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

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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.
### Theoretical background

**Hysteresis loop**

- **M**: Magnitude of magnetization
- **M_i**: Induced magnetization
- **M_r**: Remanent magnetization
- **M = M_i + M_r**

**Equations**:

- **M_i = k \times H**
- **M_r = k_r \times H**

**Graphs**:

- **Saturation magnetization**
- **Remanent magnetization**
- **Coercive force**
- **Paramagnetic**
- **Diamagnetic**
- **Ferro magnetic**

**Induced magnetization**

**Remanent magnetization**

**Magnetic susceptibility**

**Remanent susceptibility**
Susceptibility vs. Remanence

<table>
<thead>
<tr>
<th>Diamagnetism</th>
<th>Paramagnetism</th>
<th>Ferromagnetism (s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k &lt; 0$</td>
<td>$k &gt; 0$</td>
<td>$k &gt;&gt; 0$</td>
</tr>
</tbody>
</table>

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 suscebtibility 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

\[
\begin{pmatrix}
M_{r1} \\
M_{r2} \\
M_{r3}
\end{pmatrix} =
\begin{pmatrix}
k_{r11} & k_{r12} & k_{r13} \\
k_{r21} & k_{r22} & k_{r23} \\
k_{r31} & k_{r32} & k_{r33}
\end{pmatrix}
\begin{pmatrix}
H_1 \\
H_2 \\
H_3
\end{pmatrix}
\]
Concept of magnetic fabric

Principal remaneibilities

\[ k_1 \geq k_2 \geq k_3 \]

Mean remaneability

\[ k_m = \frac{k_1 + k_2 + k_3}{3} \]

Degree of anisotropy

\[ P = \frac{k_1}{k_3} \]

Shape parameter

\[ T = \frac{2 \eta_2 - \eta_1 - \eta_3}{\eta_1 - \eta_3} \]

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

a) AF Demagnetization

b) Anhysteretic Magnetization

c) Pulse Magnetization

d) Pulse Magnetization
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

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
Rema6
Instrument control SW for JR-6(A)

LDA5
Instrument control SW for LDA5
Even a small baby can handle anisotropy of magnetic remanence (with AGICO instruments)!
<table>
<thead>
<tr>
<th>Name</th>
<th>Rock type</th>
<th>Location</th>
<th>Ferromagnetic carrier (?)</th>
<th>Magnetic susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS32</td>
<td>Limestone</td>
<td>Italy</td>
<td>Magnetite</td>
<td>ca. 10 E-6</td>
</tr>
<tr>
<td>CS34</td>
<td>Camptonite (volcanic rock)</td>
<td>Czech Republic</td>
<td>Titanomagnetite</td>
<td>ca. 150 E-3</td>
</tr>
<tr>
<td>JH10</td>
<td>Shale</td>
<td>Czech Republic</td>
<td>Pyrrhotite</td>
<td>ca. 800 E-6</td>
</tr>
<tr>
<td>VIK01</td>
<td>Mudstone</td>
<td>Svalbard</td>
<td>Magnetite</td>
<td>ca. 300 E-6</td>
</tr>
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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
Geographic Coordinate System
Equal-Area Projection
N = 10

Geographic Coordinate System
Equal-Area Projection
N = 7

Max
Int
Min

Max
Int
Min

Kmean E-06 SI

T

P

T

P
**AS32 – Directional Acquisition of ARM**

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

**Weak magnetization**

**Weak anisotropy**

- **Magnetizing directions**
- **Residuals**
- **AARM tensors**

**Graphs and Diagrams**

- Magnetizing directions for different modes (A, B, C, D, P).
- Residuals showing demagnetization after each position and pair of positions.
- AARM tensors with max, int, and min values highlighted.

**Related Figures**

- ARM (AC=20-40 mT, DC=0.5 mT) graph showing the change in M [A/m] across different positions.
- Magnitude of M [E-06 A/m] graph with data points over a range of values.

**Key Points**

- Weak magnetization and weak anisotropy properties are discussed.
- Magnetizing directions and residual analysis are graphically represented.
- AARM tensors are illustrated with max, int, and min values.

**Legend**

- **Red**: Demag after each pair.
- **Blue**: Demag after each position.
- **Legend for A ARM tensors**:
  - **A mode**
  - **B mode**
  - **C mode**
  - **D mode**
  - **P mode**

**Axes**

- **Position**
- **M [A/m]**
- **M [E-06 A/m]**

**Graph Titles**

- ARM (AC=20-40 mT, DC=0.5 mT)
- Magnitude of M [E-06 A/m]
CS34 – Magnetic characteristics

**pARM Acquisition (H\textsubscript{DC} = 0.5 mT)**

**ARM Acquisition Curve (H\textsubscript{DC} = 0.5 mT)**

**ARM(H\textsubscript{DC})**

**Normalized ARM(H\textsubscript{DC})**

**Viscous Decay of ARM (H\textsubscript{DC} = 0.5 mT)**

**IRM & ARM Acquisition**
Very strong magnetization!
Weak anisotropy

Magnetizing directions

Residuals

AARM tensors

H_{AC} = 0 - 40 \text{ mT}, \ H_{DC} = 0.5 \text{ mT}
Example 3: JH10 – Location

(a) Avalonian–Cadomian belt
(c. 570 Ma)

(b) Late Paleozoic

(c) Paleolatitude

(d) Bohemian Massif

Examination:
- Lower Paleozoic sedimentary sequences of the Teplá-Barrandian Unit
- Low- to medium-grade metamorphic units
- Neoproterozoic volcano-sedimentary sequences of the Teplá-Barrandian Unit
- High-grade metamorphic units
- Cambrian - Lower Carboniferous sedimentary sequences
- Cretaceous sedimentary sequences
- Plutonic rocks (undifferentiated)
JH10 – Site characteristics

Courtesy of Jaroslava Hajna, Prague
JH10 – Magnetic susceptibility

(a) Frequency distribution of bulk susceptibility in SI units.

(b) Two-dimensional scatter plot of AMS ellipsoids showing high-intensity oblate and prolate specimens.

(c) Graph showing variation of k with temperature T.

(d) Graph showing variation of k with magnetic field H.
AMS

Geographic Coordinate System
Equal-Area Projection
N = 14

Max
Int
Min

AMS vs. AAMR

AAMR

Geographic Coordinate System
Equal-Area Projection
N = 9

Max
Int
Min

Kmean [E-06 Si]
JH10 – Magnetic characteristics

pARM Acquisition ($H_{dc} = 0.5$ mT)

ARM Acquisition Curve ($H_{dc} = 0.5$ mT)

ARM(HDC)

Normalized ARM(HDC)

Viscous Decay of ARM ($H_{dc} = 0.5$ mT)

IRM & ARM Acquisition
**H\textsubscript{AC} = 10 - 40 mT, H\textsubscript{DC} = 0.5 mT**

**Strong magnetization**

**Very strong anisotropy!**

**Magnetizing directions**

**Residuals**

**AARM tensors**

**ARM (AC = 20-40 mT, DC = 0.5 mT)**

**M [E-03 A/m]**

**T**

**P**
JH10 – AARM in various bias DC field

Geographic Coordinate System

Equal-Area Projection
N = 6

0

90

270

180

Max

Int

Min

Field [A/m]

Normalized ARM(HDC)

Hₐ Window

- 0-10 mT
- 10-20 mT
- 20-30 mT
- 30-40 mT
- 40-50 mT

0.0

0.5

1.0

0.0

0.5

1.0

Field [A/m]

T

P

550

500

450

400

350

300

250

200

150

100

50

0

550

500

450

400

350

300

250

200

150

100

50

0
JH10 – AIRM in various DC field

Geographic Coordinate System

Equal-Area Projection
N = 6

Max
Int
Min

Field [A/m]

P

T

Field [A/m]

DC [mT]
Example 4: VIK01 – Location

Stage 1: compression
53 - 47 Ma (An 24 - 21)

Stage 2: dextral transpression
47 - 34 Ma (An 21 - 13)

Norwegian Polar Institute

Piepjohn et al., 2016, J. Geol. Soc.
Hornsund, TWN site

Bellsund, REIN site

Sassenfjorden, VIK2 site

Sassenfjorden, VIK2 site

Courtesy of Katarzina Dudzisz, Warsaw, Poland
VIK01 – Inverse fabric carried by siderite

Mineralogically controlled

<table>
<thead>
<tr>
<th>Structurally normal anisotropy</th>
<th>Crystallographically normal magnetic anisotropy</th>
<th>Crystallographically inverse magnetic anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td><img src="image" alt="Diagram A" /></td>
<td><img src="image" alt="Diagram B" /></td>
</tr>
<tr>
<td>B</td>
<td><img src="image" alt="Diagram C" /></td>
<td><img src="image" alt="Diagram D" /></td>
</tr>
</tbody>
</table>

Explanations:
- $K_1$ Direction
- $c$-axis of a Mineral
- Bedding Plane
- Mineral Grain/Crystal

Černý, 2017, PhD Thesis
VIK01 – Magnetic characteristics

**pARM Acquisition (H\textsubscript{DC} = 0.5 mT)**

**ARM Acquisition Curve (H\textsubscript{DC} = 0.5 mT)**

**ARM(H\textsubscript{DC})**

**Normalized ARM(H\textsubscript{DC})**

**Viscous Decay of ARM (H\textsubscript{DC} = 0.5 mT)**

**IRM & ARM Acquisition**

**H\textsubscript{DC} Window**
- 0-10 mT
- 10-20 mT
- 20-30 mT
- 30-40 mT
- 40-50 mT
- 0-50 mT
**VIK01 – Directional Acquisition of ARM**

**Moderate magnetization**

**Weak anisotropy**

\[ H_{AC} = 10 - 40 \text{ mT}, \quad H_{DC} = 0.05 \& 0.5 \text{ mT} \]

---

**Residuals**

**Magnetizing directions**

**AARM tensors**

**H}_{AC} = 10 - 40 \text{ mT}, \quad H}_{DC} = 0.05 \& 0.5 \text{ mT} \]
$H_{AC} = 10\text{ - }40\text{ mT},\ H_{DC} = 0.5\text{ mT}$

**Strong residual artifact!**

**Magnetizing directions**

**Residuals**

**AARM tensors**
VIK01 – AARM in various coercivity windows

Geographic Coordinate System

Equal-Area Projection
N = 5

Max
Min

pARM Acquisition (H_{DC} = 0.5 mT)

M [A/m]

H_{AC} [mT]

T

P

1.0

0.5

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
VIK01 – AARM in various bias DC fields

Geographic Coordinate System
Equal-Area Projection
N = 6

Normalized ARM(HDC)

Field [A/m]

P

T

Field [A/m]

Hc Window
- 0-10 mT
- 10-20 mT
- 20-30 mT
- 30-40 mT
- 40-50 mT
- 0-50 mT
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.


Cautionary note!!!
Thanks for your attention!

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