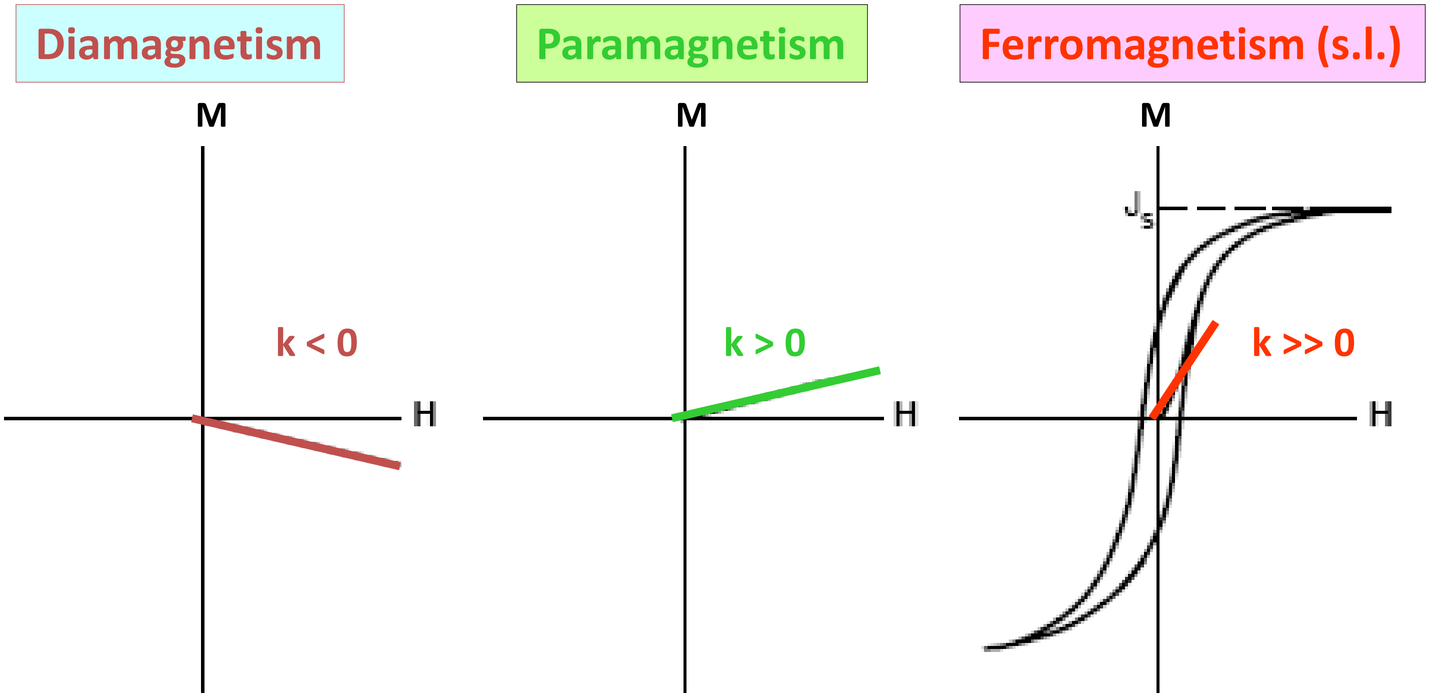
$$\mathbf{M_i} = k \times \mathbf{H}$$

Magnetic susceptibility (k)

$$\mathbf{M_r} = k_r \times \mathbf{H}$$

Remanent susceptiblity (k_r)

Susceptibility vs. Remanence

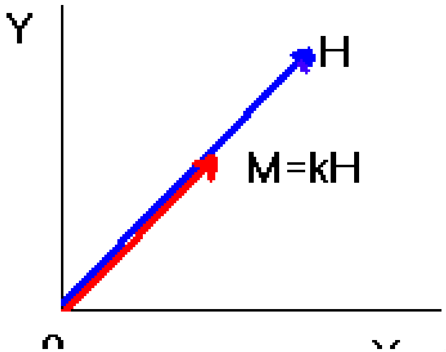


Induced magnetization antiparallel to the external field	Induced magnetization parallel to the external field	Complex relationship between external field and induced magnetization: hysteresis curve
Magnetic susceptibility relatively **low** and **negative**	Magnetic susceptibility relatively **low** and **positive**	Magnetic susceptibiliy relatively **high**
No remanence	**No remanence**	**Remanent magnetization**
quartz *calcite* *aragonite*	*pyroxene* *hornblende* *olivine* *micas*	*iron* *(titano-) magnetite* *pyrrhotite* *hematite*

Tensor notation of AMR (or AMS)

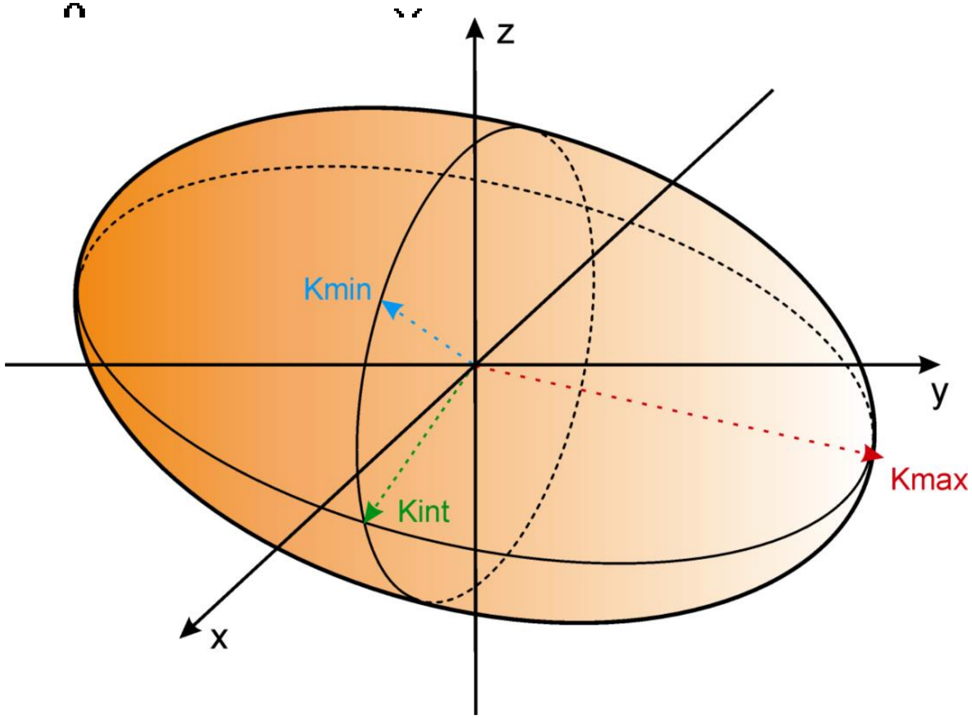
Magnetically isotropic material

$$M_{r1} = k_r H_1$$
$$M_{r2} = k_r H_2$$
$$M_{r3} = k_r H_3$$



Magnetization of anisotropic materials

$$M_{r1} = k_{r11} H_1 + k_{r12} H_2 + k_{r13} H_3$$
$$M_{r2} = k_{r21} H_1 + k_{r22} H_2 + k_{r23} H_3$$
$$M_{r3} = k_{r31} H_1 + k_{r32} H_2 + k_{r33} H_3$$



Matrix notation

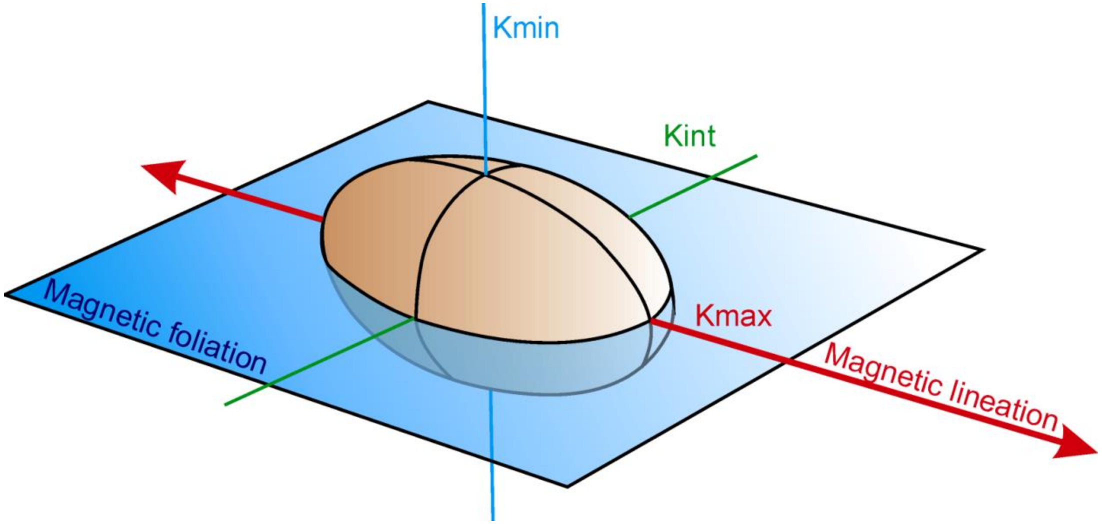
$$\begin{vmatrix} M_{r1} \\ M_{r2} \\ M_{r3} \end{vmatrix} = \begin{vmatrix} k_{r11} & k_{r12} & k_{r13} \\ k_{r21} & k_{r22} & k_{r23} \\ k_{r31} & k_{r32} & k_{r33} \end{vmatrix} \begin{vmatrix} H_1 \\ H_2 \\ H_3 \end{vmatrix}$$

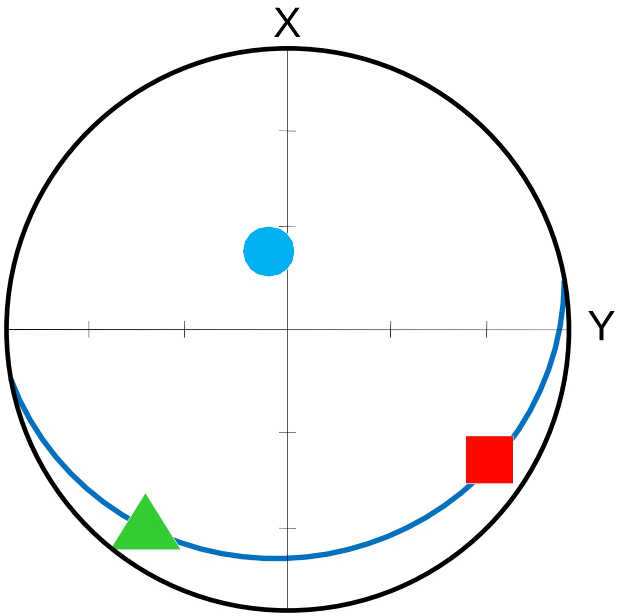
Vector of magnetization

Remanebility tensor

Vector of field intensity

Concept of magnetic fabric





Principal remanebilities

$$k_1 \geq k_2 \geq k_3$$

Mean remanebility

$$k_m = (k_1 + k_2 + k_3) / 3$$

Degree of anisotropy

$$P = k_1 / k_3$$

Shape parameter

$$T = (2\eta_2 - \eta_1 - \eta_3) / (\eta_1 - \eta_3)$$

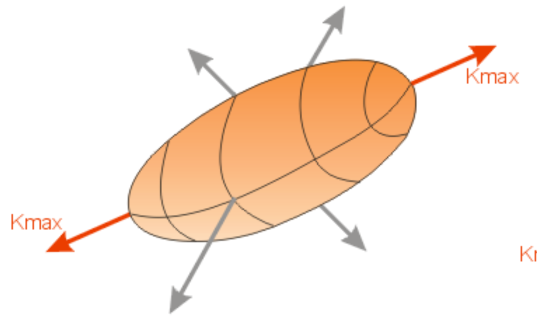
where $\eta_1 = \ln k_1$, $\eta_2 = \ln k_2$, $\eta_3 = \ln k_3$

$+1 > T > 0$ oblate (planar) fabric

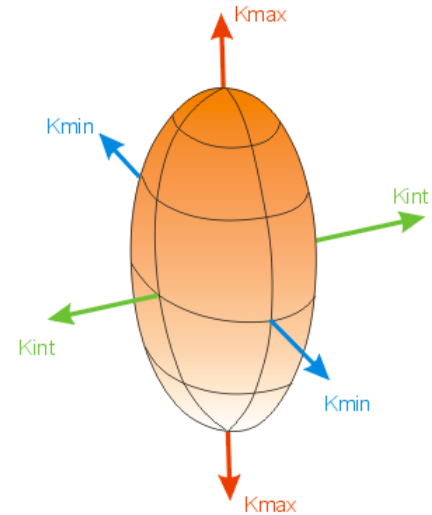
$-1 < T < 0$ prolate (linear) fabric

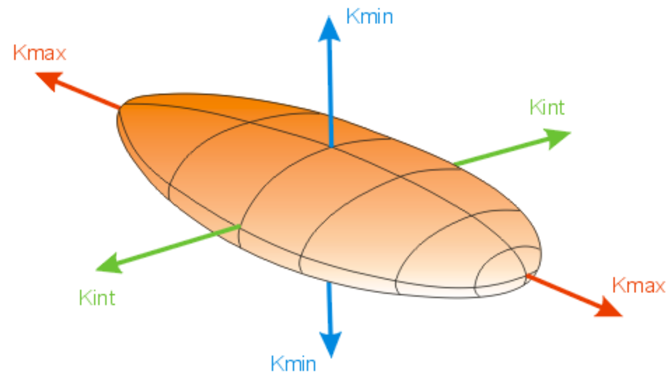
Shapes of fabric ellipsoids

Rotational prolate

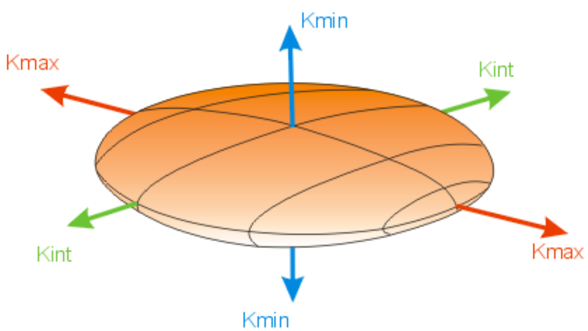


Triaxial prolate

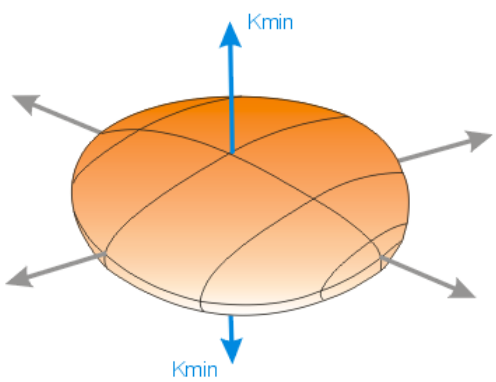




Neutral

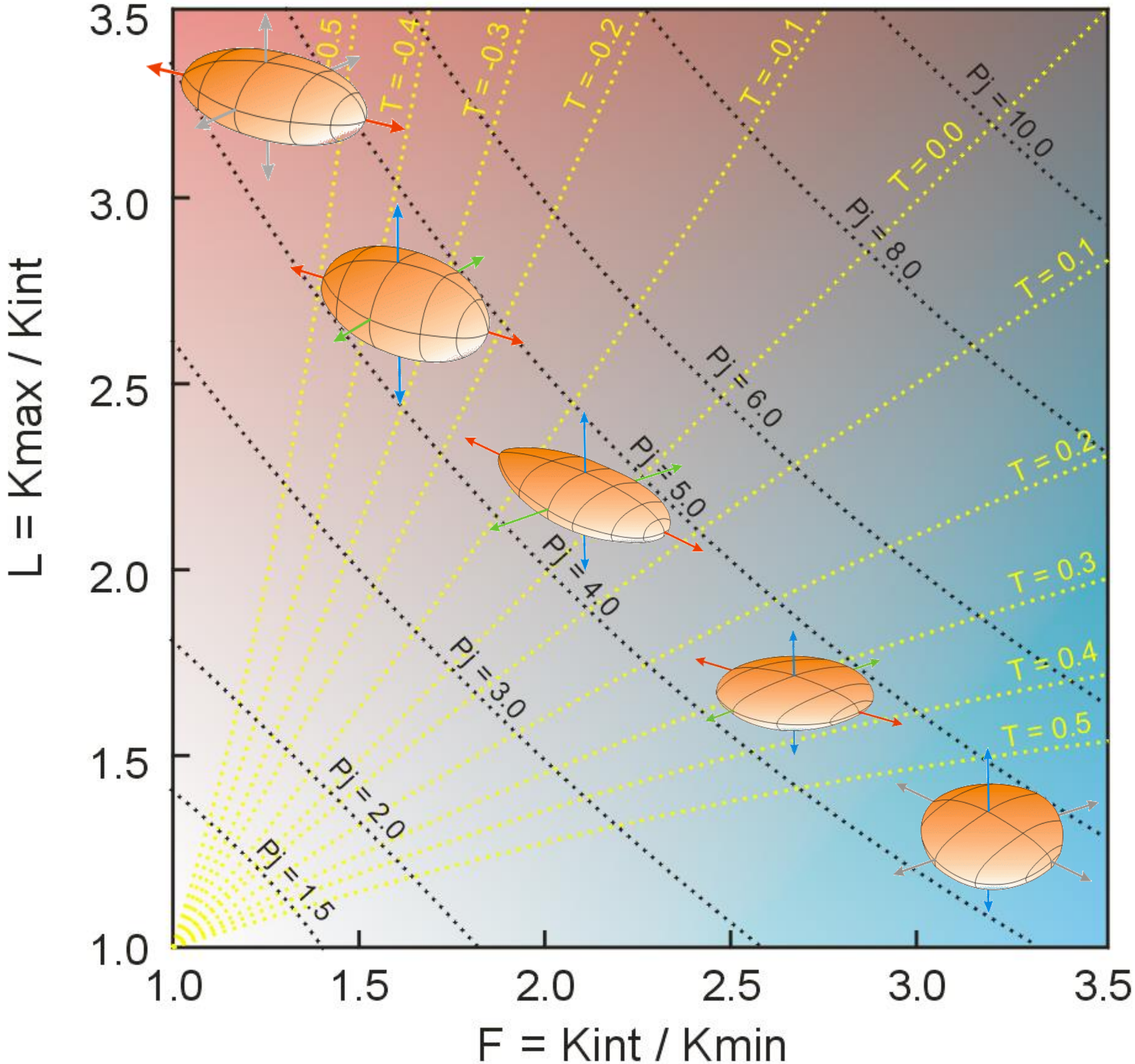


Triaxial oblate

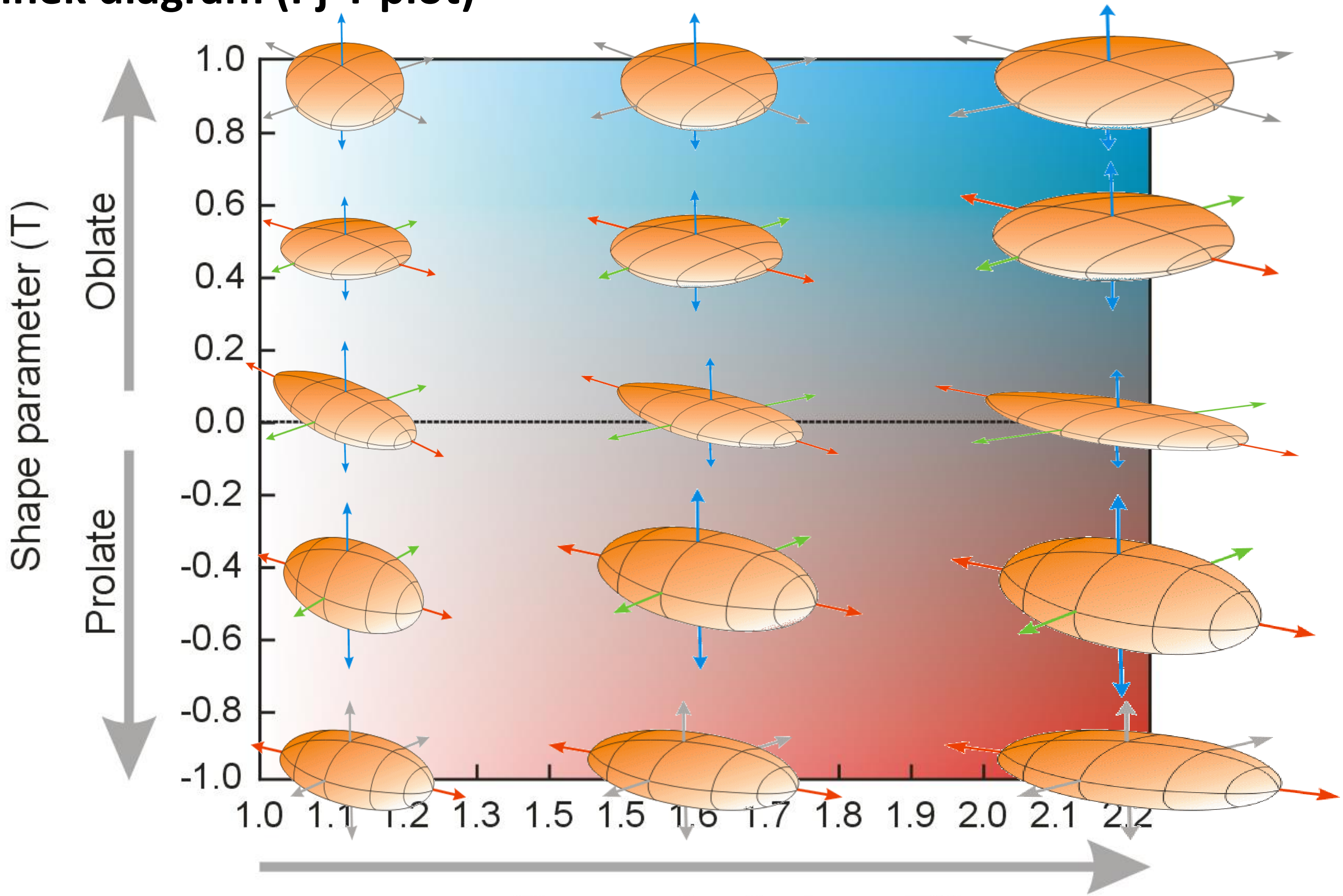


Rotational oblate

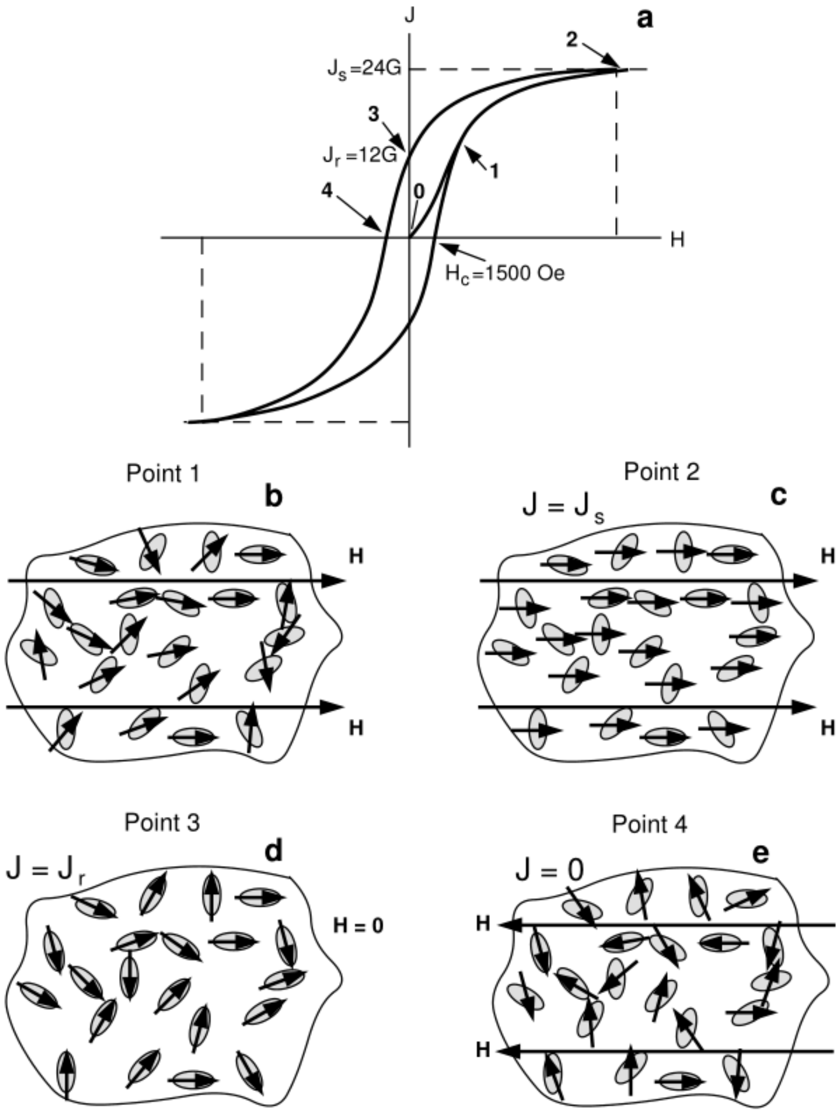
Flinn diagram (L-F plot)

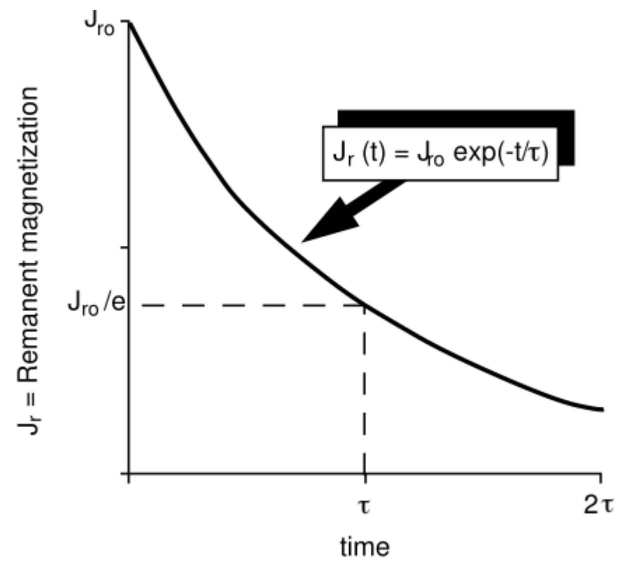


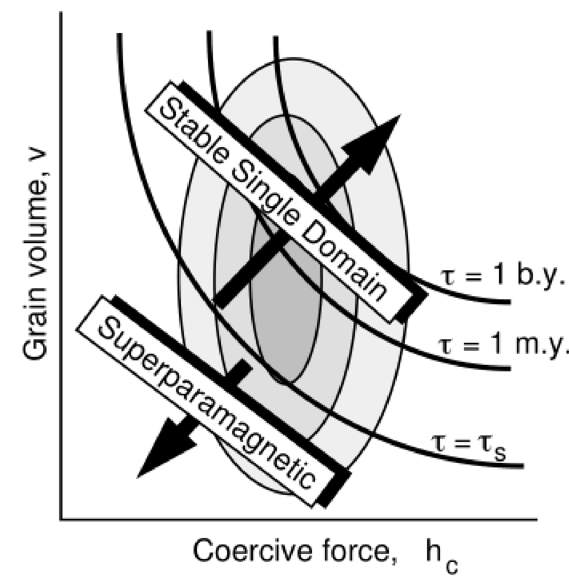
Jelinek diagram (Pj-T plot)



Acquisition of isothermal remanence





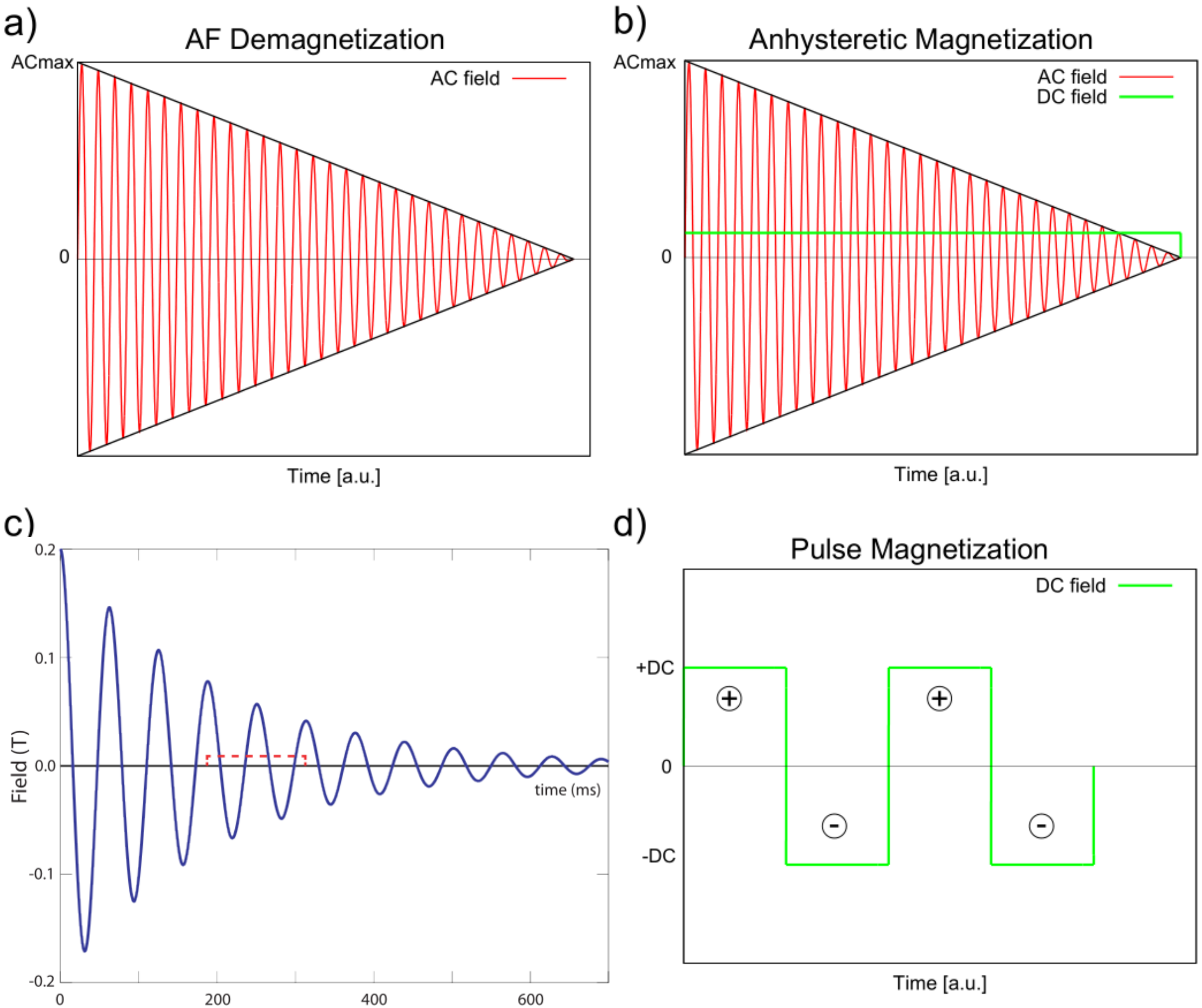


Butler 1992

Types of anisotropy of magnetic remanence (AMR)

- Anisotropy of Anhysteretic Remanent Magnetization (AARM)
  - Anisotropy of partial ARM (ApARM)
- Anisotropy of Isothermal Remanent Magnetization (AIRM)
  - low field IRM
  - high field IRM or saturation IRM (SIRM)
- Anisotropy of Thermal Remanent Magnetization (ATRM)
  - Anisotropy of partial TRM (ApTRM)

Acquisition of ARM (pARM) and IRM



Application of AMR

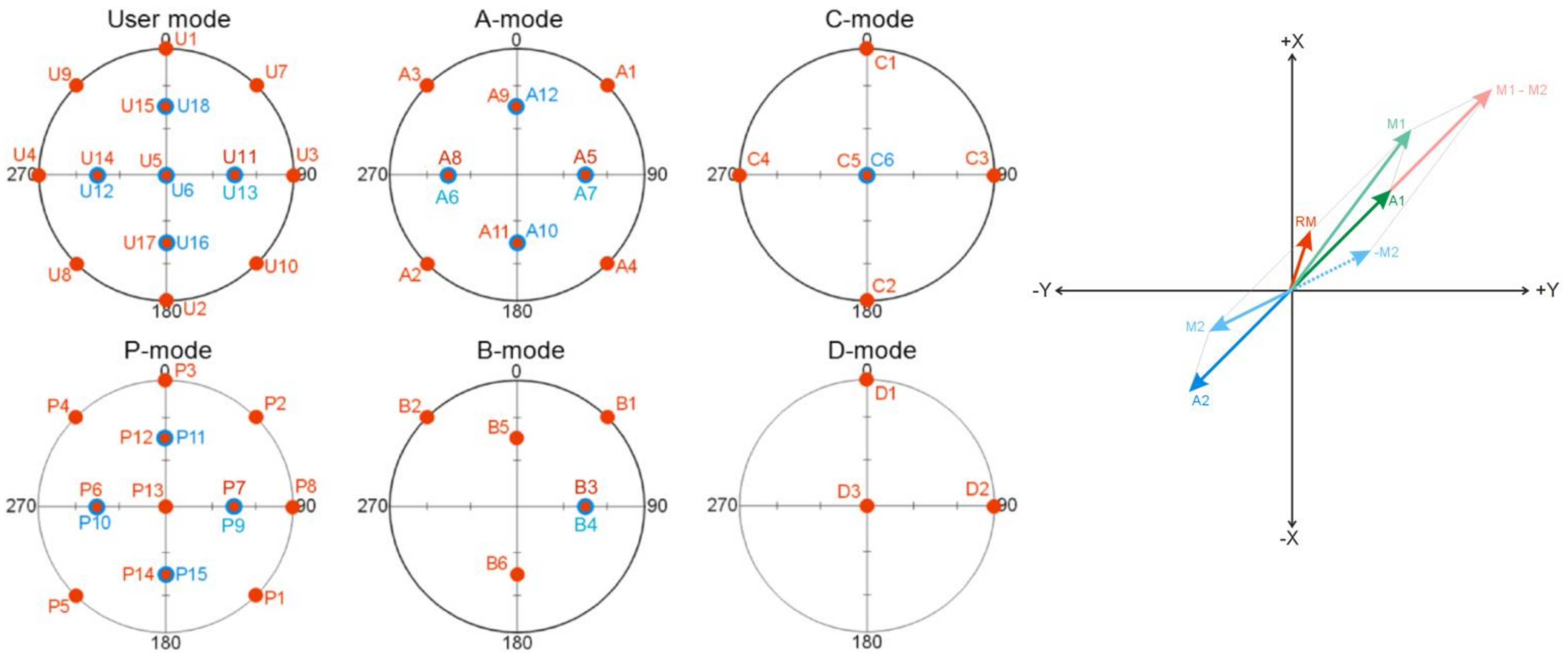
- Preferential orientation of ferromagnetic (remanence-carrying) minerals
- Coaxial and non-coaxial fabrics
- Timing of mineral formation
- Change is strain field
- Deflection of paleomagnetic vectors
- Paleointensity
- Paleopole – plate reconstruction

Gilder, S.A., K. He, M. Wack, and J. Ježek (2019), Relative paleointensity estimates from magnetic anisotropy: Proof of concept, Earth and Planetary Science Letters, 519, 83-91

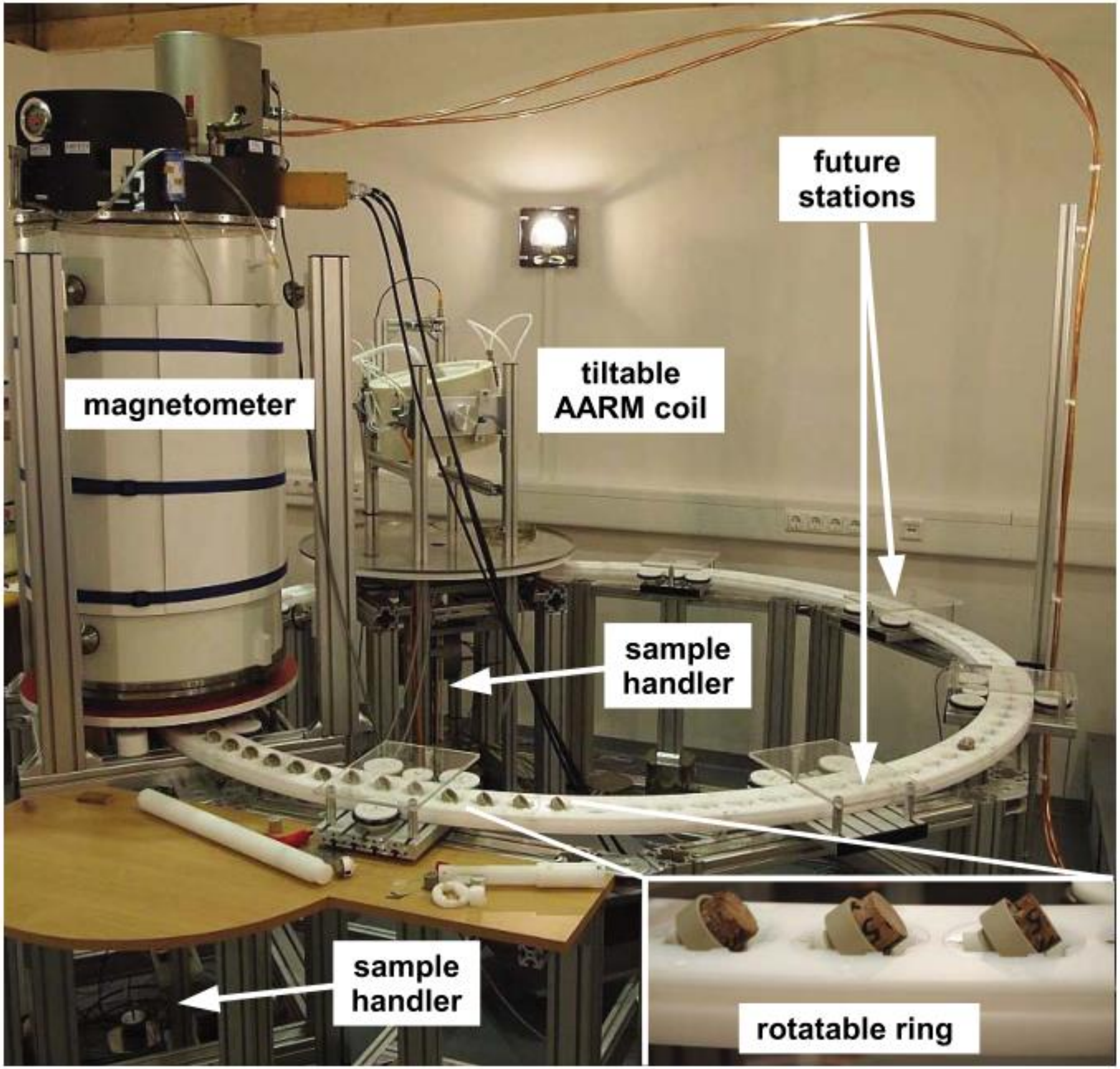
Pros & Cons (advantages & disadvantages)

- AARM: easy to apply and remove, but limited in coercivity range
- AIRM: useful for high coercivity minerals, but question about repeatability of acquired magnetization.
- ATRM: useful for low and high coercivity minerals, but rocks cannot produce new ferromagnetic phases with heating.

Directional schemes for AMR acquisition



SushiBar Munich



AGICO LDA5/PAM1 Magnetizer & JR-6(A) Magnetometer

- Both instruments controlled from one computer
- Timer starts when magnetization pulse terminates
- Repeated measurement of viscous decay of IRM

Specifications

LDA5

Specimen shape: cube: 20x20x20 mm
cylinder: 25.4 mm diameter
22 mm height

AF Demagnetizing Field: 1 to 200 mT

Power requirements: 230 V / 50 Hz, 400 VA
(optionally 120 V / 60 Hz)

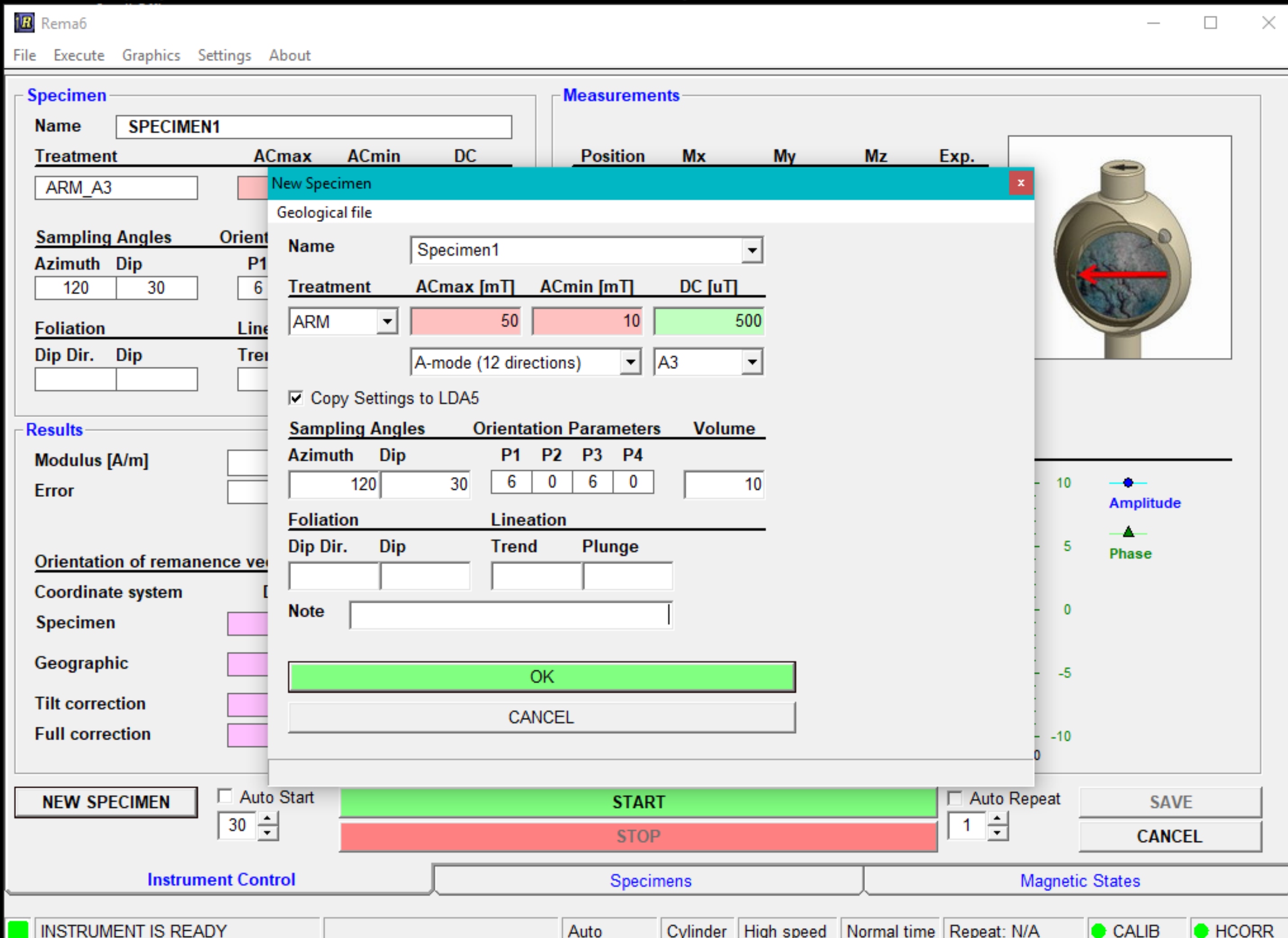
Dimensions, Mass:

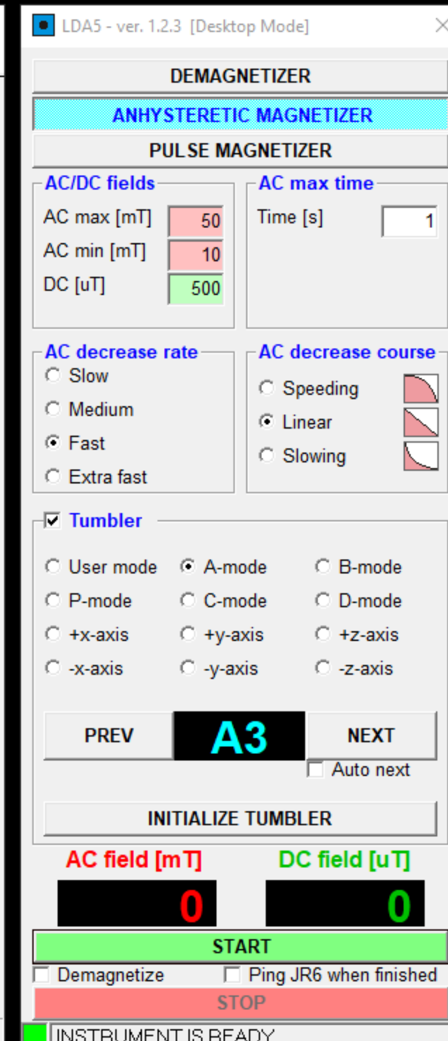
Specimen Unit: 110 x 39 x 46 cm, 95 kg
Electronic Unit: 47 x 38 x 17 cm, 30 kg

PAM1

Anhysteretic Magnetizer
Direct Magnetizing Field: 0 to 500 μT

Pulse Magnetizer
Direct Magnetizing Field: 0 to 20 mT
Length of Direct Field Pulses: 0.01 to 10 s





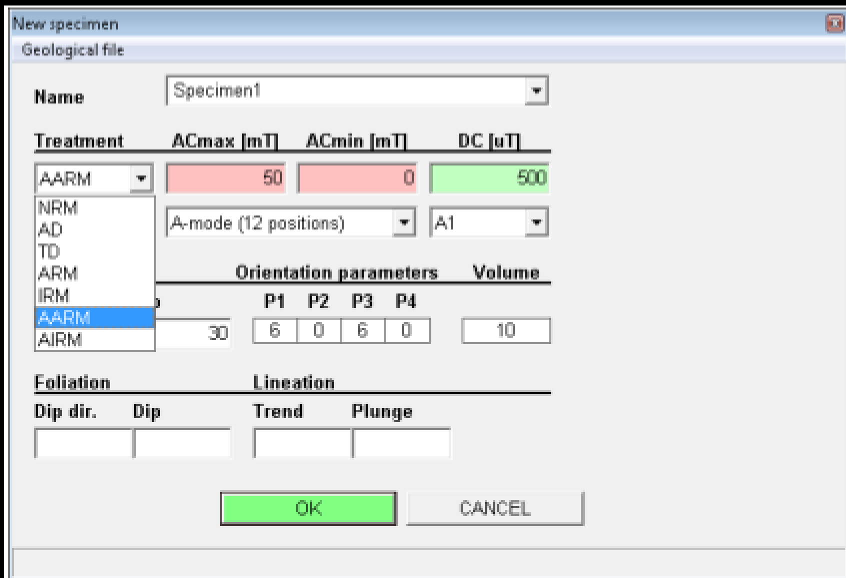
Rema6

Instrument control SW for JR-6(A)

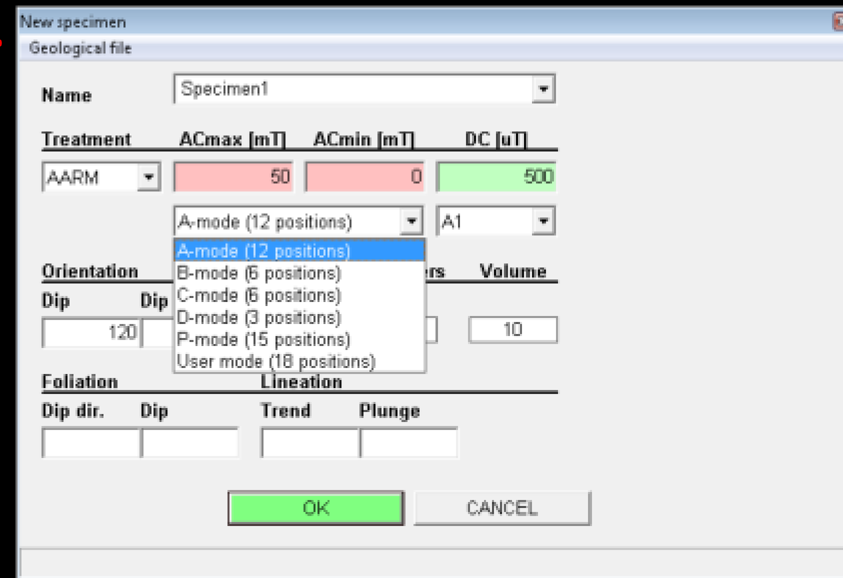
LDA5

Instrument control SW for LDA5

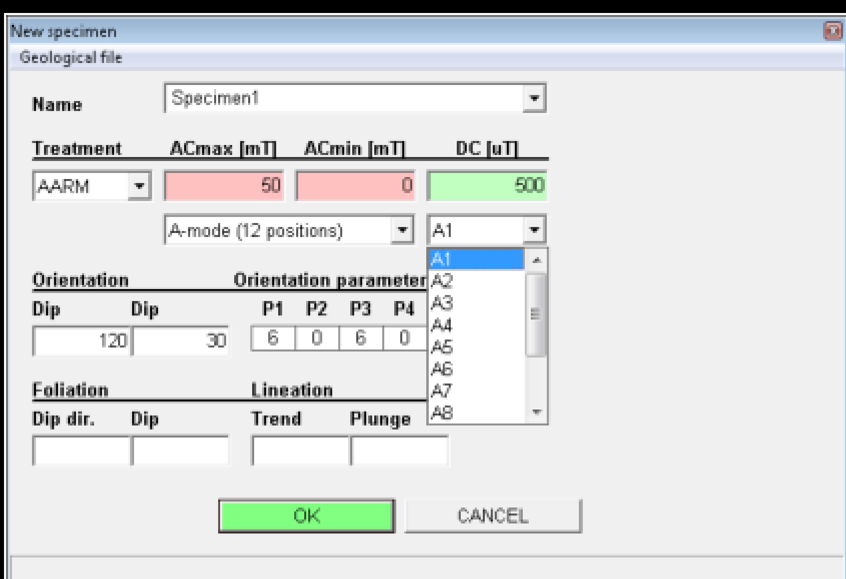
1.


New specimen
Geological file
Name
Specimen1
Treatment
ACmax [mT]
ACmin [mT]
DC [uT]
AARM
50
0
500
NRM
AD
TD
ARM
IRM
AARM
AIRM
A-mode (12 positions)
A1
Orientation parameters
Volume
P1
P2
P3
P4
30
6
0
6
0
10
Foliation
Lineation
Dip dir.
Dip
Trend
Plunge
OK
CANCEL

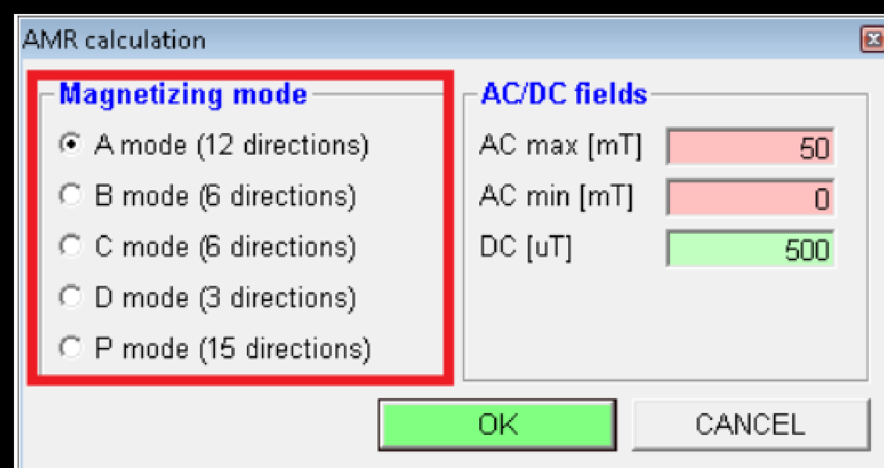
2.


New specimen
Geological file
Name
Specimen1
Treatment
ACmax [mT]
ACmin [mT]
DC [uT]
AARM
50
0
500
A-mode (12 positions)
A1
A-mode (12 positions)
B-mode (6 positions)
C-mode (6 positions)
D-mode (3 positions)
P-mode (15 positions)
User mode (18 positions)
Orientation
Volume
Dip
Dip
120
10
Foliation
Lineation
Dip dir.
Dip
Trend
Plunge
OK
CANCEL

3.

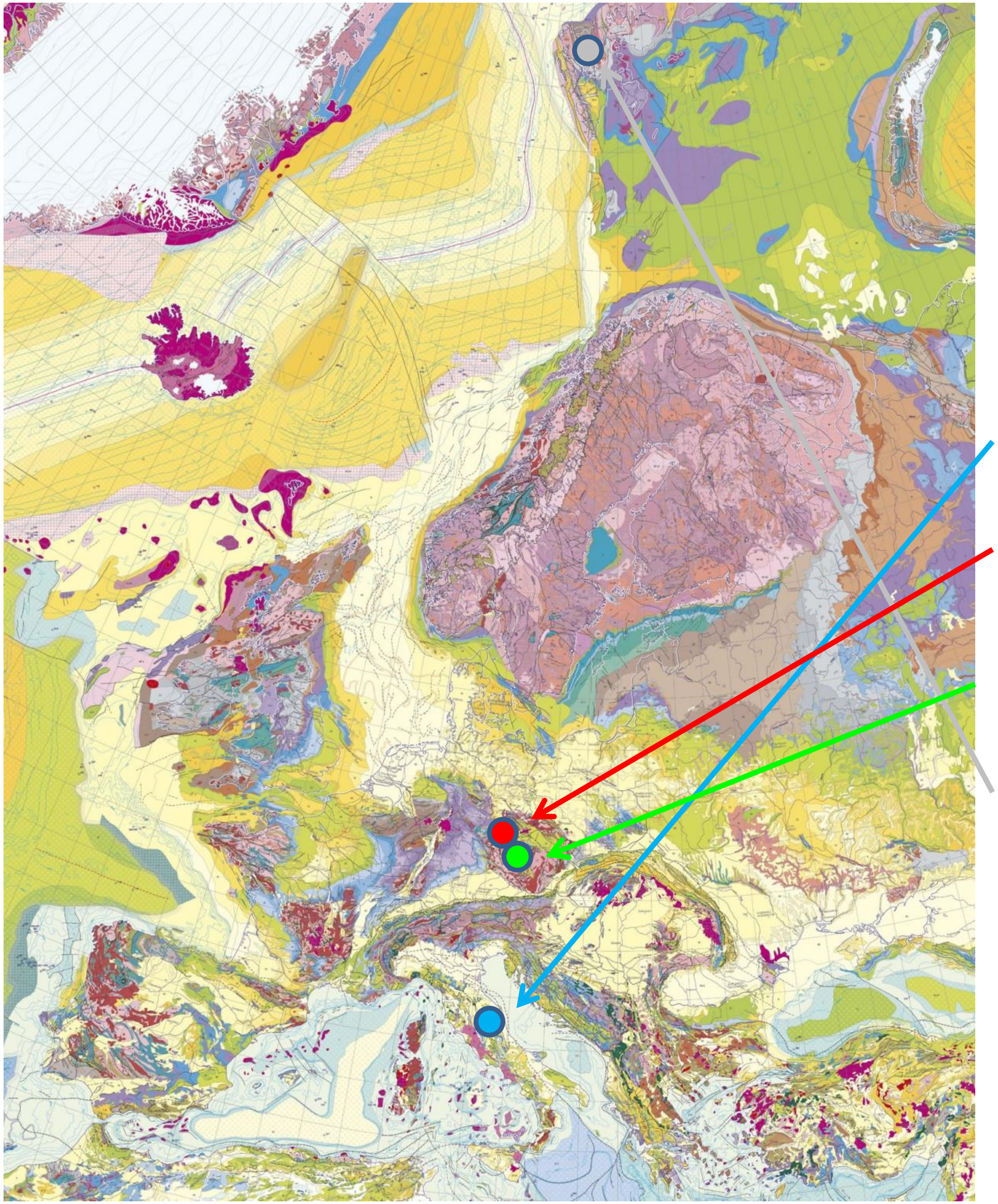

New specimen
Geological file
Name
Specimen1
Treatment
ACmax [mT]
ACmin [mT]
DC [uT]
AARM
50
0
500
A-mode (12 positions)
A1
A1
A2
A3
A4
A5
A6
A7
A8
Orientation
Orientation parameter
Dip
Dip
P1
P2
P3
P4
120
30
6
0
6
0
Foliation
Lineation
Dip dir.
Dip
Trend
Plunge
OK
CANCEL

4.

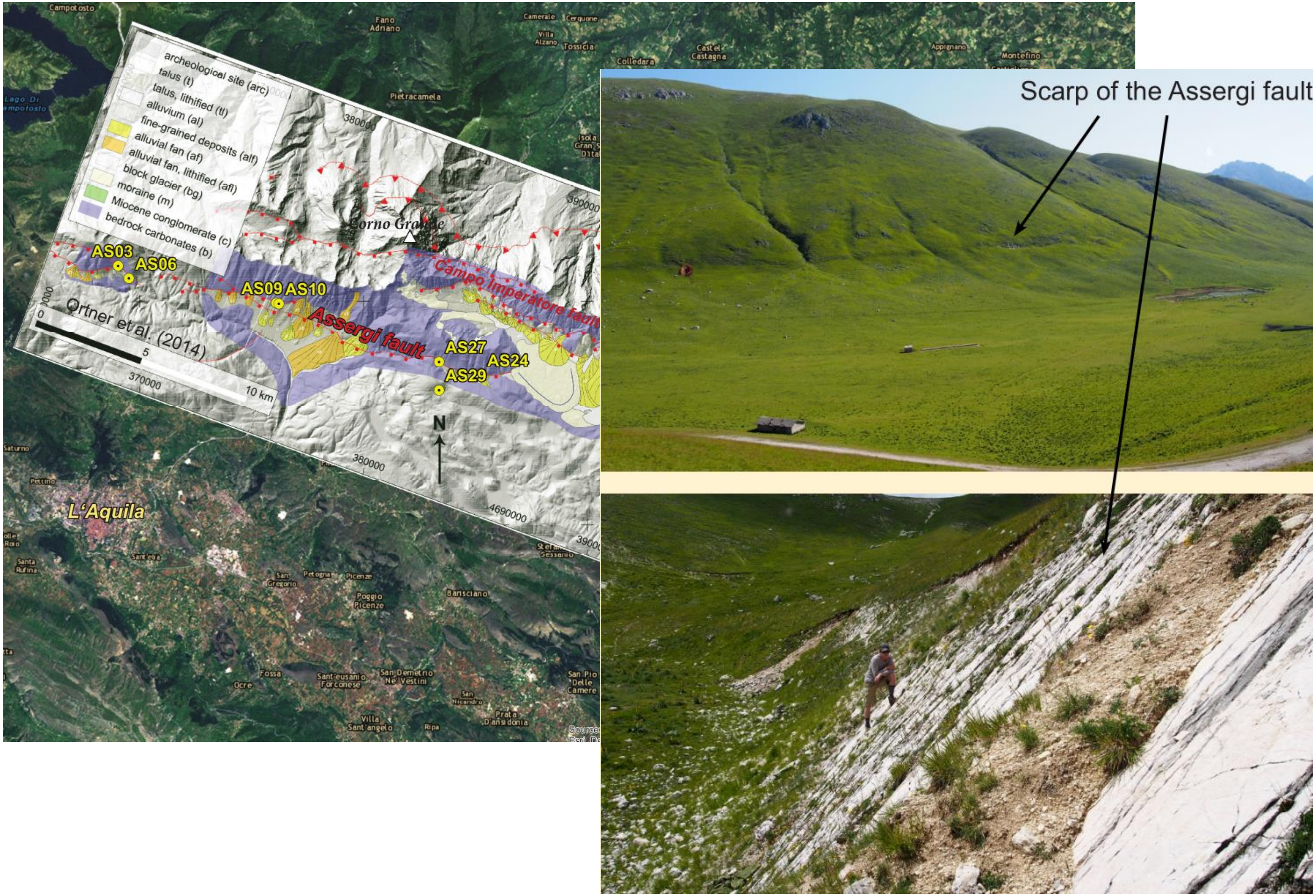

AMR calculation
Magnetizing mode
A mode (12 directions)
B mode (6 directions)
C mode (6 directions)
D mode (3 directions)
P mode (15 directions)
AC/DC fields
AC max [mT]
50
AC min [mT]
0
DC [uT]
500
OK
CANCEL

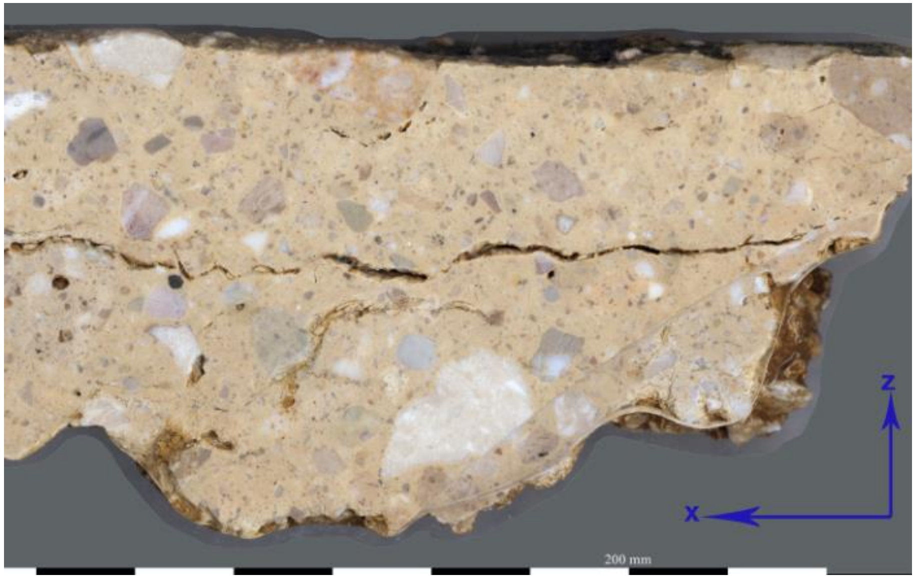
Even a small baby can handle anisotropy of magnetic remanence (with AGICO instruments)!

Name	Rock type	Location	Ferromagnetic carrier (?)	Magnetic susceptibility
AS32	Limestone	Italy	Magnetite	ca. 10 E-6
CS34	Camptonite (volcanic rock)	Czech Republic	Titanomagnetite	ca. 150 E-3
JH10	Shale	Czech Republic	Pyrrhotite	ca. 800 E-6
VIK01	Mudstone	Svalbard	Magnetite	ca. 300 E-6



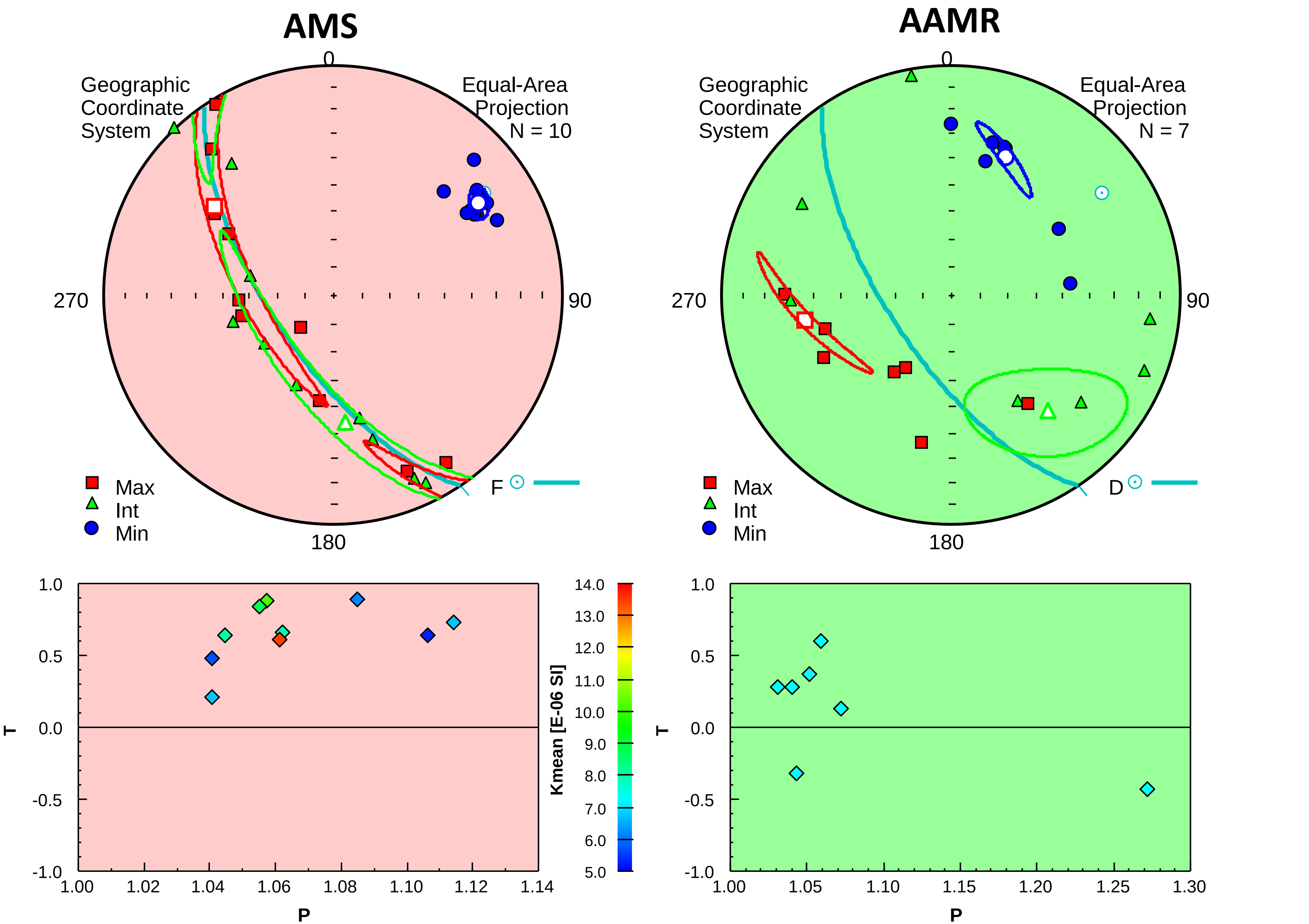
Name	Rock type
AS32	Limestone
CS34	Camptonite (volcanic rock)
JH10	Shale
VIK01	Mudstone

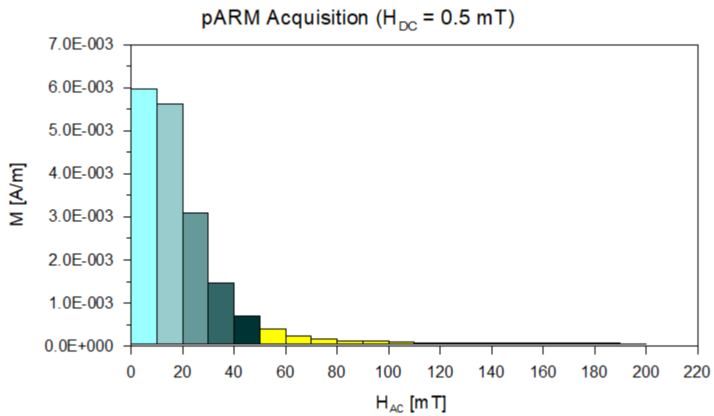

archeological site (arc)
talus (t)
talus, lithified (tl)
alluvium (al)
fine-grained deposits (alf)
alluvial fan (af)
alluvial fan, lithified (afl)
block glacier (bg)
moraine (m)
Miocene conglomerate (c)
bedrock carbonates (b)
AS03
AS06
AS09
AS10
AS27
AS24
AS29
Assergi fault
Campo Imperatore fault
Ortner et al. (2014)
0
5
10 km
N
L'Aquila
Scarp of the Assergi fault

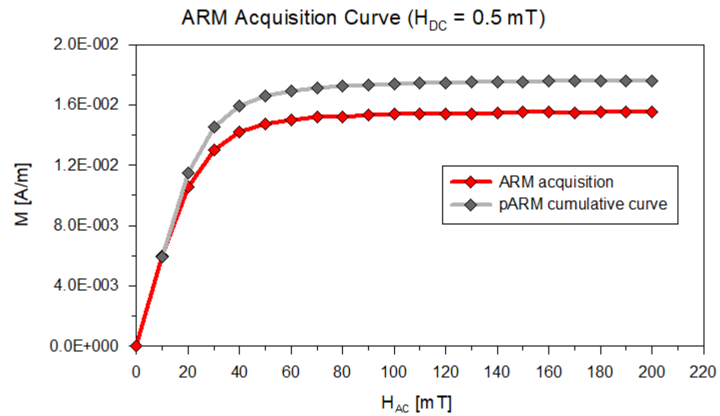


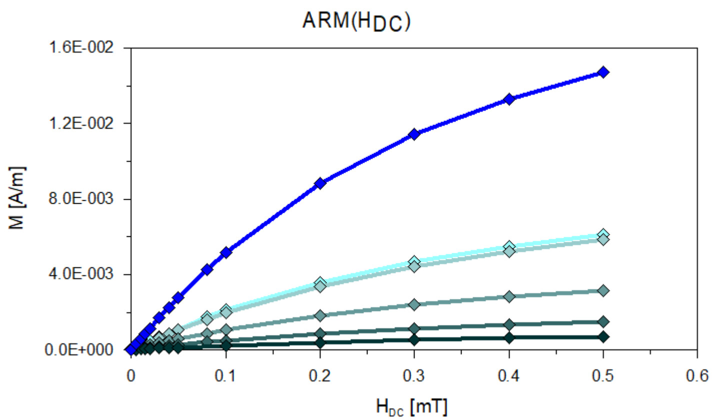
Ultracataclastic talus breccia. The fault rock is polymict and has the strongest susceptibility in this dataset. Nevertheless the magnetic fabric is not stronger or better constrained than in the other sites. K3 axes plot perfectly in the fault plane pole, whereas K1 and K2 are nearly undefined. Weak positive susceptibility.

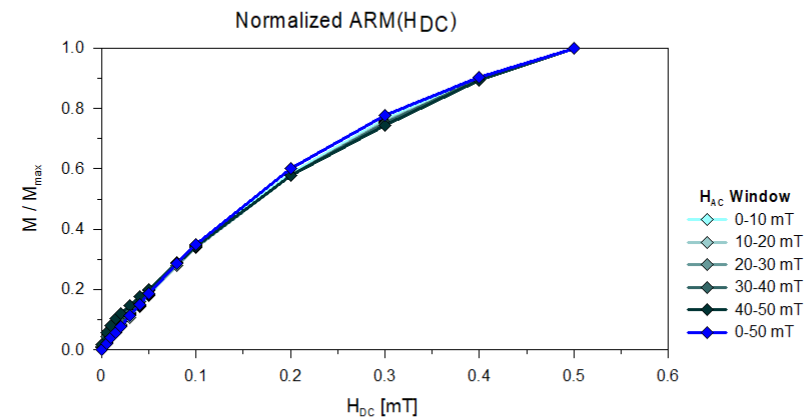
Courtesy of Hannah Pomella, Insbruck, Austria

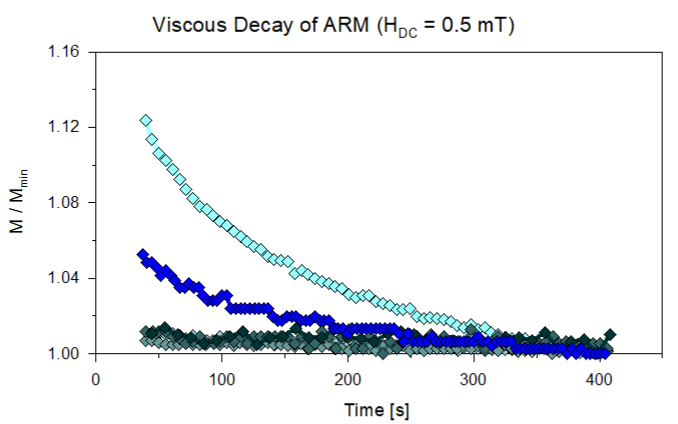

AMS
AAMR
0
Geographic
Coordinate
System
Equal-Area
Projection
N = 10
N = 7
270
90
180
Max
Int
Min
F
D
1.0
0.5
0.0
-0.5
-1.0
T
P
1.00
1.02
1.04
1.06
1.08
1.10
1.12
1.14
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
Kmean [E-06 SI]
1.05
1.10
1.15
1.20
1.25
1.30

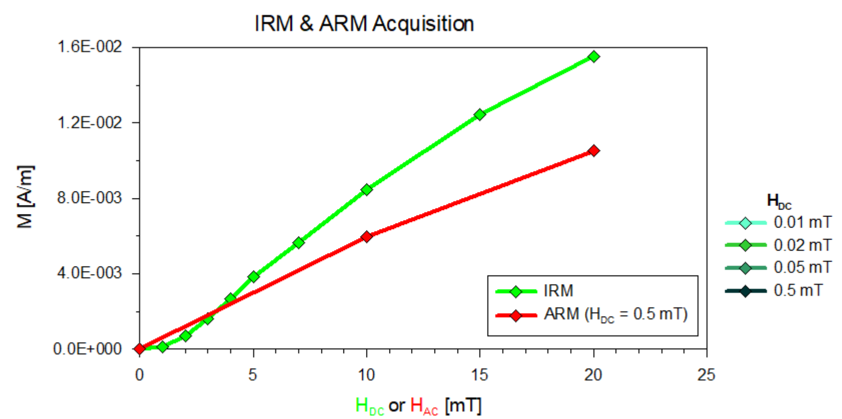

pARM Acquisition (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]


ARM Acquisition Curve (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]
ARM acquisition
pARM cumulative curve


ARM(H_DC)
M [A/m]
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT


Normalized ARM(H_DC)
M / M_max
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT

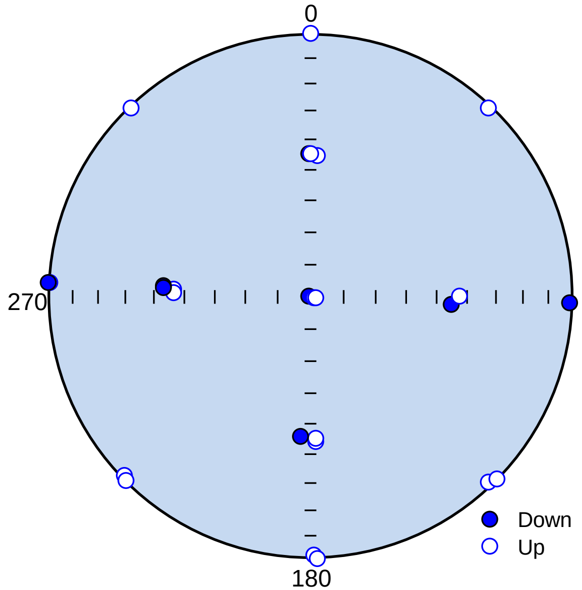

Viscous Decay of ARM (H_DC = 0.5 mT)
M / M_min
Time [s]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT


IRM & ARM Acquisition
M [A/m]
H_DC or H_AC [mT]
IRM
ARM (H_DC = 0.5 mT)
H_DC
0.01 mT
0.02 mT
0.05 mT
0.5 mT

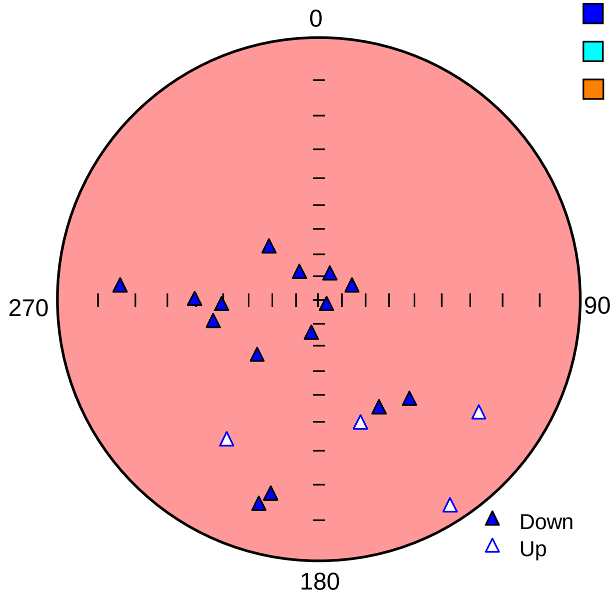
H_{AC} = 20 - 40 mT, H_{DC} = 0.5 mT

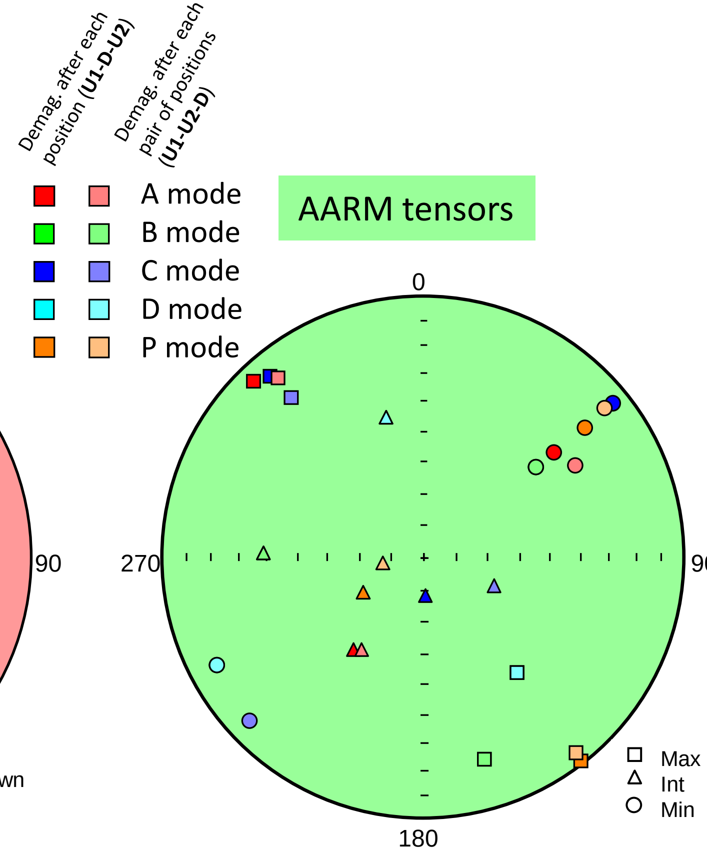
Weak magnetization
Weak anisotropy

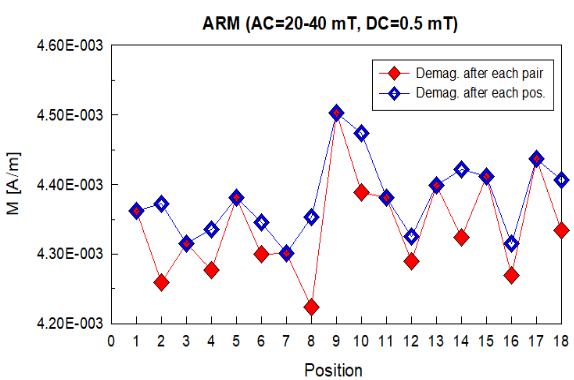
Magnetizing directions

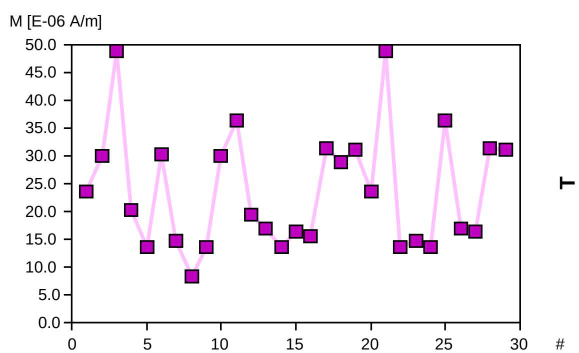


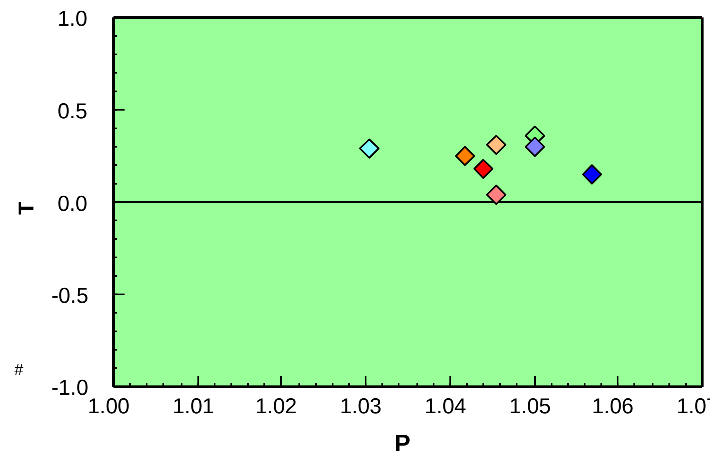
Residuals

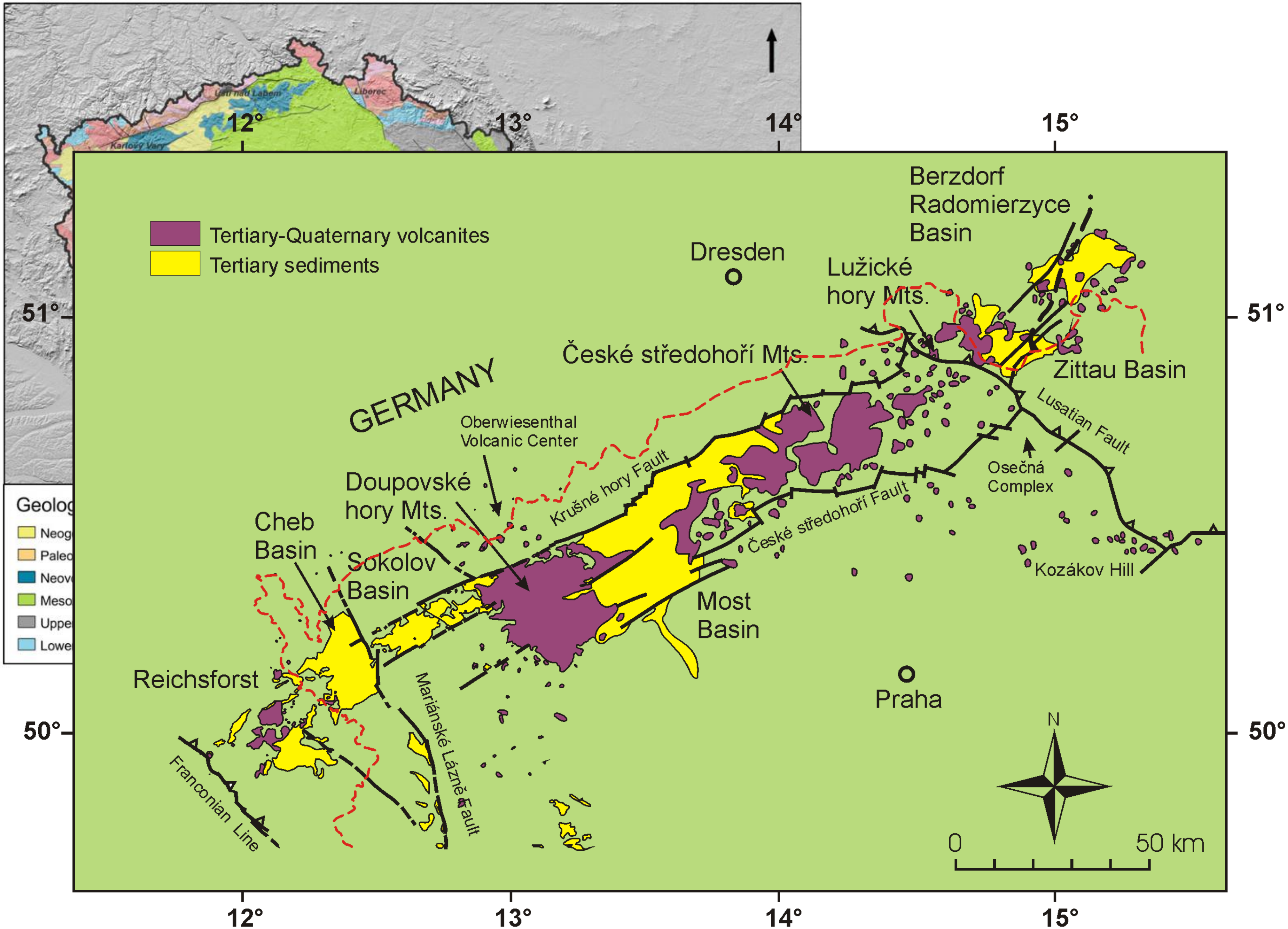




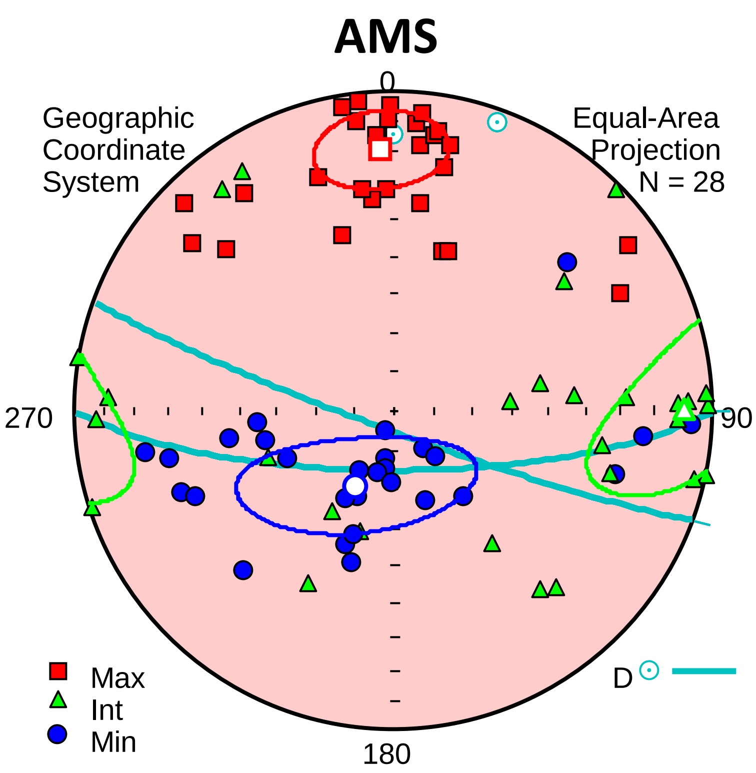







Tertiary-Quaternary volcanites
Tertiary sediments
Dresden
Berzdorf Radomierzyce Basin
Lužické hory Mts.
Zittau Basin
České středohoří Mts.
Lusatian Fault
GERMANY
Oberwiesenthal Volcanic Center
Krušné hory Fault
Doupovské hory Mts.
Osečná Complex
Cheb Basin
Sokolov Basin
České středohoří Fault
Kozákov Hill
Most Basin
Reichsforst
Praha
Mariánské Lázně Fault
Franconian Line
N
0
50 km
12°
13°
14°
15°
51°
50°
Geolog
Neog
Paleo
Neov
Meso
Uppe
Lowe
Ústí nad Labem
Liberec
Karlovy Vary

CS34 – Site view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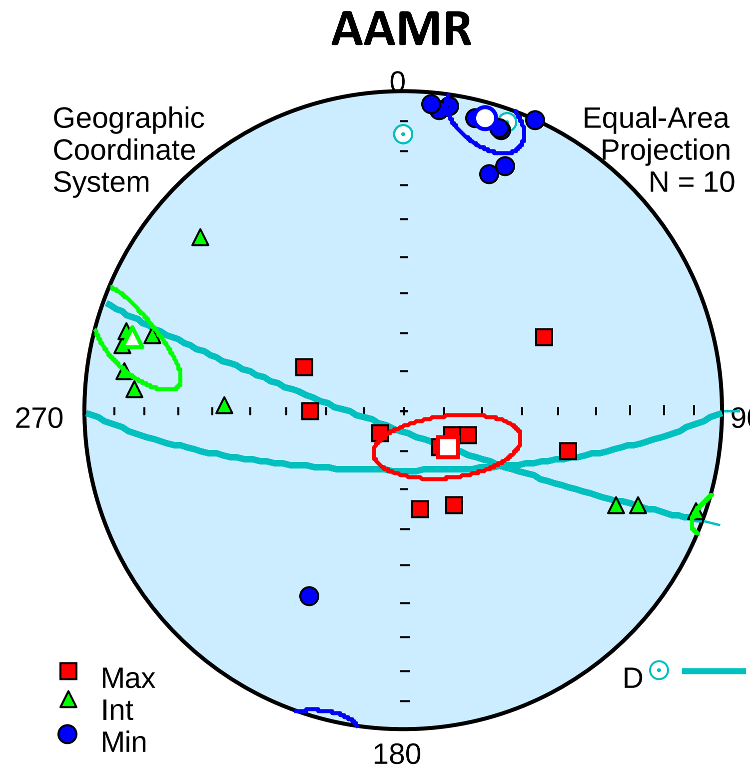
Geographic
Coordinate
System
Equal-Area
Projection
N = 28
270
90
180
Max
Int
Min
D


AAMR
0
Geographic
Coordinate
System
Equal-Area
Projection
N = 10
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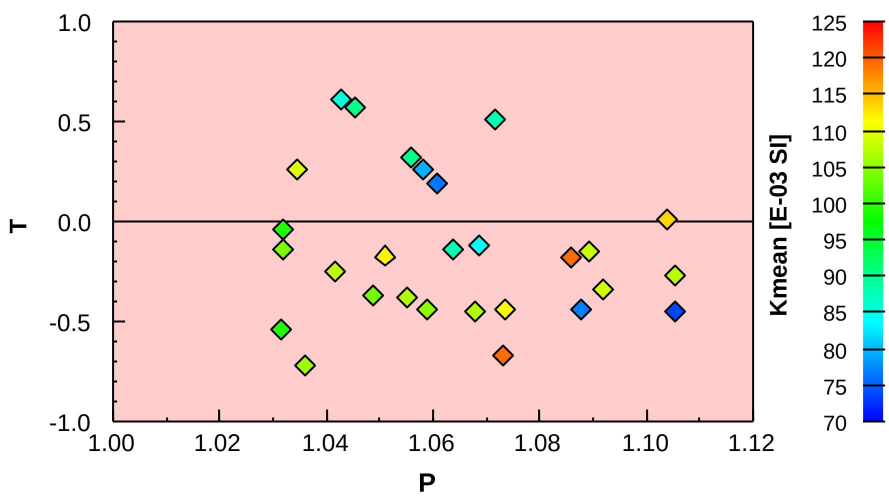
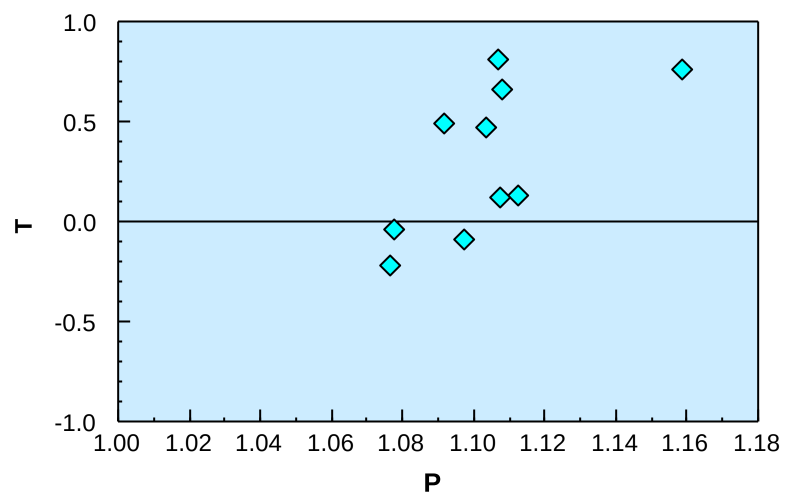
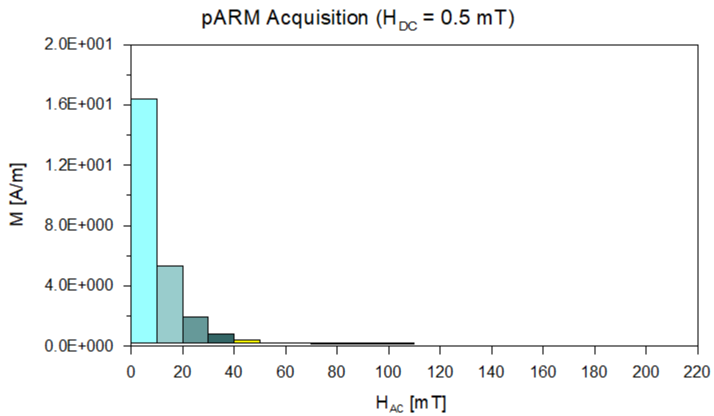
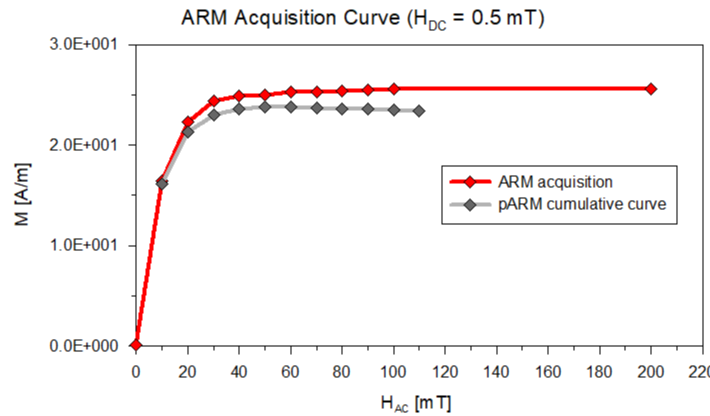
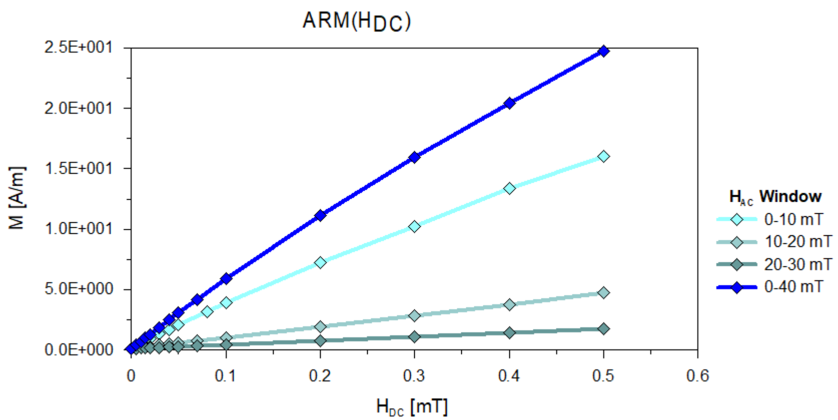
90
180
Max
Int
Min
D

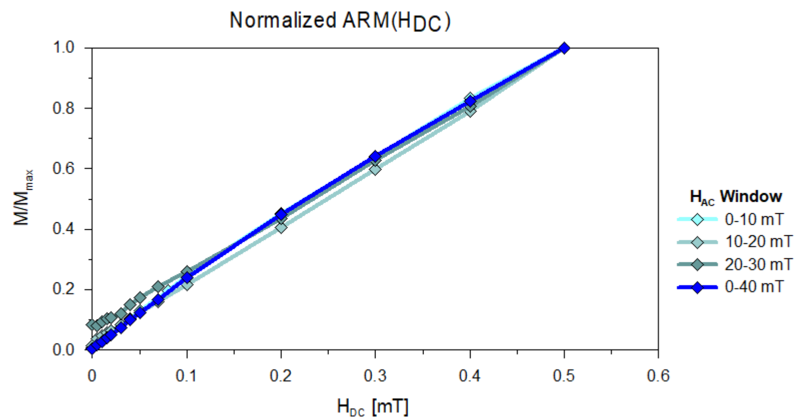

1.0
0.5
0.0
-0.5
-1.0
T
1.00
1.02
1.04
1.06
1.08
1.10
1.12
P
Kmean [E-03 SI]
125
120
115
110
105
100
95
90
85
80
75
70

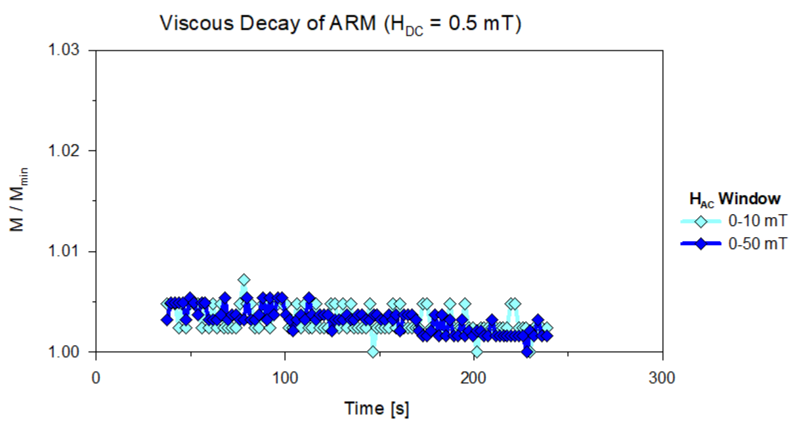

1.0
0.5
0.0
-0.5
-1.0
T
1.00
1.02
1.04
1.06
1.08
1.10
1.12
1.14
1.16
1.18
P

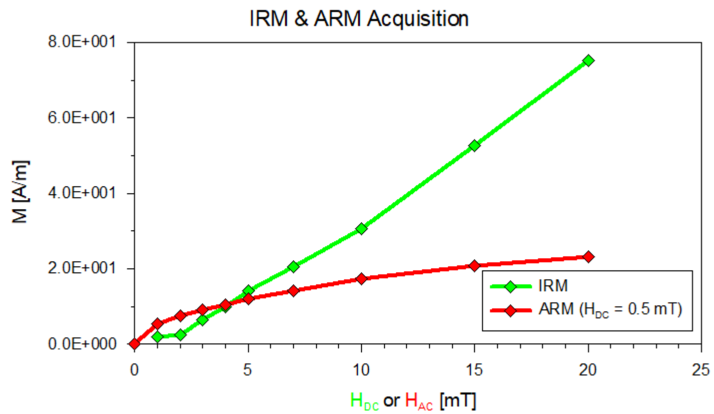

pARM Acquisition (H_{DC} = 0.5 mT)
M [A/m]
2.0E+001
1.6E+001
1.2E+001
8.0E+000
4.0E+000
0.0E+000
0 20 40 60 80 100 120 140 160 180 200 220
H_{AC} [mT]


ARM Acquisition Curve (H_{DC} = 0.5 mT)
M [A/m]
3.0E+001
2.0E+001
1.0E+001
0.0E+000
0 20 40 60 80 100 120 140 160 180 200 220
H_{AC} [mT]
ARM acquisition
pARM cumulative curve


ARM(H_{DC})
M [A/m]
2.5E+001
2.0E+001
1.5E+001
1.0E+001
5.0E+000
0.0E+000
0 0.1 0.2 0.3 0.4 0.5 0.6
H_{DC} [mT]
H_{AC} Window
0-10 mT
10-20 mT
20-30 mT
0-40 mT


Normalized ARM(H_{DC})
M/M_{max}
1.0
0.8
0.6
0.4
0.2
0.0
0 0.1 0.2 0.3 0.4 0.5 0.6
H_{DC} [mT]
H_{AC} Window
0-10 mT
10-20 mT
20-30 mT
0-40 mT


Viscous Decay of ARM (H_{DC} = 0.5 mT)
M / M_{min}
1.03
1.02
1.01
1.00
0 100 200 300
Time [s]
H_{AC} Window
0-10 mT
0-50 mT

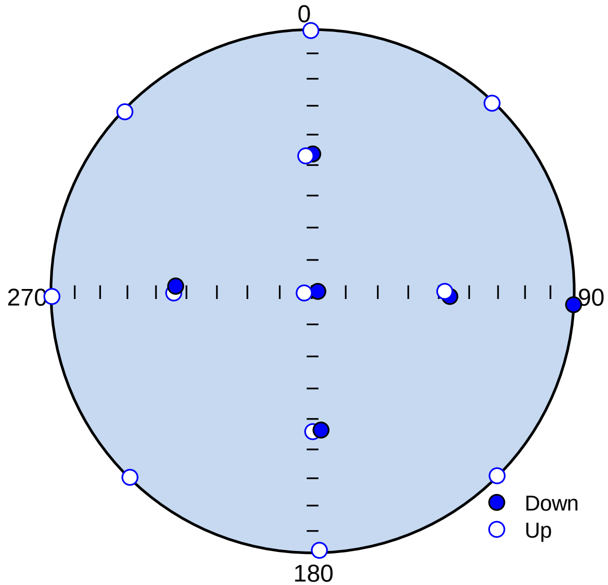

IRM & ARM Acquisition
M [A/m]
8.0E+001
6.0E+001
4.0E+001
2.0E+001
0.0E+000
0 5 10 15 20 25
H_{DC} or H_{AC} [mT]
IRM
ARM (H_{DC} = 0.5 mT)

H_{AC} = 0 - 40 mT, H_{DC} = 0.5 mT

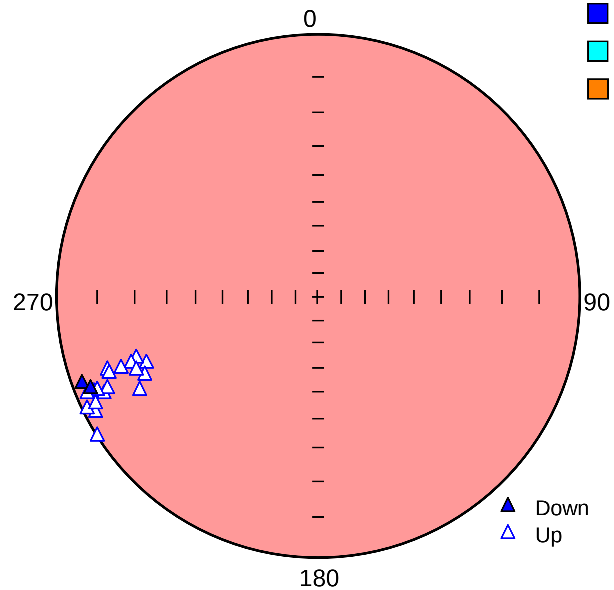
Very strong magnetization!

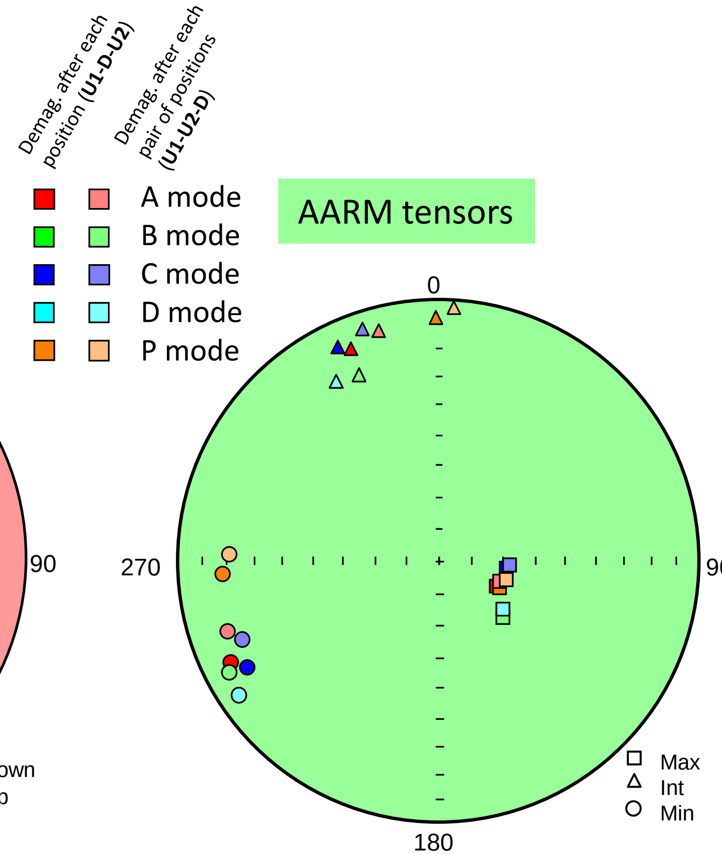
Weak anisotropy

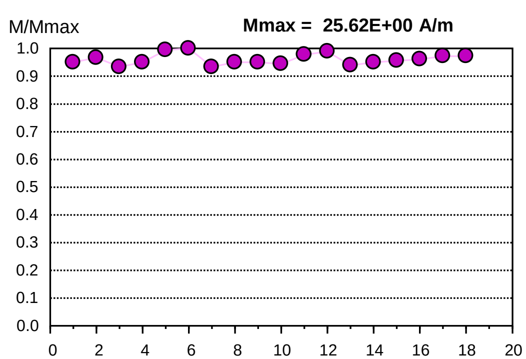
Magnetizing directions

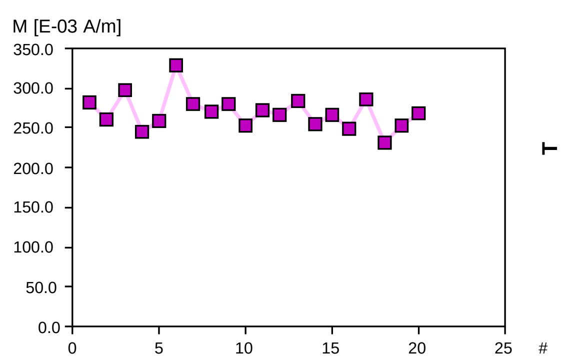


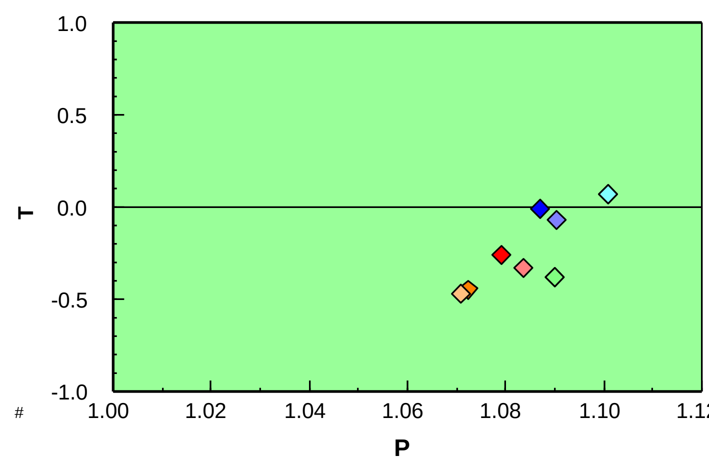
Residuals

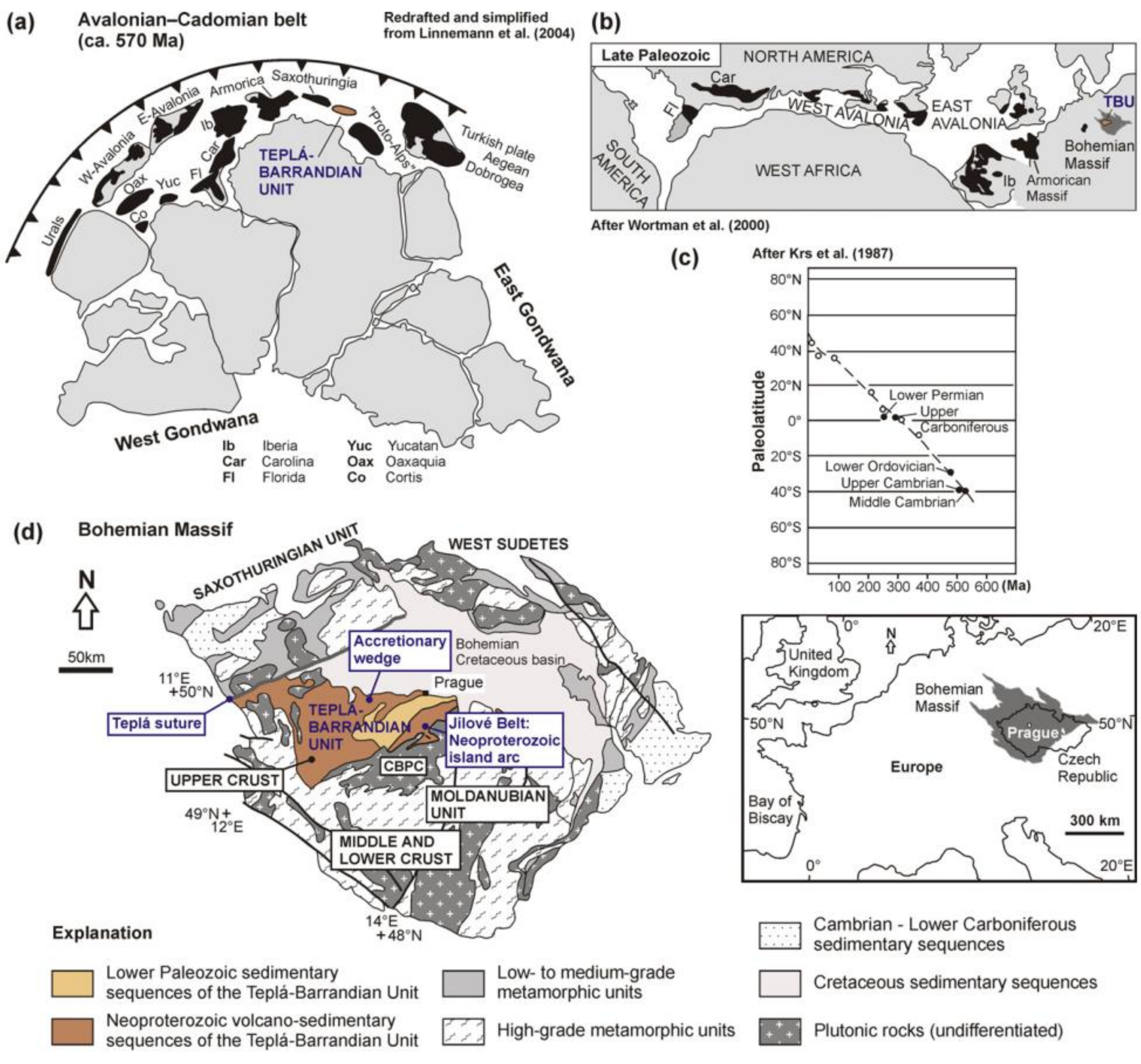


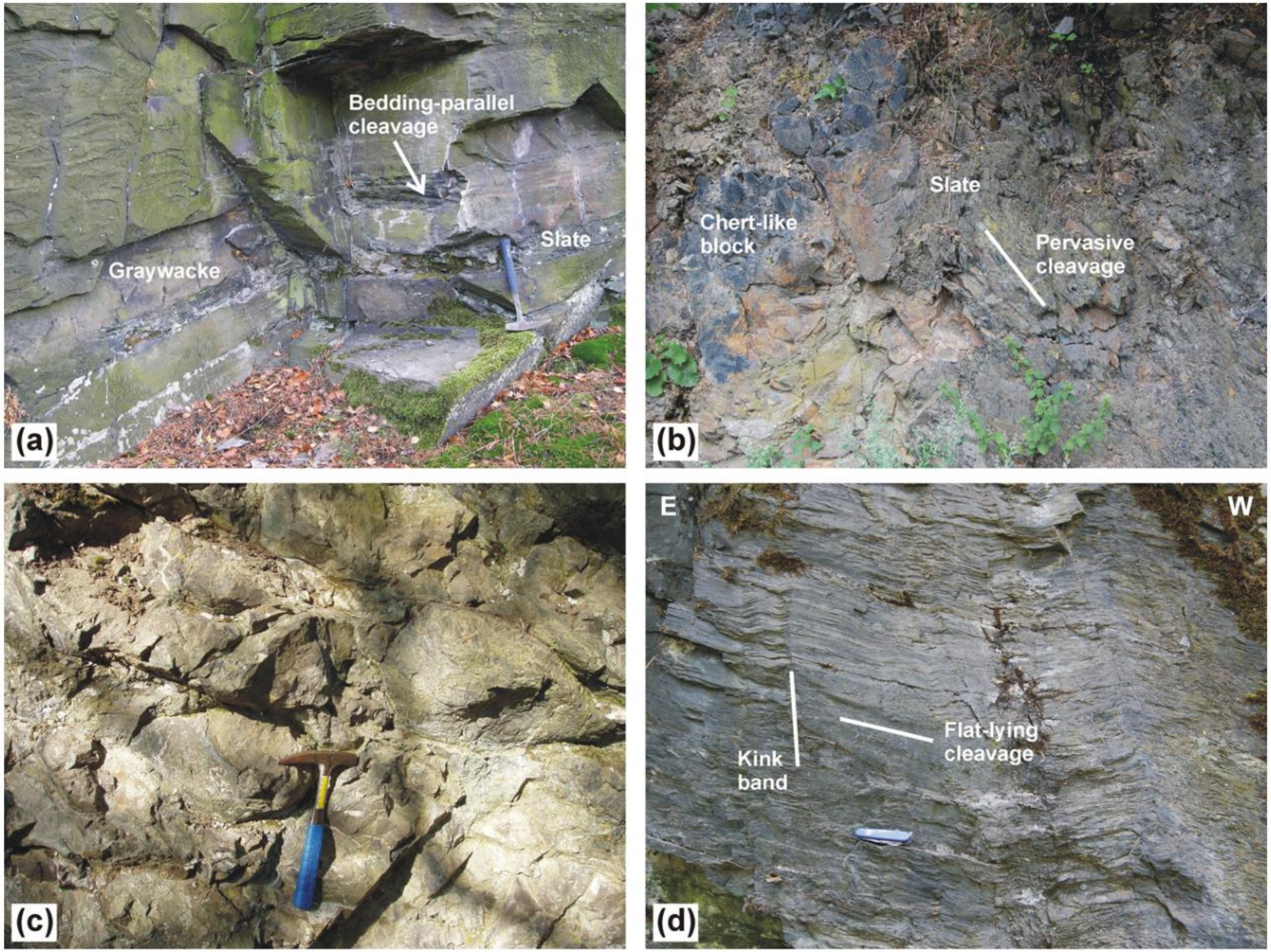




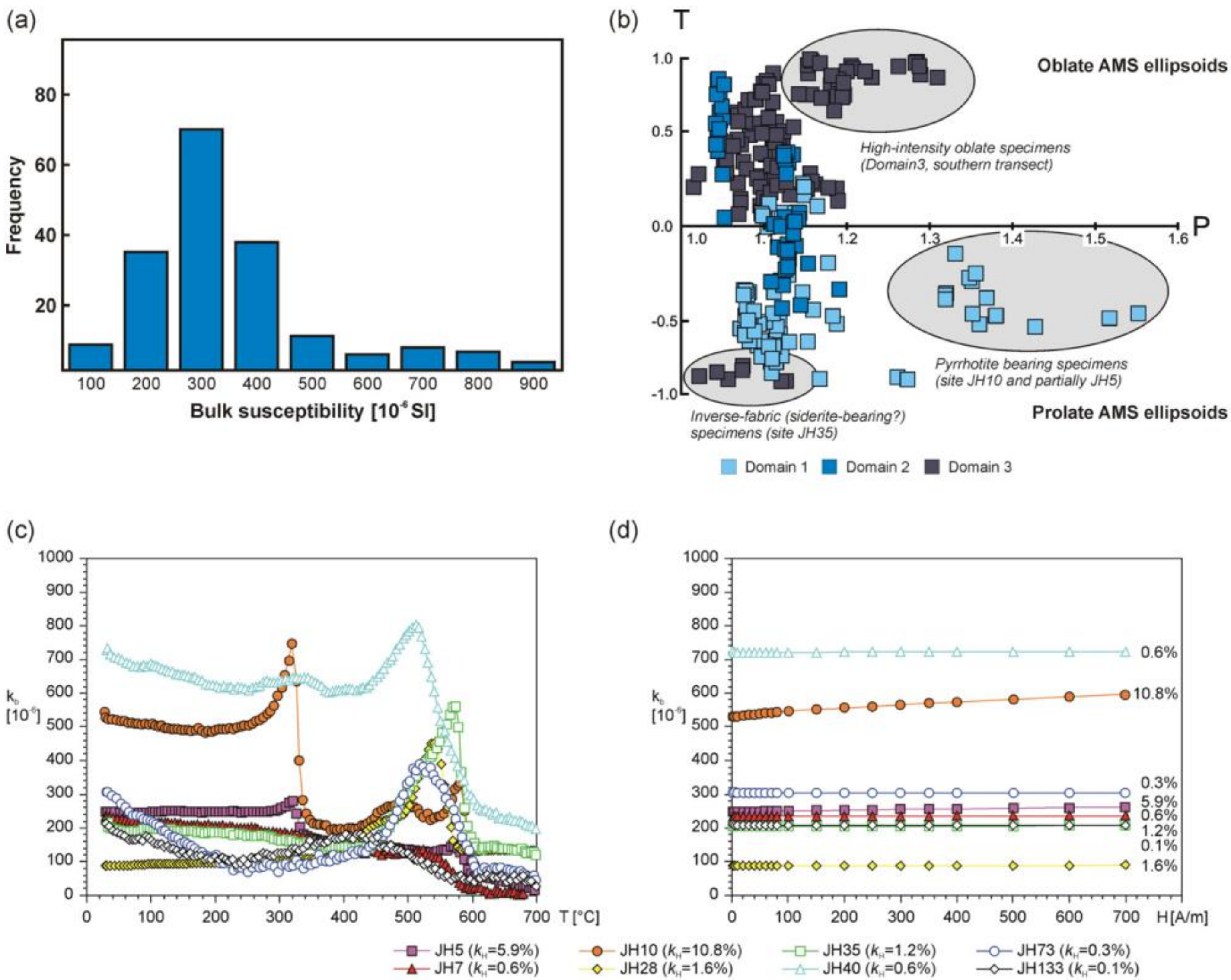


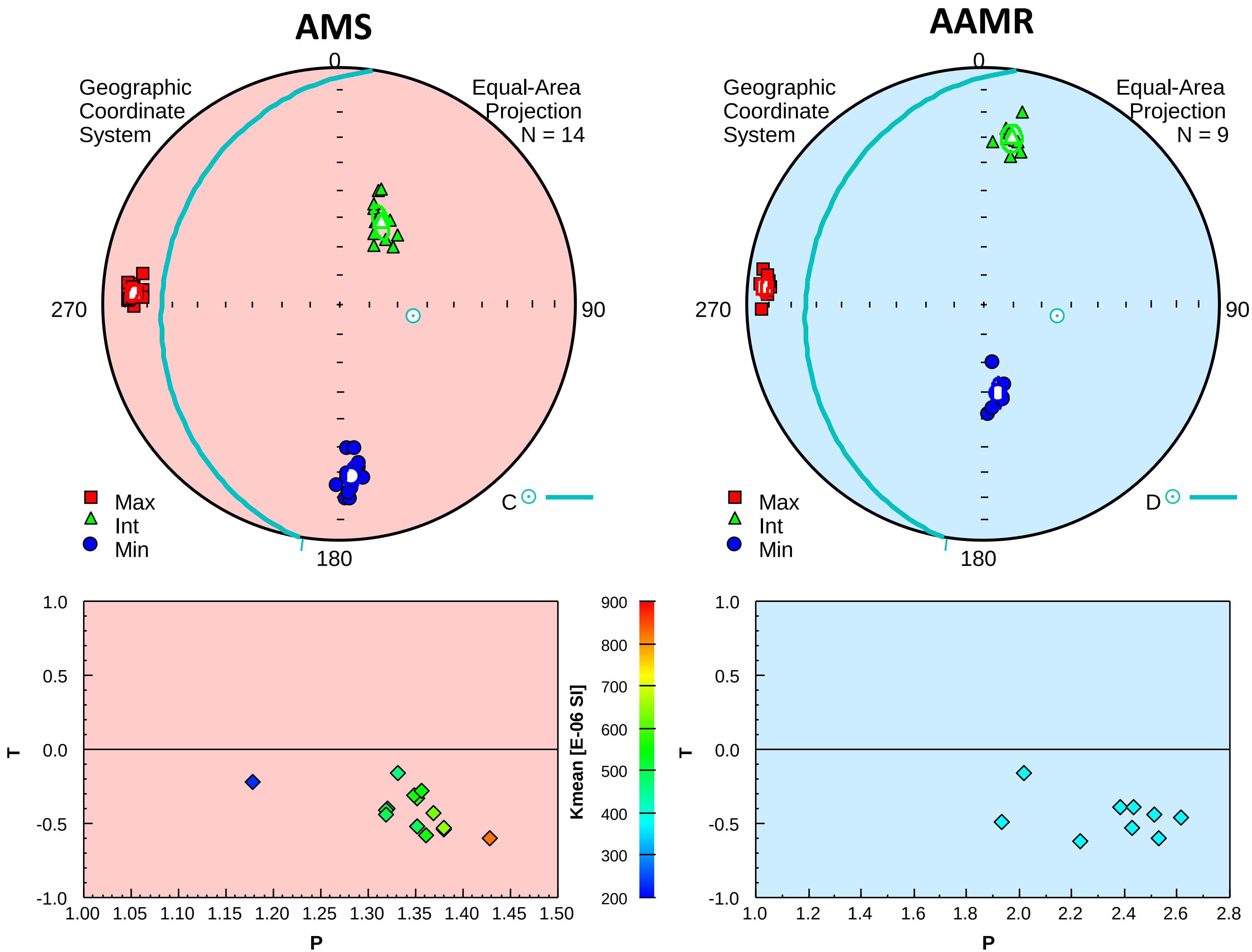


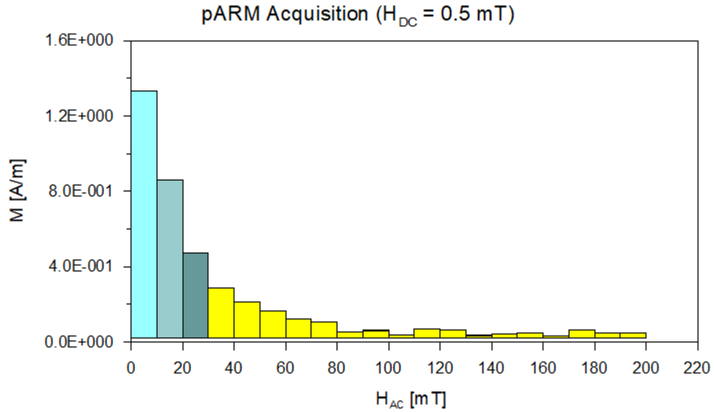

(a) Avalonian–Cadomian belt (ca. 570 Ma)
Redrafted and simplified from Linnemann et al. (2004)
TEPLÁ-BARRANDIAN UNIT
East Gondwana
West Gondwana
Ib Iberia
Car Carolina
Fl Florida
Yuc Yucatan
Oax Oaxaquia
Co Cortis
(b) Late Paleozoic
NORTH AMERICA
WEST AVALONIA
EAST AVALONIA
SOUTH AMERICA
WEST AFRICA
TBU
Bohemian Massif
Armorican Massif
After Wortman et al. (2000)
(c) After Krs et al. (1987)
Paleolatitude
Lower Permian
Upper Carboniferous
Lower Ordovician
Upper Cambrian
Middle Cambrian
(d) Bohemian Massif
SAXOTHURINGIAN UNIT
WEST SUDETES
Accretionary wedge
Bohemian Cretaceous basin
Prague
Teplá suture
TEPLÁ-BARRANDIAN UNIT
Jílové Belt: Neoproterozoic island arc
CBPC
UPPER CRUST
MOLDANUBIAN UNIT
MIDDLE AND LOWER CRUST
50km
United Kingdom
Bohemian Massif
Europe
Prague
Czech Republic
Bay of Biscay
300 km
Explanation
Lower Paleozoic sedimentary sequences of the Teplá-Barrandian Unit
Neoproterozoic volcano-sedimentary sequences of the Teplá-Barrandian Unit
Low- to medium-grade metamorphic units
High-grade metamorphic units
Cambrian - Lower Carboniferous sedimentary sequences
Cretaceous sedimentary sequences
Plutonic rocks (undifferentiated)

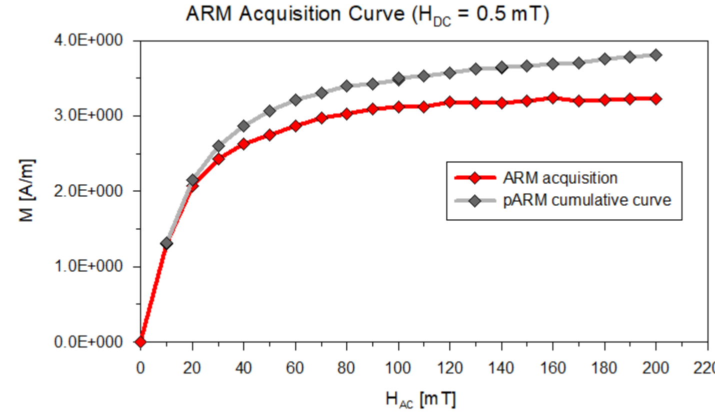


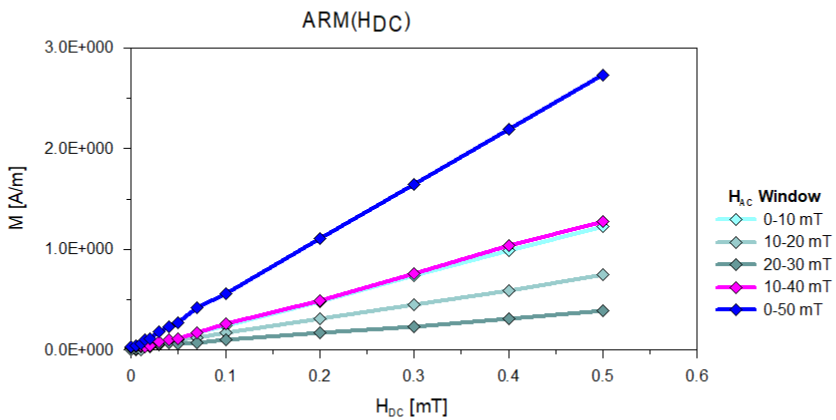
Courtesy of Jaroslava Hajna, Prague

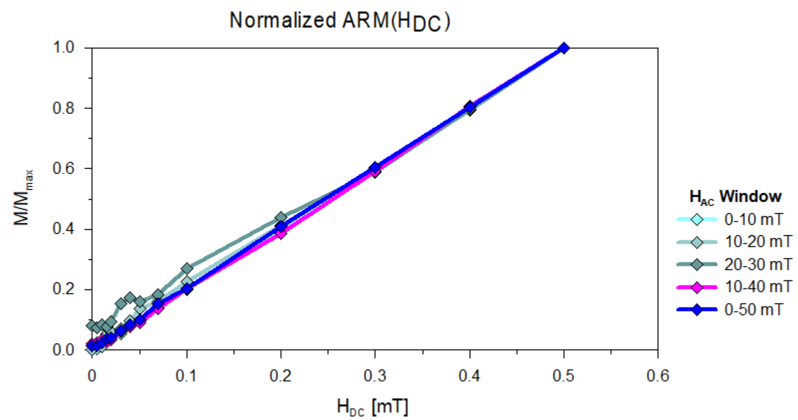

(a)
Frequency
Bulk susceptibility [10^{-6} SI]
(b)
T
P
Oblate AMS ellipsoids
High-intensity oblate specimens (Domain3, southern transect)
Pyrrhotite bearing specimens (site JH10 and partially JH5)
Inverse-fabric (siderite-bearing?) specimens (site JH35)
Prolate AMS ellipsoids
Domain 1
Domain 2
Domain 3
(c)
k_b [10^{-6}]
T [°C]
(d)
k_b [10^{-6}]
H [A/m]
0.6%
10.8%
0.3%
5.9%
0.6%
1.2%
0.1%
1.6%
JH5 (k_H=5.9%)
JH7 (k_H=0.6%)
JH10 (k_H=10.8%)
JH28 (k_H=1.6%)
JH35 (k_H=1.2%)
JH40 (k_H=0.6%)
JH73 (k_H=0.3%)
JH133 (k_H=0.1%)

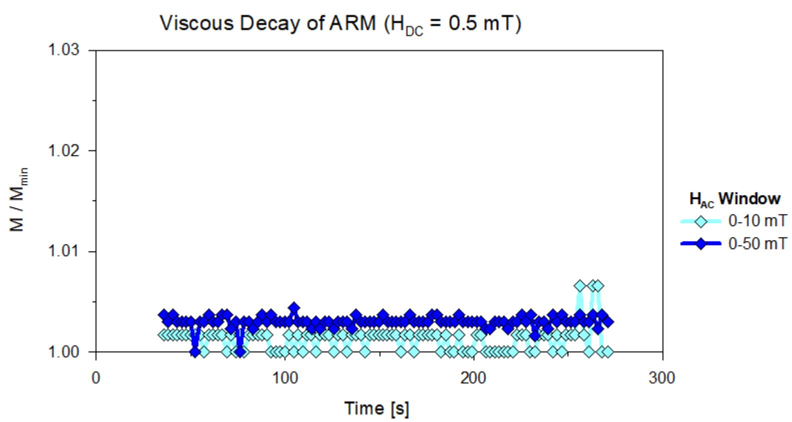

AMS
0
90
180
270
Geographic Coordinate System
Equal-Area Projection
N = 14
C
Max
Int
Min
AAMR
0
90
180
270
Geographic Coordinate System
Equal-Area Projection
N = 9
D
Max
Int
Min
T
P
1.0
0.5
0.0
-0.5
-1.0
1.00
1.05
1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
Kmean [E-06 SI]
900
800
700
600
500
400
300
200
T
P
1.0
0.5
0.0
-0.5
-1.0
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

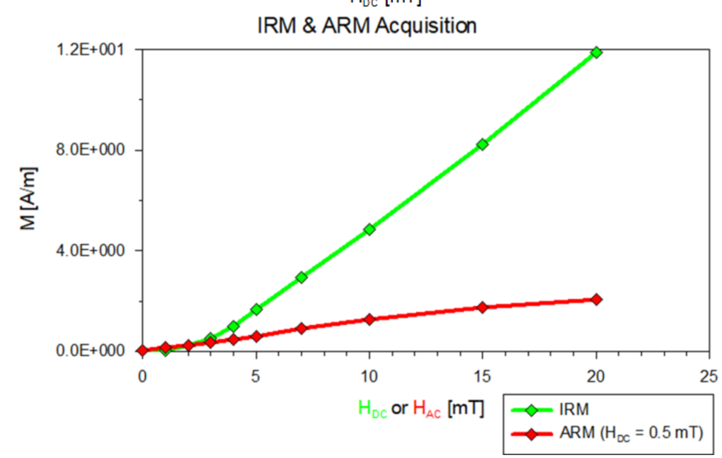

pARM Acquisition (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]
1.6E+000
1.2E+000
8.0E-001
4.0E-001
0.0E+000
0 20 40 60 80 100 120 140 160 180 200 220


ARM Acquisition Curve (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]
ARM acquisition
pARM cumulative curve
4.0E+000
3.0E+000
2.0E+000
1.0E+000
0.0E+000
0 20 40 60 80 100 120 140 160 180 200 220


ARM(HDC)
M [A/m]
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
10-40 mT
0-50 mT
3.0E+000
2.0E+000
1.0E+000
0.0E+000
0 0.1 0.2 0.3 0.4 0.5 0.6


Normalized ARM(HDC)
M/M_max
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
10-40 mT
0-50 mT
1.0
0.8
0.6
0.4
0.2
0.0
0 0.1 0.2 0.3 0.4 0.5 0.6

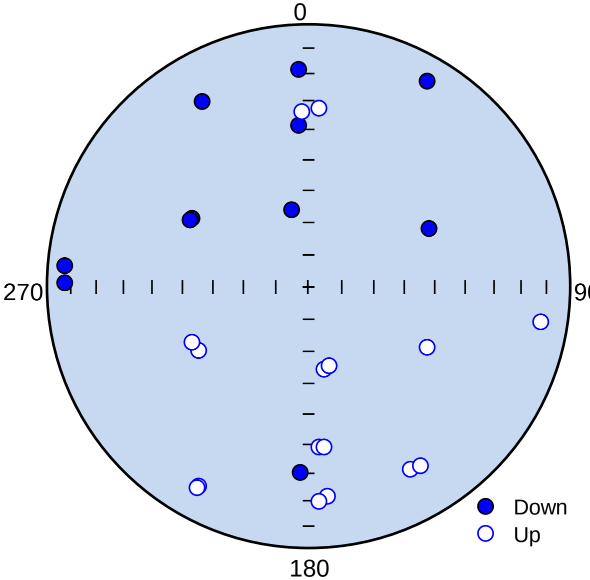

Viscous Decay of ARM (H_DC = 0.5 mT)
M / M_min
Time [s]
H_AC Window
0-10 mT
0-50 mT
1.03
1.02
1.01
1.00
0 100 200 300


IRM & ARM Acquisition
M [A/m]
H_DC or H_AC [mT]
IRM
ARM (H_DC = 0.5 mT)
1.2E+001
8.0E+000
4.0E+000
0.0E+000
0 5 10 15 20 25

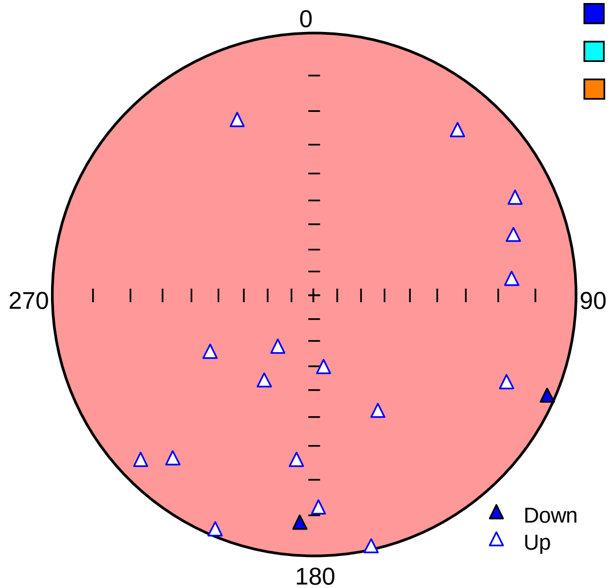
H_{AC} = 10 - 40 mT, H_{DC} = 0.5 mT

Strong magnetization
Very strong anisotropy!

Magnetizing directions

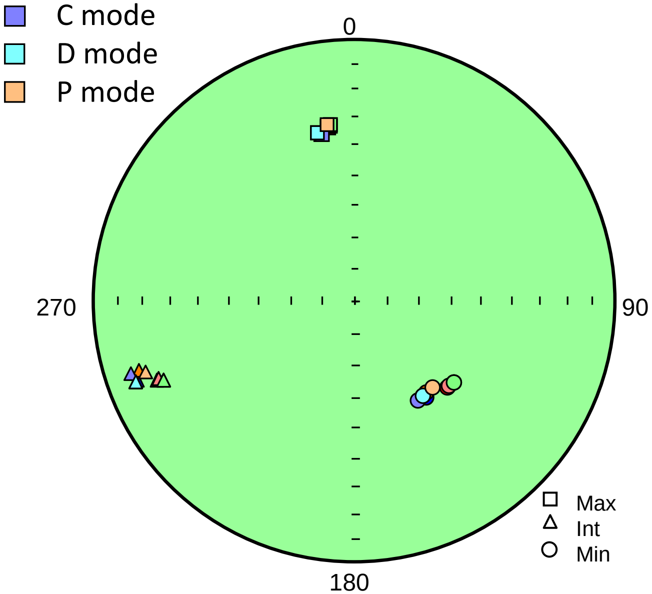


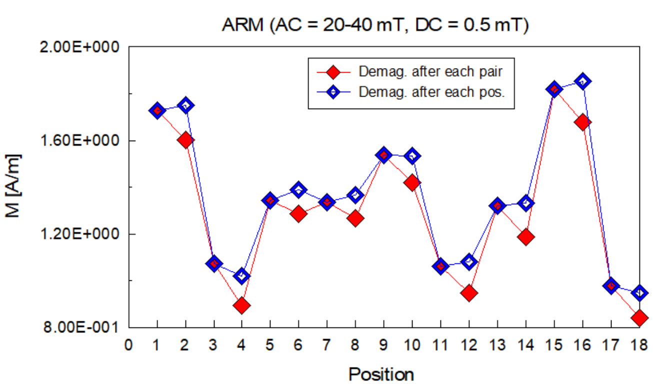
Residuals

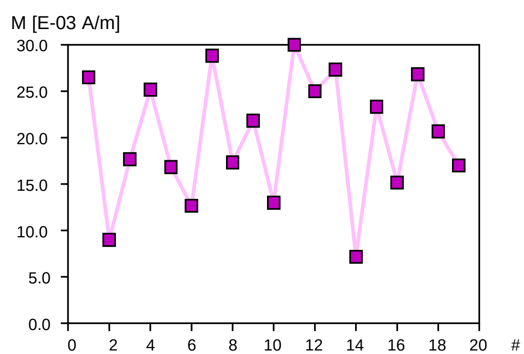


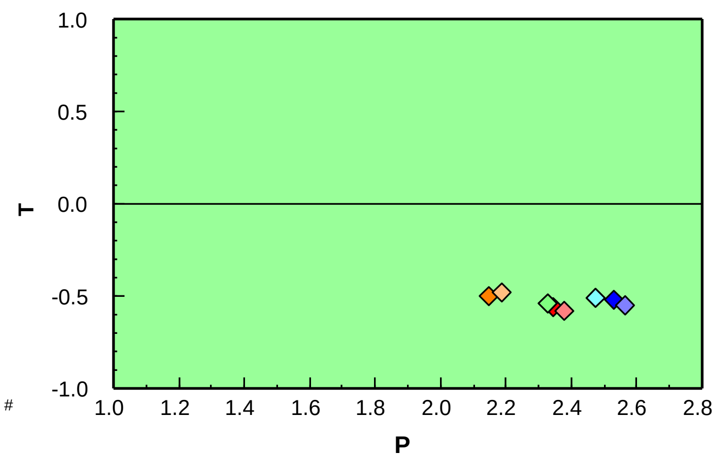
Demag. after each position (U1-D-U2)	Demag. after each pair of positions (U1-U2-D)	
■	■	A mode
■	■	B mode
■	■	C mode
■	■	D mode
■	■	P mode

AARM tensors

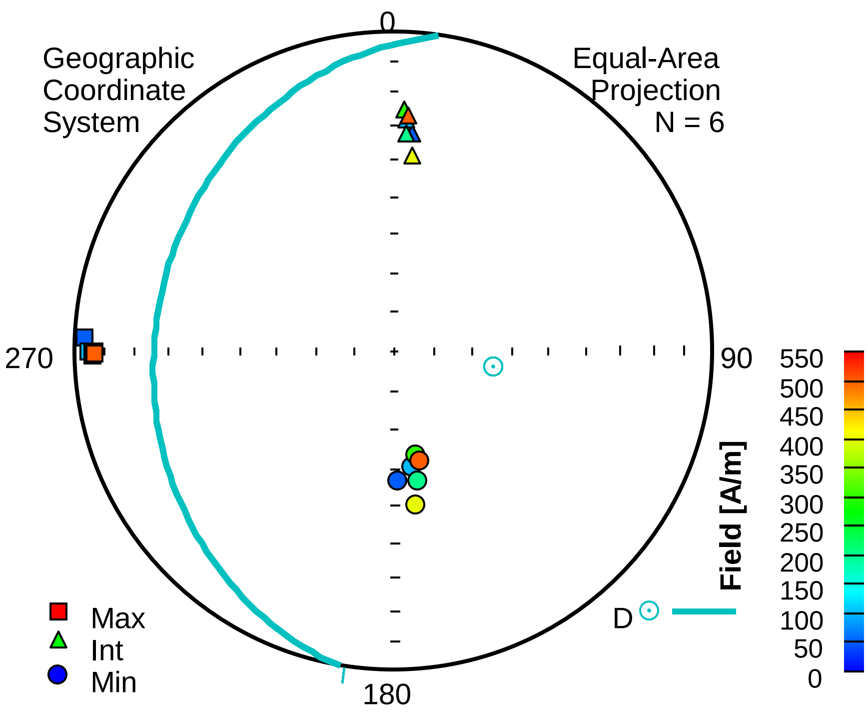


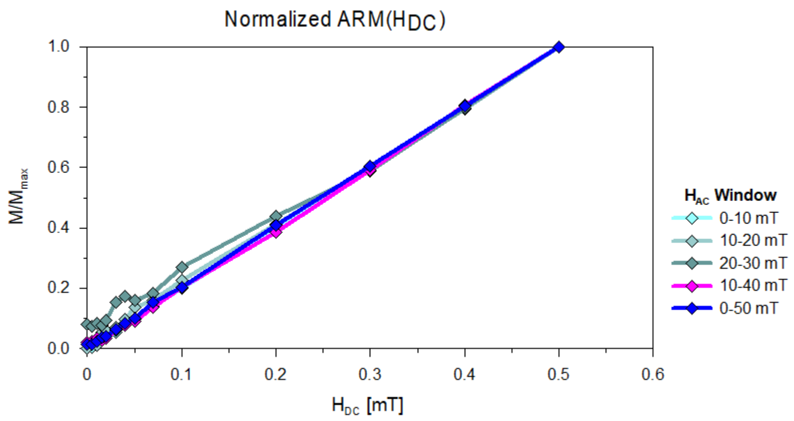


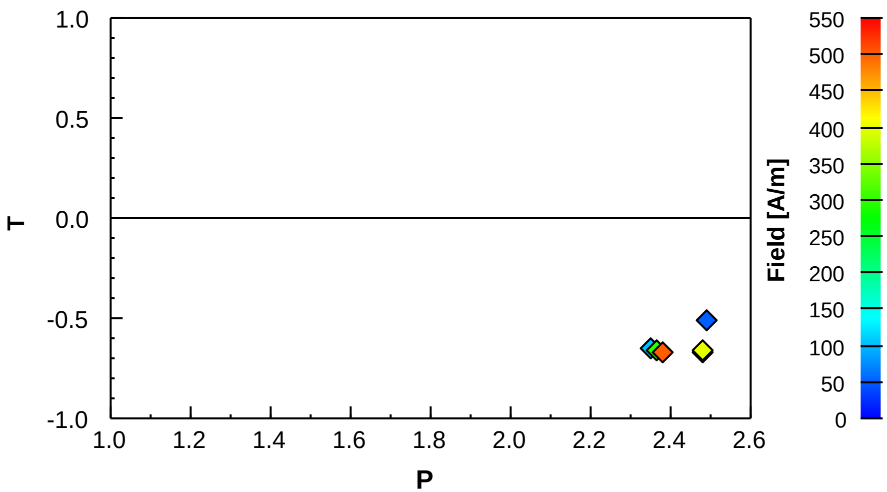


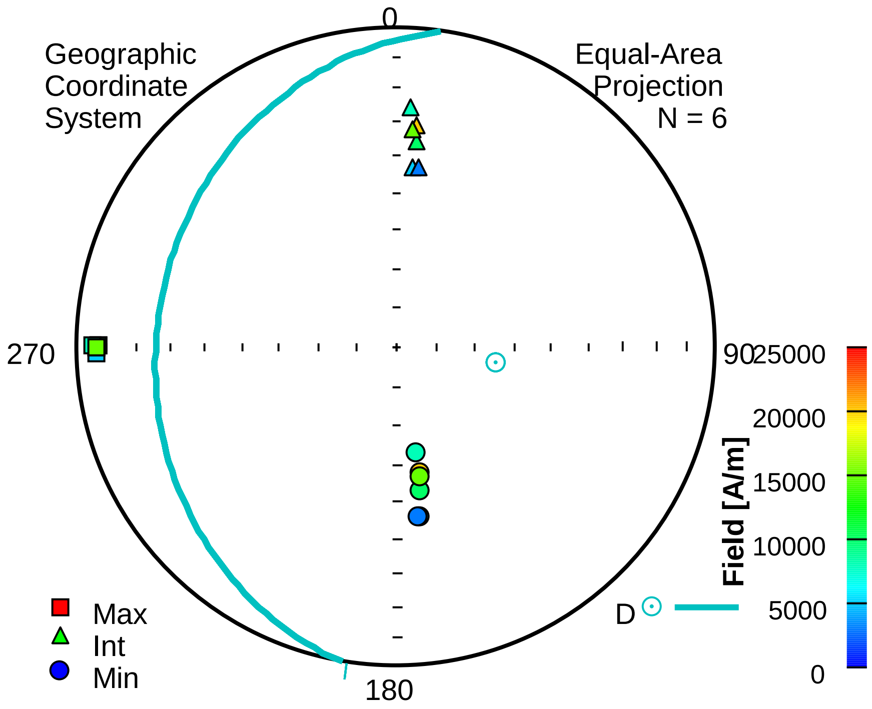


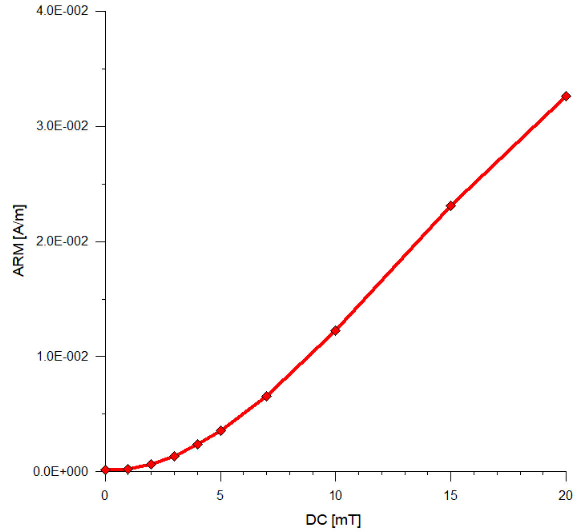
JH10 – AARM in various bias DC field

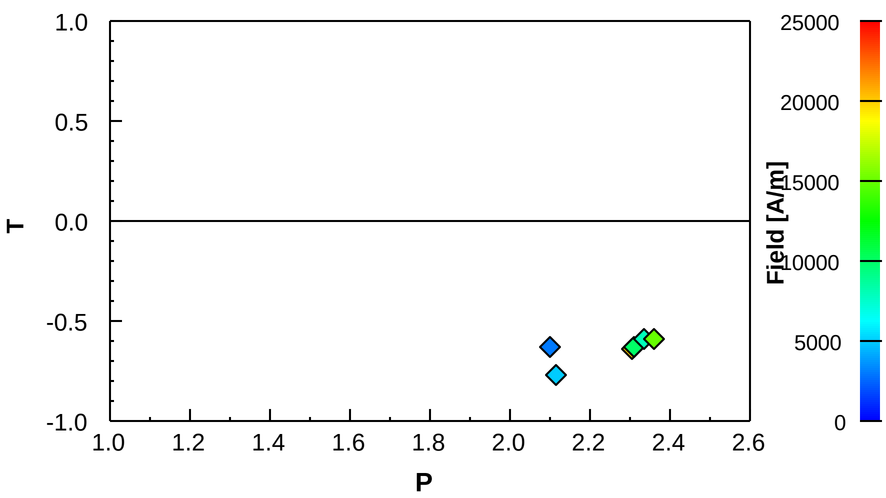




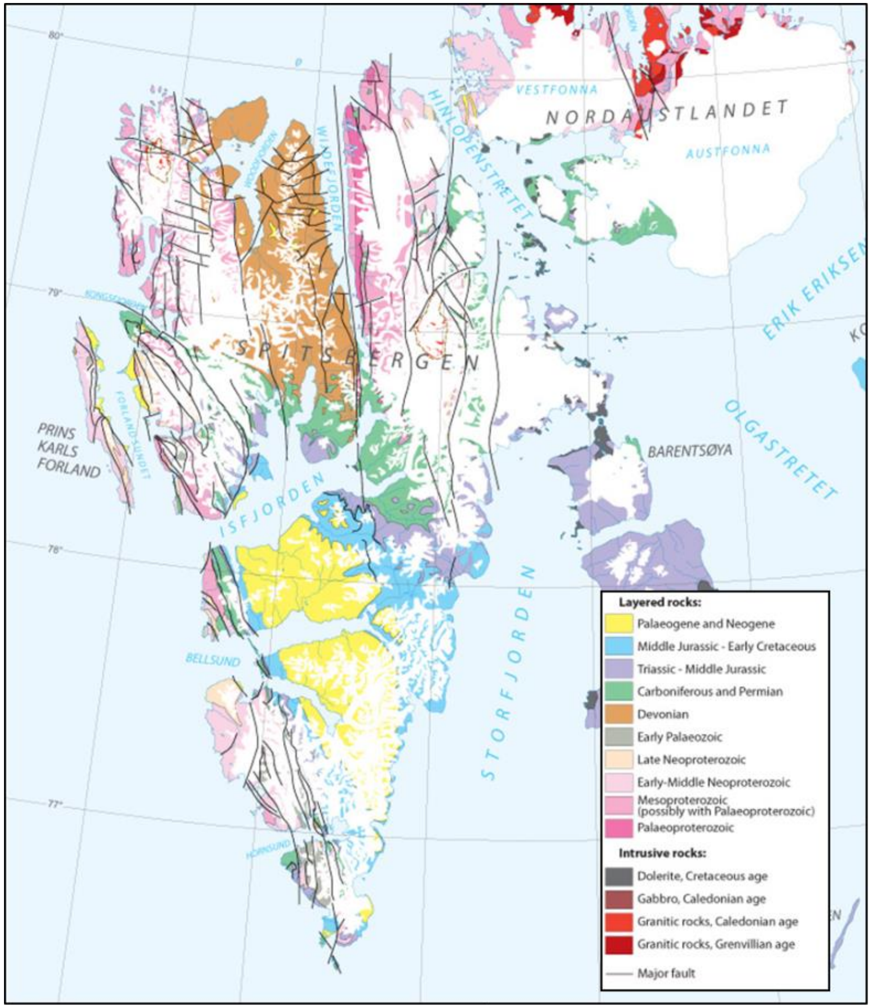



Geographic
Coordinate
System
Equal-Area
Projection
N = 6
0
90
180
270
Max
Int
Min
D
Field [A/m]
25000
20000
15000
10000
5000
0

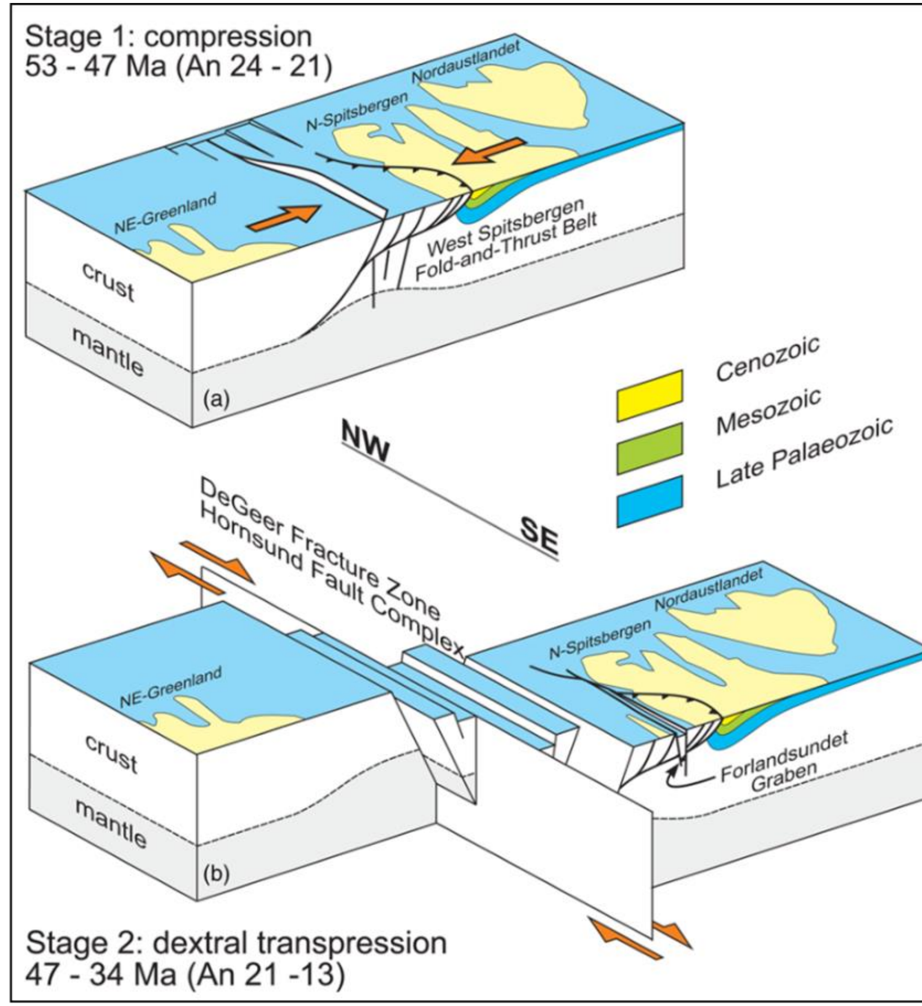

4.0E-002
3.0E-002
2.0E-002
1.0E-002
0.0E+000
ARM [A/m]
0
5
10
15
20
DC [mT]


1.0
0.5
0.0
-0.5
-1.0
T
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
P
Field [A/m]
25000
20000
15000
10000
5000
0

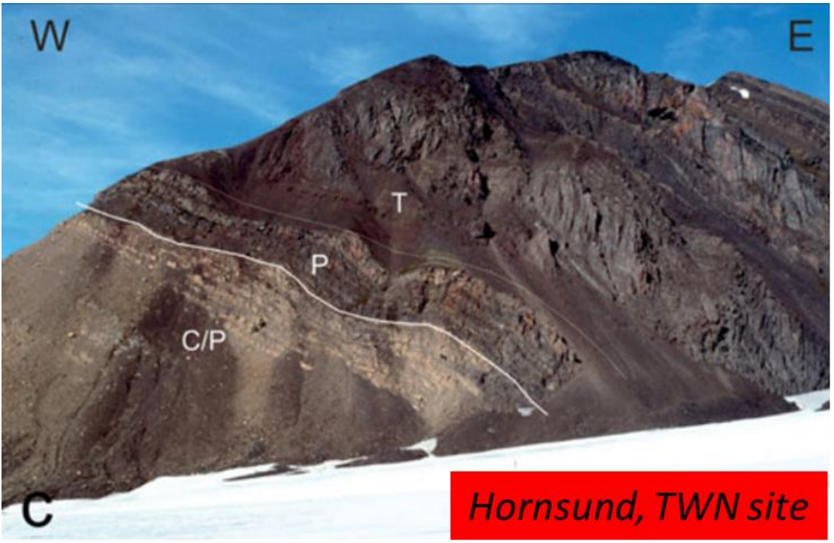
Example 4: VIK01 – Location



Norwegian Polar Institute



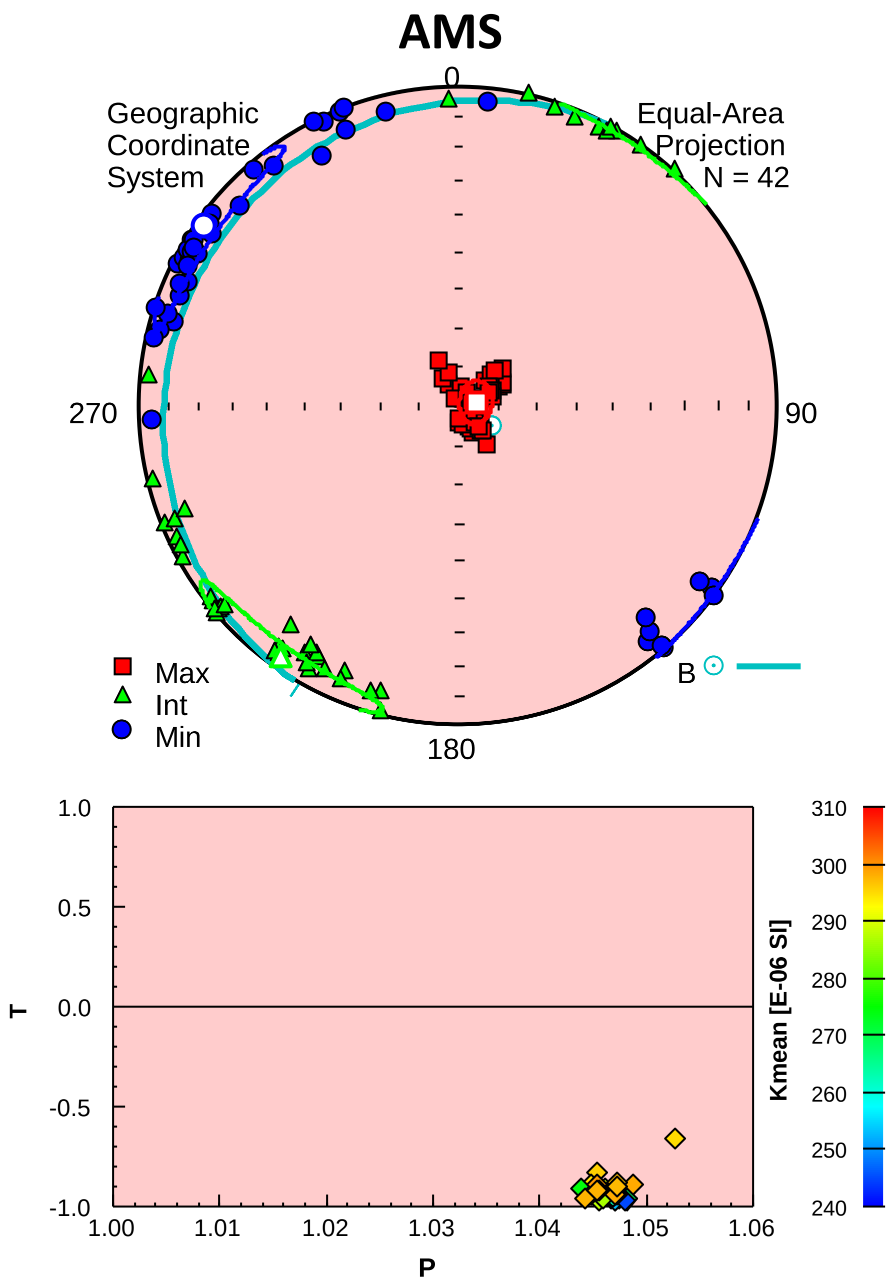
Piepjohn et al., 2016, J. Geol. Soc.

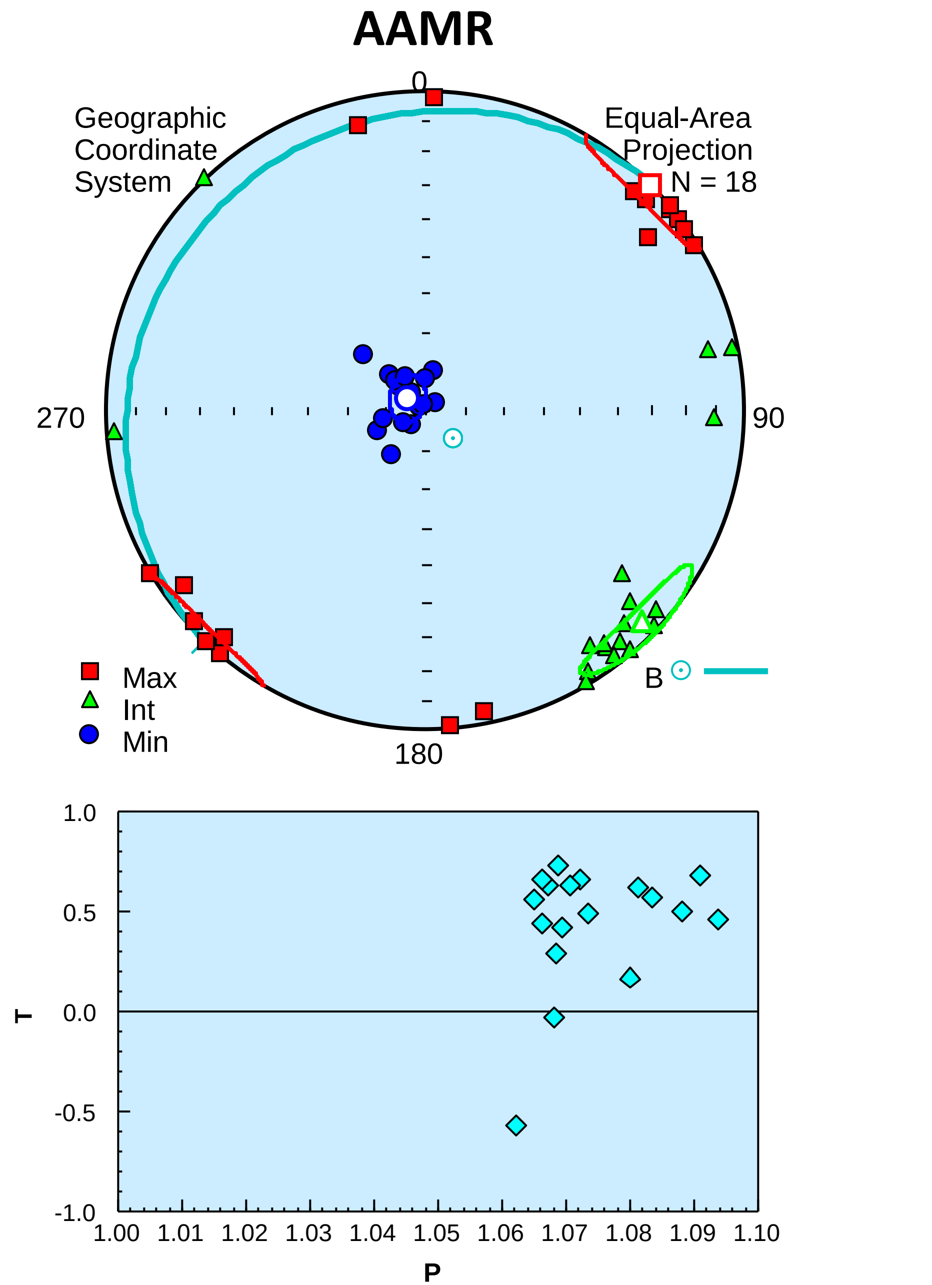


FOLD AND FOLD BELT

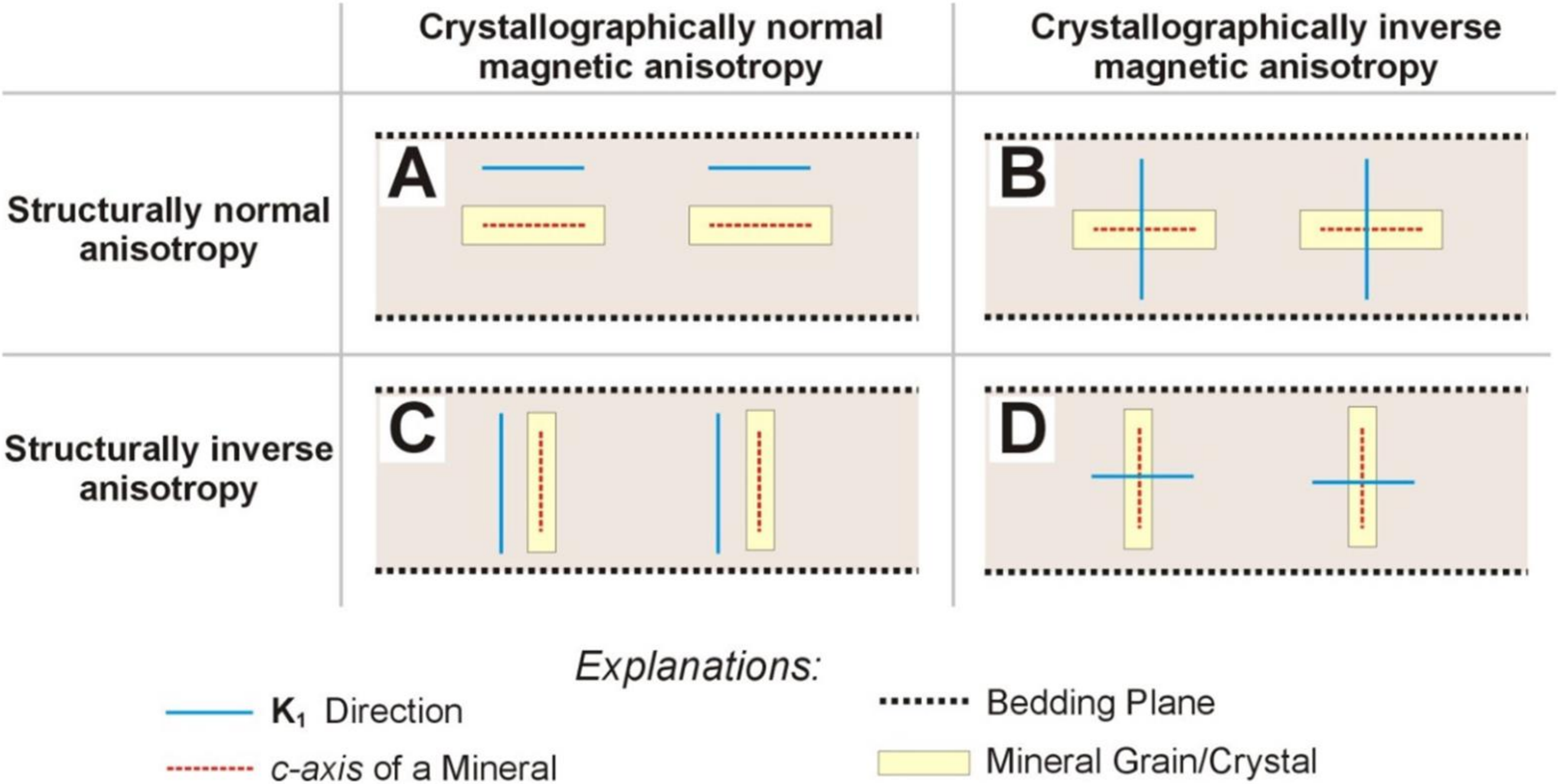
UNDEFORMED FORELAND

Courtesy of Katarzina Dudzisz, Warsaw, Poland

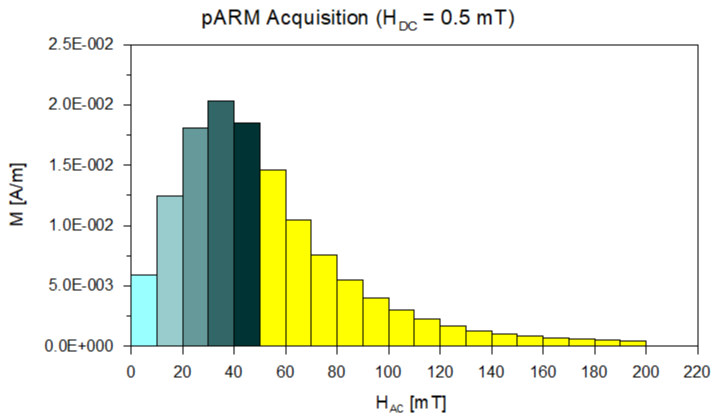

AMS
0
Geographic Coordinate System
Equal-Area Projection
N = 42
270
90
180
Max
Int
Min
B
1.0
0.5
0.0
-0.5
-1.0
T
1.00
1.01
1.02
1.03
1.04
1.05
1.06
P
310
300
290
280
270
260
250
240
Kmean [E-06 SI]

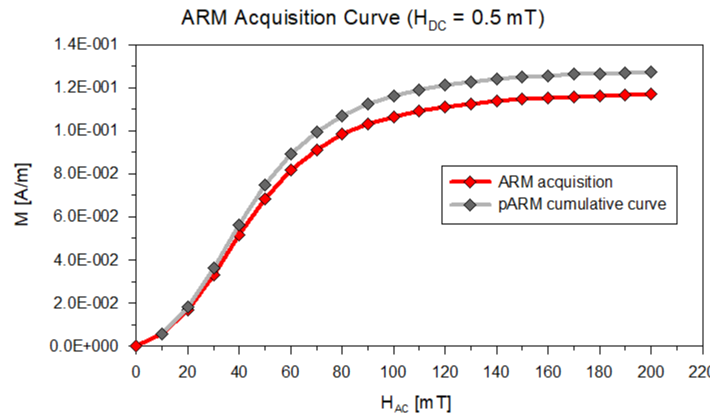

AAMR
0
Geographic Coordinate System
Equal-Area Projection
N = 18
270
90
180
Max
Int
Min
B
1.0
0.5
0.0
-0.5
-1.0
T
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
1.08
1.09
1.10
P

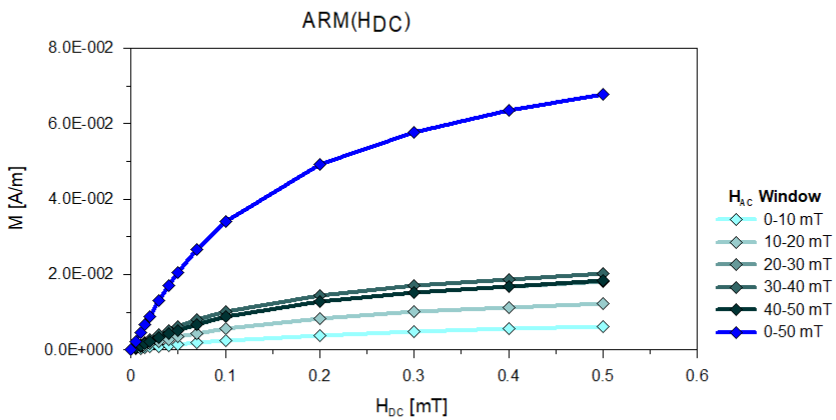
Mineralogically controlled

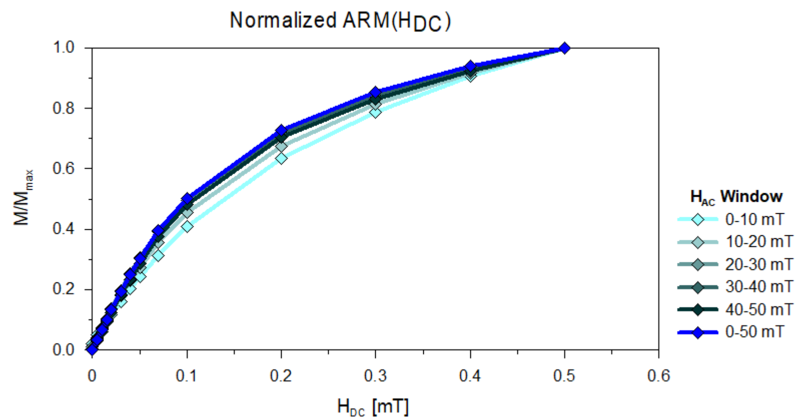


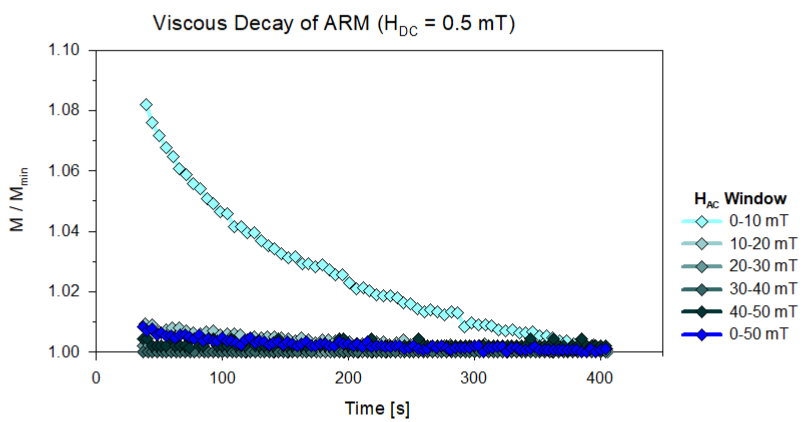
Černý, 2017, PhD Thesis

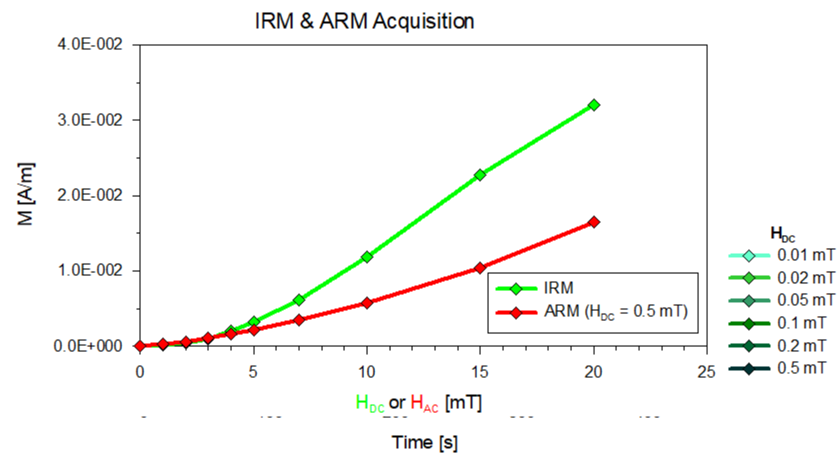

pARM Acquisition (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]


ARM Acquisition Curve (H_DC = 0.5 mT)
M [A/m]
H_AC [mT]
ARM acquisition
pARM cumulative curve


ARM(HDC)
M [A/m]
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT


Normalized ARM(HDC)
M/M_max
H_DC [mT]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT


Viscous Decay of ARM (H_DC = 0.5 mT)
M / M_min
Time [s]
H_AC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT

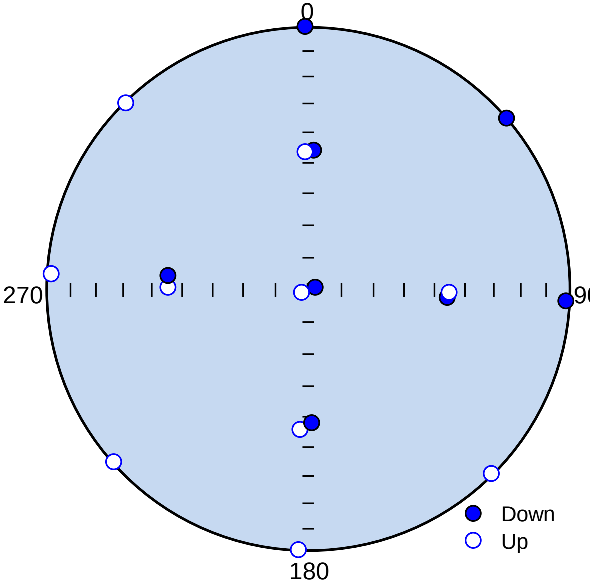

IRM & ARM Acquisition
M [A/m]
H_DC or H_AC [mT]
IRM
ARM (H_DC = 0.5 mT)
H_DC
0.01 mT
0.02 mT
0.05 mT
0.1 mT
0.2 mT
0.5 mT
Time [s]

H_{AC} = 10 - 40 mT, H_{DC} = 0.05 & 0.5 mT

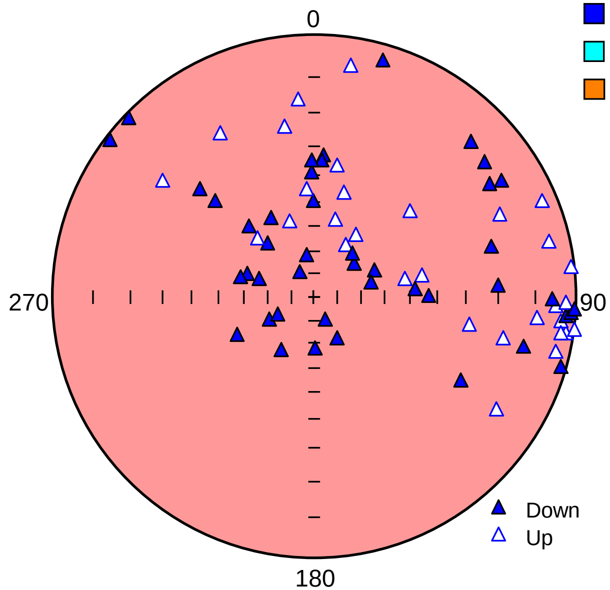
Moderate magnetization

Weak anisotropy

Magnetizing directions



Residuals

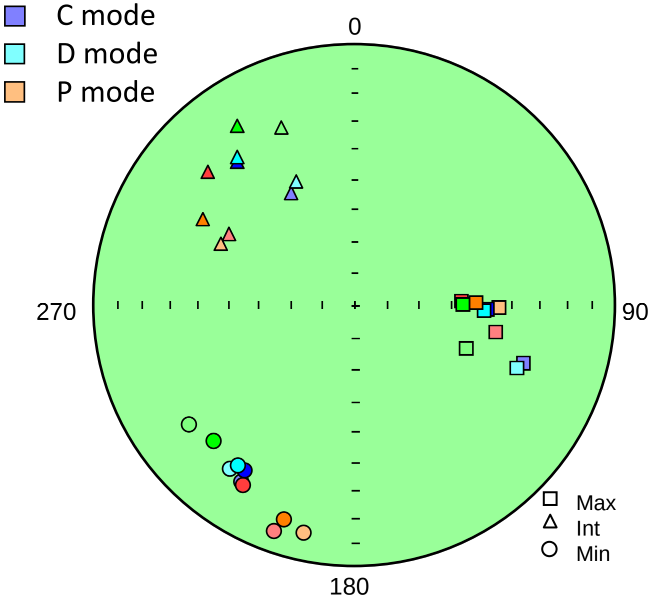


Demag. after each position (U1-D-U2) H_{DC} = 0.5 mT

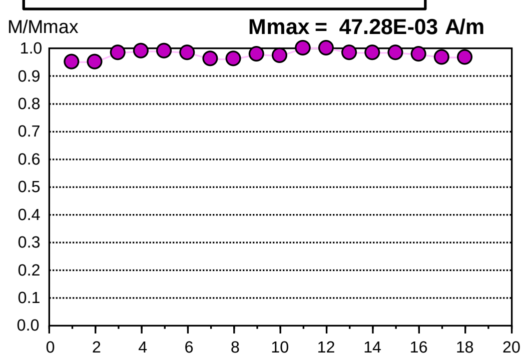
Demag. after each position (U1-D-U2) H_{DC} = 0.05 mT

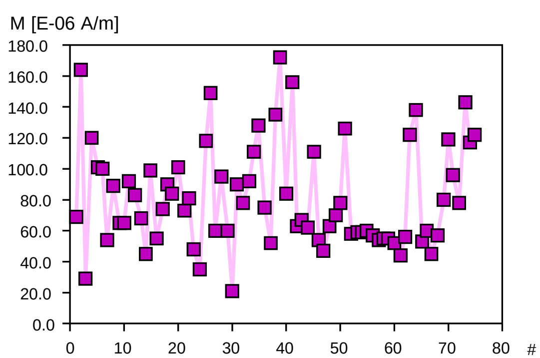
A mode
B mode
C mode
D mode
P mode

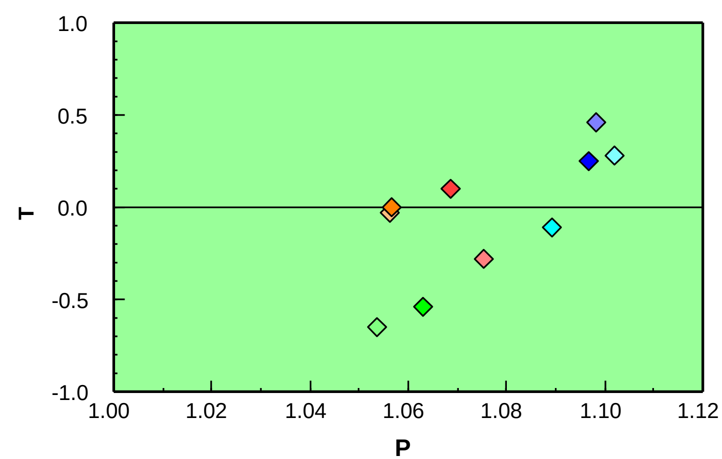
AARM tensors



H_{AC} = 10 - 40 mT, H_{DC} = 0.5 mT





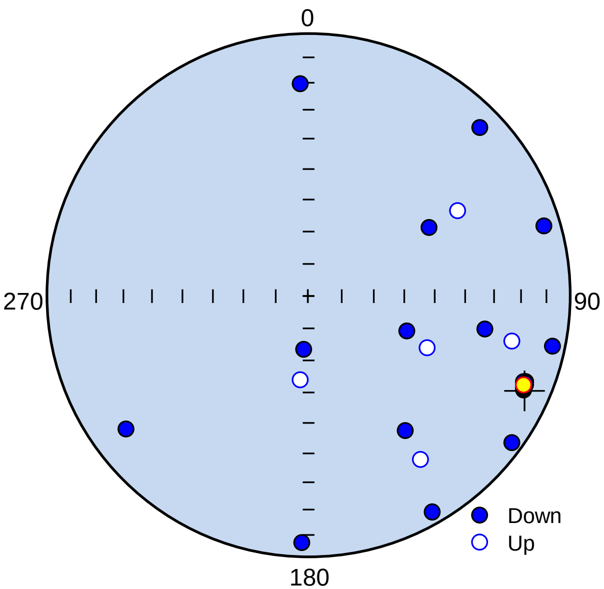


H_{AC} = 10 - 40 mT, H_{DC} = 0.5 mT

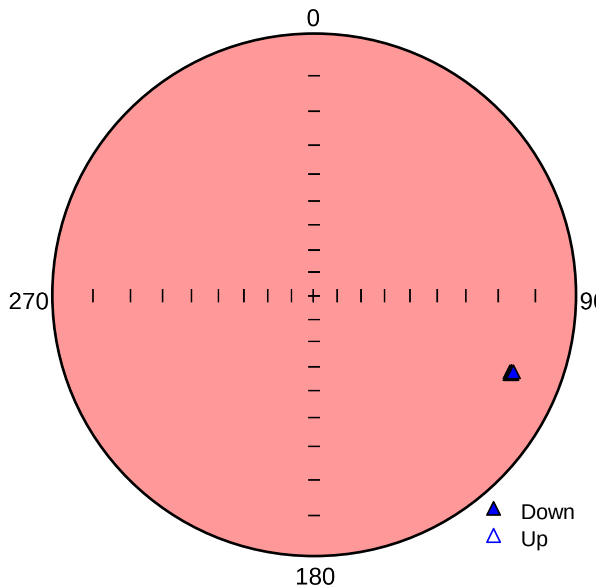
Strong residual artifact!

Demag. after each position **(U1-D-U2)**

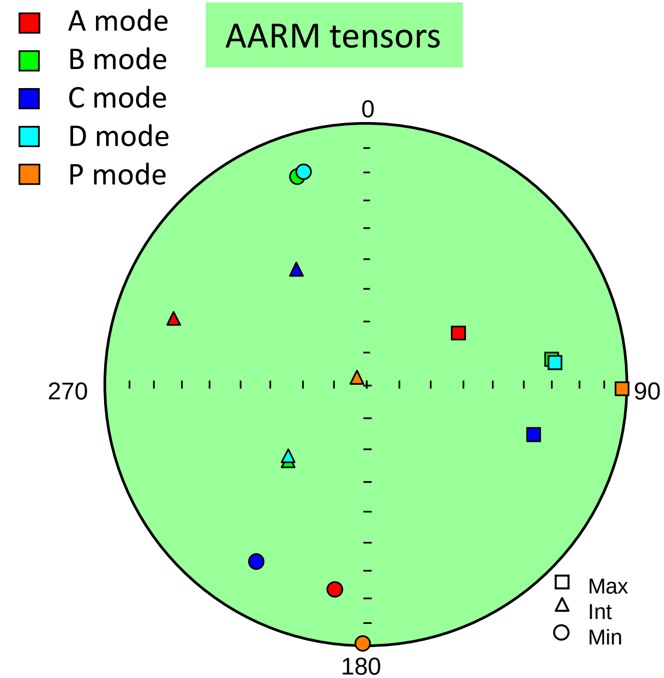
Magnetizing directions

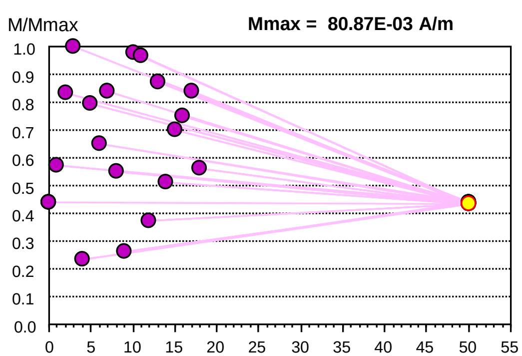


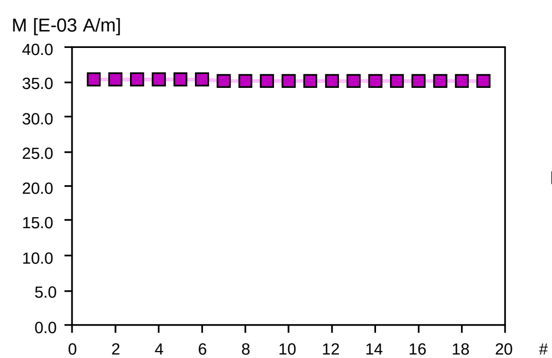
Residuals

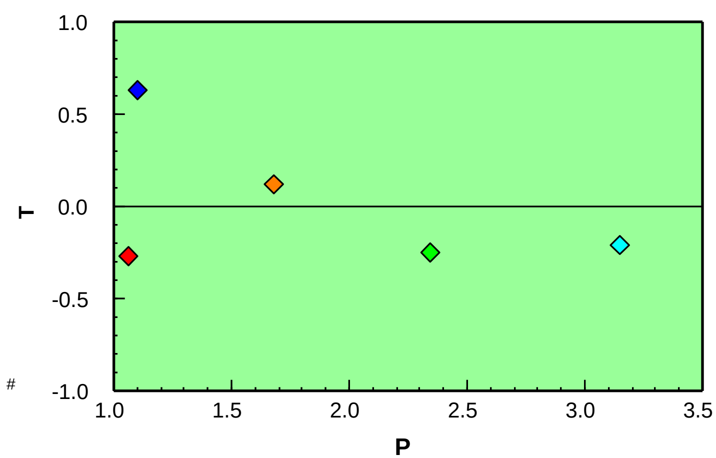


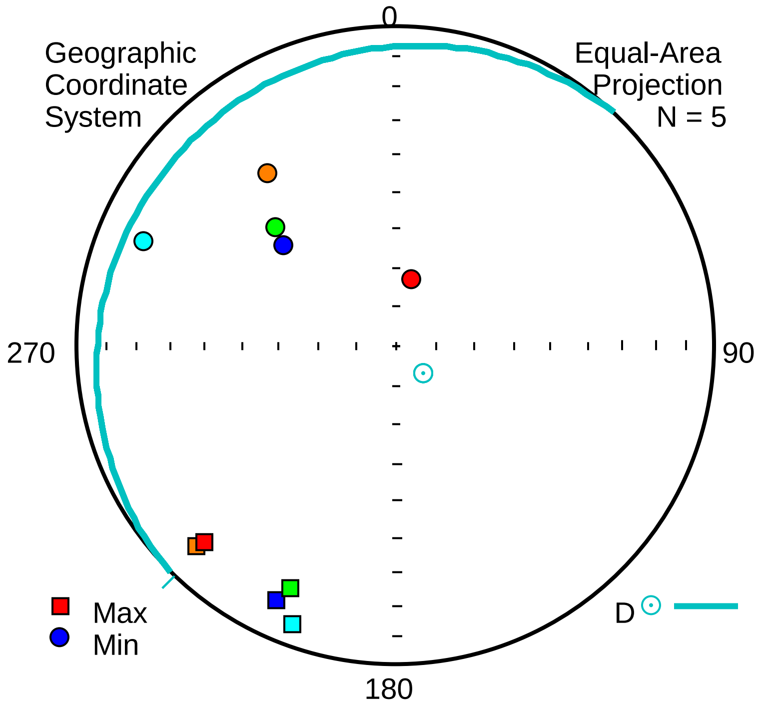
AARM tensors

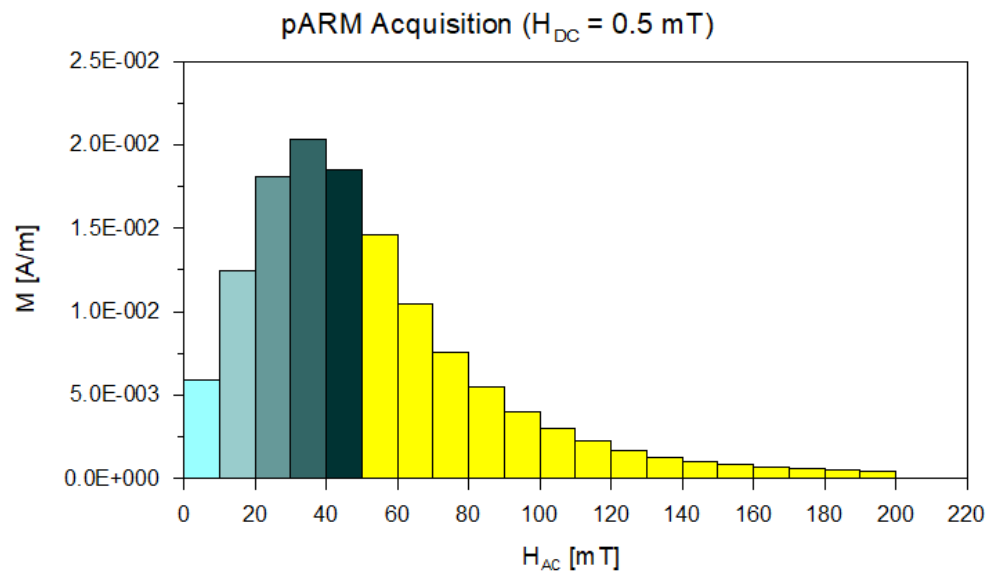


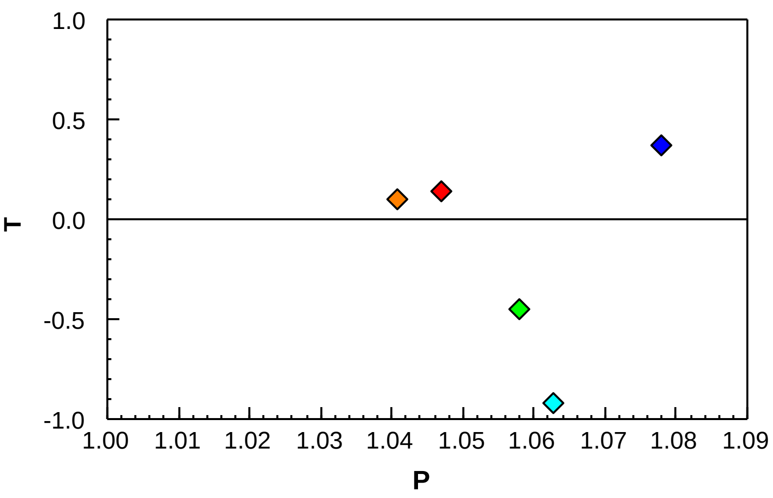


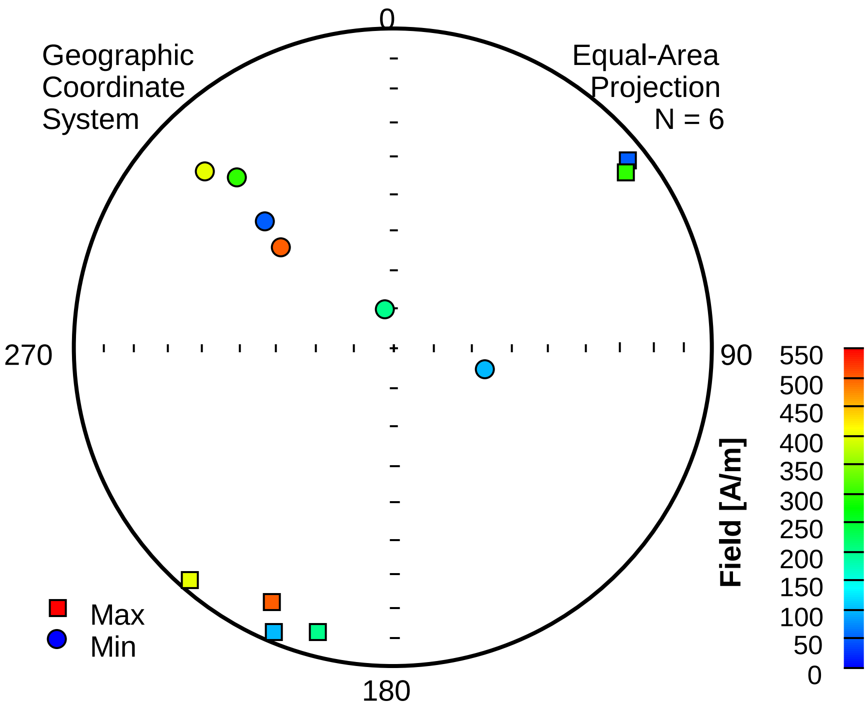


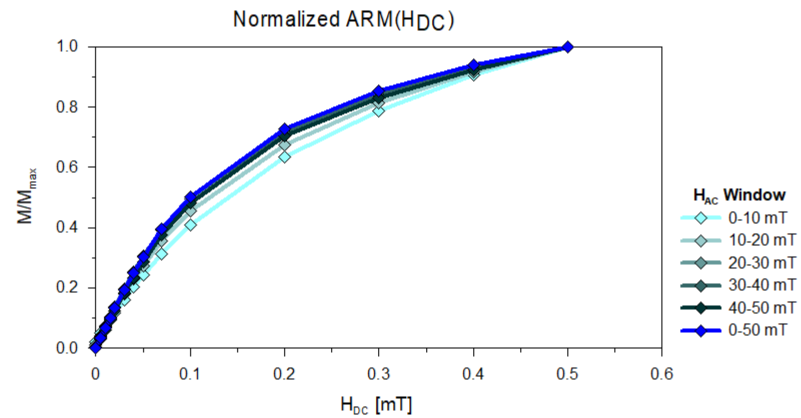


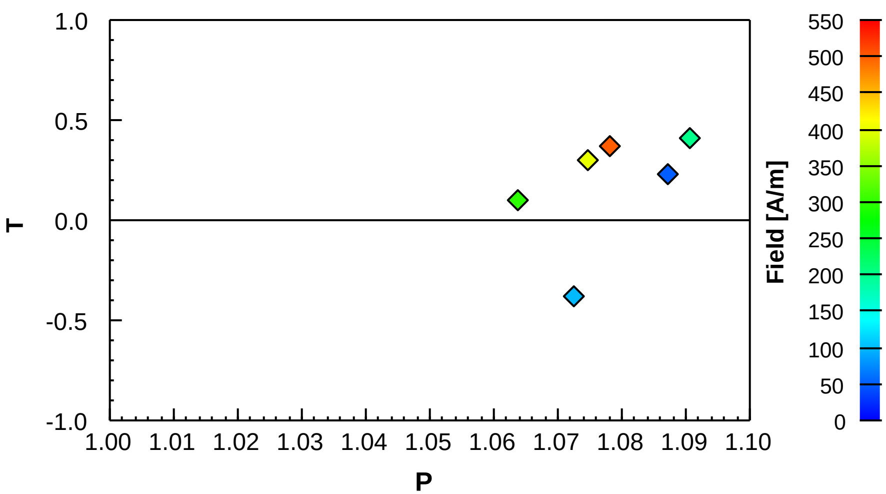

0
90
180
270
Geographic
Coordinate
System
Equal-Area
Projection
N = 5
Max
Min
D

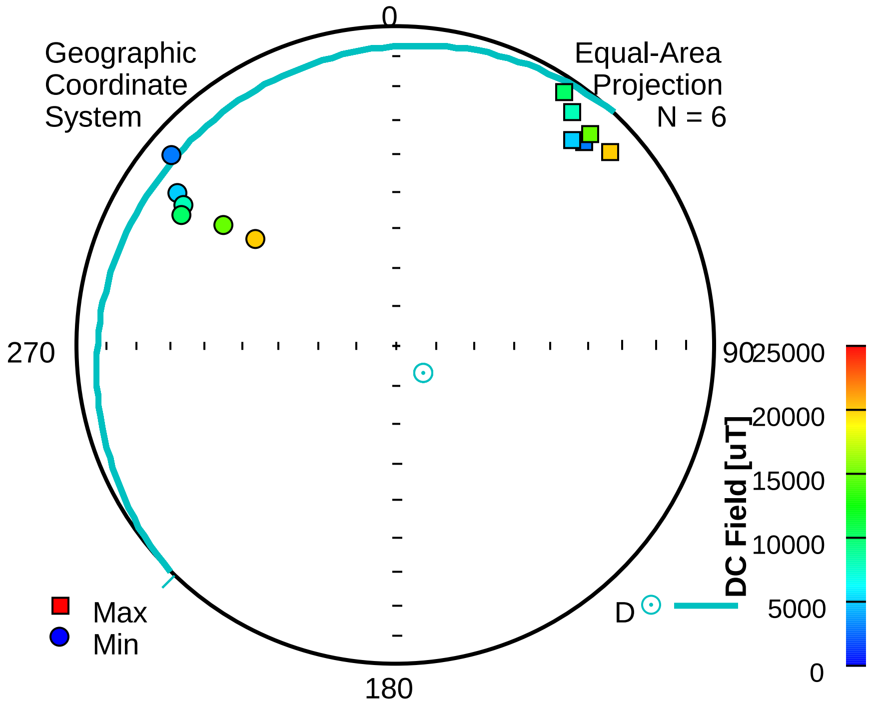

pARM Acquisition (H_{DC} = 0.5 mT)
M [A/m]
2.5E-002
2.0E-002
1.5E-002
1.0E-002
5.0E-003
0.0E+000
0
20
40
60
80
100
120
140
160
180
200
220
H_{AC} [mT]

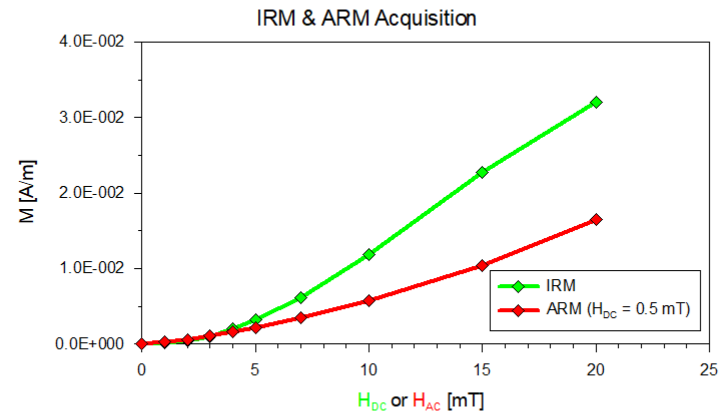

1.0
0.5
0.0
-0.5
-1.0
T
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
1.08
1.09
P

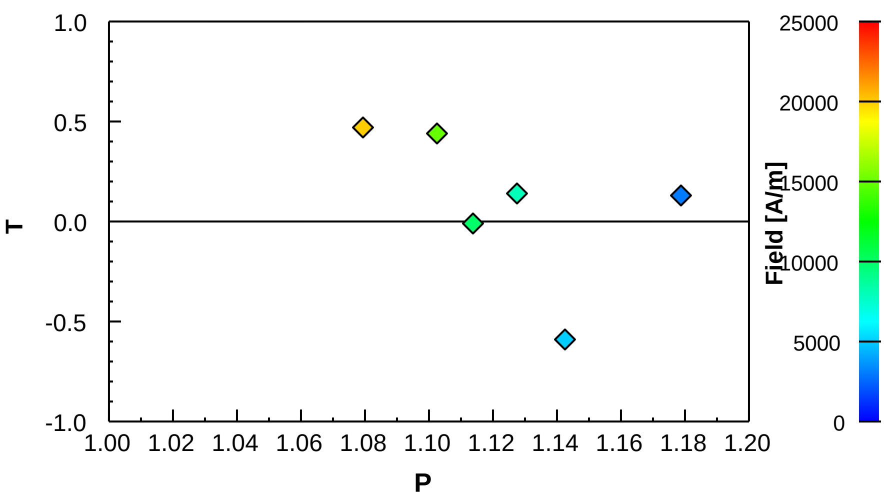

0
Geographic
Coordinate
System
Equal-Area
Projection
N = 6
270
90
180
Max
Min
Field [A/m]
550
500
450
400
350
300
250
200
150
100
50
0


Normalized ARM(HDC)
M/Mmax
1.0
0.8
0.6
0.4
0.2
0.0
0
0.1
0.2
0.3
0.4
0.5
0.6
HDC [mT]
HAC Window
0-10 mT
10-20 mT
20-30 mT
30-40 mT
40-50 mT
0-50 mT


1.0
0.5
T
0.0
-0.5
-1.0
1.00
1.01
1.02
1.03
1.04
1.05
1.06
1.07
1.08
1.09
1.10
P
Field [A/m]
550
500
450
400
350
300
250
200
150
100
50
0


0
Geographic
Coordinate
System
Equal-Area
Projection
N = 6
270
90
180
Max
Min
D
DC Field [uT]
25000
20000
15000
10000
5000
0


IRM & ARM Acquisition
M [A/m]
4.0E-002
3.0E-002
2.0E-002
1.0E-002
0.0E+000
0
5
10
15
20
25
IRM
ARM (H_DC = 0.5 mT)
H_DC or H_AC [mT]


T
1.0
0.5
0.0
-0.5
-1.0
1.00
1.02
1.04
1.06
1.08
1.10
1.12
1.14
1.16
1.18
1.20
P
Field [A/m]
25000
20000
15000
10000
5000
0

1. Acquire a **coercivity spectrum** of some representative sample(s) to decide which coercivity window is of interest (controlled by **AC field**).
2. **DC bias field** controls how much a particular coercivity sub-population is magnetized. Test whether acquired ARM is linear as a function of DC field and try to set the highest DC field which still falls within a linear range. Note that by selecting higher DC field, one may reach up to two orders of magnitude difference between the magnetized and demagnetized states.
3. Test whether acquired ARM is **stable in time** (effect of viscous decay), if not, each directional ARM should be measured in the same time after ARM has been acquired or long time after that to allow the viscous magnetization to relax.
4. Try to reach the optimum balance between precision and speed (number of magnetizing directions). The precise fitting of AARM tensor strongly depends on the **residual magnetization**. Prior to any directional ARM acquisition, demagnetize a sample using the highest AC field possible. If the strength of the residual magnetization is in the same order of magnitude as that of magnetized states, one is strongly advised to use magnetizing design employing pairs of antipodal magnetizing directions (**A-** or **C-modes**) where the constant residue is compensated.
5. If the residual magnetization is comparable or higher than that of magnetized states, AAMR tensor fitting may be very imprecise even when the antipodal magnetizing directions are used.

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Lanza, R. & Meloni, A. 2006. The Earth's Magnetism: An Introduction for Geologist. *Springer*, 278 pp. (Chapter 5).

Jackson, M., 1991. Anisotropy of magnetic remanence: a brief review of mineralogical sources, physical origins, and geological applications, and comparison with susceptibility anisotropy. Pure and Applied Geophysics, 136: 1–28.

Hirt, A. 2007. Magnetic Remanence, Anisotropy. Encyclopedia of Geomagnetism and Paleomagnetism. *Springer*. 535-540.

Jackson, M. 2007. Magnetization, Isothermal Remanent. Encyclopedia of Geomagnetism and Paleomagnetism. *Springer*. 589-594.

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Gilder, S.A., K. He, M. Wack, and J. Ježek (2019), Relative paleointensity estimates from magnetic anisotropy: Proof of concept, Earth and Planetary Science Letters, 519, 83-91.

Cautionary note!!!

Thanks for your attention!

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