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Reproducibility of High Field Magnetic Remanence: Implications for Precision of High Field Remanence Anisotropy

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Study Purpose

- ☐ Final goal of the present investigation is to develop a technique for measurement of the Anisotropy of High Field Magnetic Remanence (hf-AMR) of rocks and minerals.
- ☐ Measurement of hf-AMR is not a single measuring process, it consists of several separated procedures as demagnetization, impulse magnetization, measurement of remanent magnetization, processing of measurement. It is important to reveal how precisely is obtained the directional remanence susceptibility (remanebility), which dominantly controls the accuracy of determination of hf-AMR, through the above technique. This is the purpose of the present poster.
- ☐ There are two techniques for determination of AMR, the vectorial and projection ones. This poster exclusively deals with the latter.

Principles of High Field Anisotropy

Theory of the low-field AMS is based on assumption of linear relationship between magnetization and magnetizing field, traditionally described as

$$\boldsymbol{M} = \mathbf{K}\,\boldsymbol{H}$$

where ***M*** is magnetization vector, ***H*** is field intensity vector, and **K** is symmetric second-rank tensor of magnetic susceptibility. The anisotropy of magnetic remanence (AMR) is defined analogously (e.g., *Jackson, 1991*)

$$\boldsymbol{M}_R = \mathbf{R}\,\boldsymbol{H}$$

where $\boldsymbol{M}_R$ is remanent magnetization vector and **R** is second-rank tensor called remanence susceptibility tensor (*Jackson, 1991*) or remanebility tensor (*Jelínek, 1993*). As the AMR requires relatively strong fields, in which remanence is a non-linear function of the field intensity, M_R and H are not in general related by a second-rank tensor. Nevertheless, the AMR can still, in many cases, be described by a symmetric second-rank tensor

$$\boldsymbol{M}_R = \mathbf{R}\,\boldsymbol{H}_u\,f(H)$$

where $f(H)$ describes the non-linear field dependence and $\boldsymbol{H}_u$ is the unity vector parallel to the field vector (e.g., *Jackson, 1991; Hrouda, 2002*).

Precision of AMR Measurement

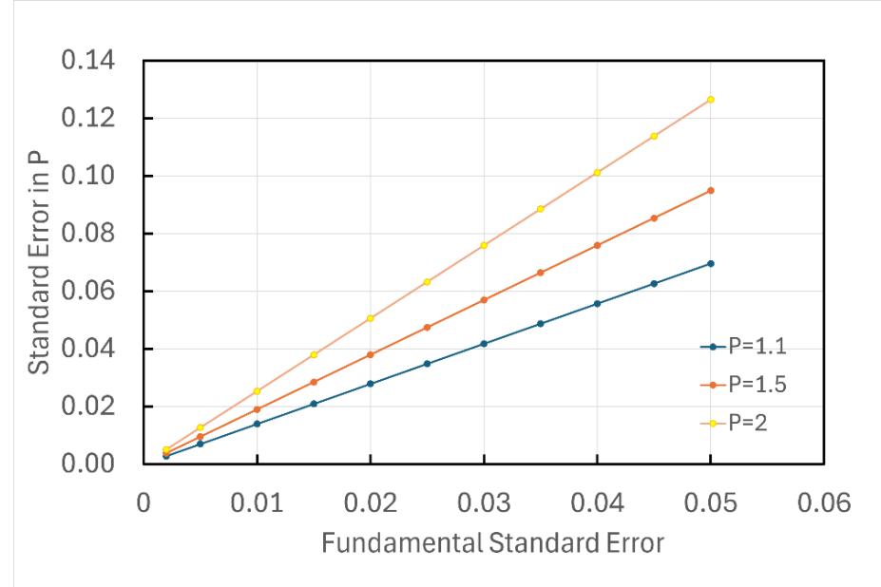
The basic parameter characterizing the precision of the AMR measurement is analogous to that of AMS, being called the Standard Error of Directional Remanebility (Jelínek, 1977)

$$s = \sqrt{\frac{1}{n-6}\sum_{i=1}^{n}(Rm_i - Rf_i)^2}$$

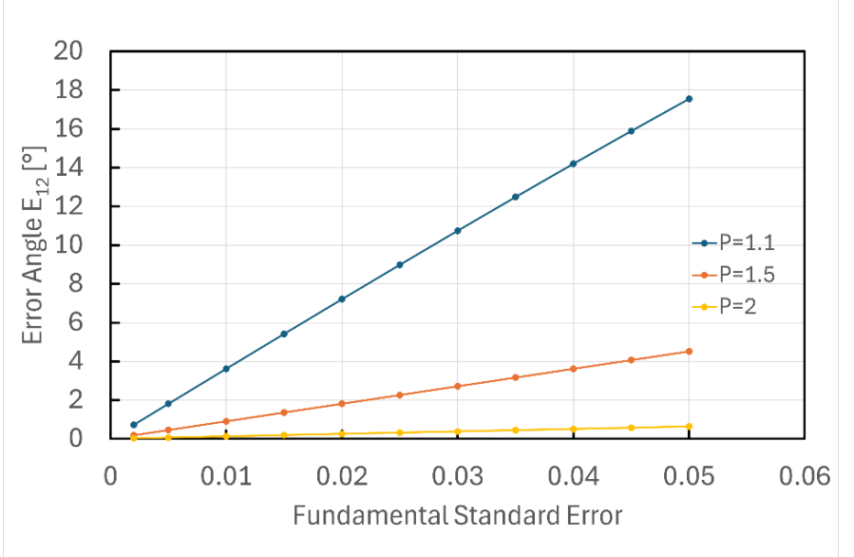
where (Rm_i) is remanebility measured in *i-th* direction, Rf_i is remanebility in the same direction calculated from the fitted tensor and n is number of measuring directions. In rotatable designs of measuring directions, the standard error of principal remanebilities is equal for all three principal values and given as $s_k = s\sqrt{6/n}$. The error, $S=s/R_m$ (R_m is mean remanebility), is called Relative Standard Error (of Directional Remanebility). The standard errors of anisotropy parameters P and T can then be calculated using the error propagation law (e.g., Hrouda et al., 2023). The error angles in determining the principal directions are parallel to the principal planes of the AMR ellipsoid. For example, the error angle in the R_1, R_2 plane is: $E_{12}=\mathrm{atan}[s/(2|R_1-R_2|)]$. The other two angles ($E_{23}$, E_{13}) are defined analogously, $E_{23}=\mathrm{atan}[s/(2|R_2-R_3|)$, $E_{13}=\mathrm{atan}[s/(2|R_1-R_3|)$.

In addition, the Standard Error of Directional Remanebility equals the Measuring Error, s, defined as standard deviation of normally distributed repeated directional measurements. The relative measuring error is s_r,$=s/R_m$.

Relationship between Measuring Error and AMR



The standard error of anisotropy degree, ΔP, ($P=R_1/R_3$ where $R_1>R_2>R_3$ are principal remanebilities) virtually linearly increases with increasing measuring error. If one considers the maximum acceptable error $\Delta P=0.01$ for $P=1.1$, $\Delta P=0.05$ for $P=1.5$, and $\Delta P=0.1$ for $P=2$, the relative standard error (measuring error σ_r) should be less than 0.007, 0.025 and 0.04, respectively.



In case of $P = 1.1$ and $E_{12} < 5°$, measuring error should be $\sigma_r < 0.015$.
In cases of $P=1.5$, $P=2$ and $E_{12}<5°$, the measuring error is sufficient to be $\sigma_r<0.05$.

Instrumentation

JR-6 - HIGH SENSITIVITY SPINNER MAGNETOMETER

PUMA - HIGH FIELD IMPULSE MAGNETIZER

LDA5 - AF DEMAGNETIZER
PAM1 - MAGNETIZER

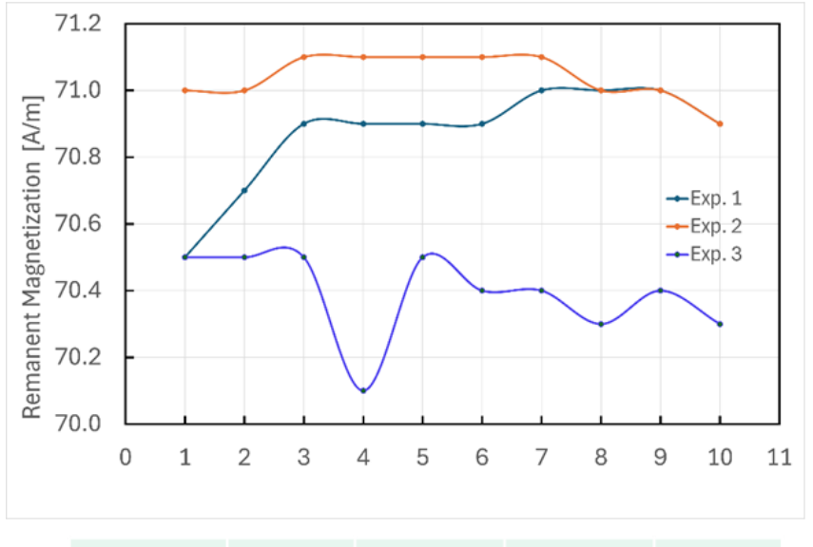
PUMA Impulse Magnetizer

- ✓ Impulse magnetization
- ✓ 1 mT - 5000 mT (5 Tesla)
- ✓ 18 magnetization directions
- ✓ 1 inch cylinders or 20/23 mm cubes
- ✓ User friendly software

Experiments, 1st Set

Purpose: Find out variation of RM after repeated magnetizing in one direction. **Material:** Artificial Magnetite disseminated in Plaster of Paris.

Before each experiment, tumble demag to10^{-3} A/m.



Experiment 1: one impulse magnetization at 1 T along *Z* axis without demag between individual magnetizations.

Experiment 2: three impulses magnetization at 1 T along *Z* axis without demag between individual magnetizations.

Experiment 3: three impulses magnetization at 1 T along *Z* axis. Tumble demag (100 mT) between magnetizations.

Experiment	Mean A/m	RMS Error A/m	RMS/Mean percentage	Dmax A/m
Exp. 1	70.87	0.1567	0.0022	0.0071
Exp. 2	71.04	0.0699	0.0010	0.0028
Exp. 3	70.39	0.1287	0.0018	0.0057

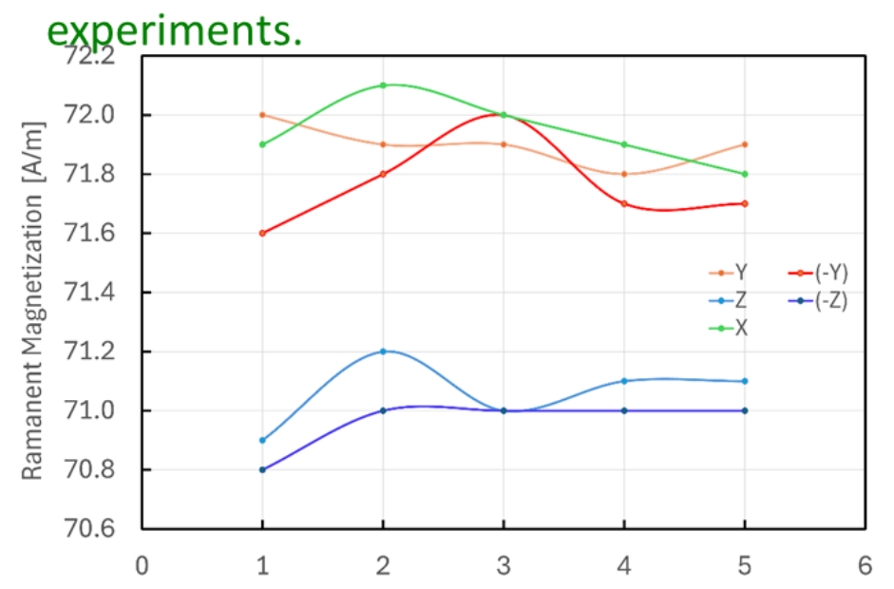
Dmax is difference between maximum and minimum values.

Relative Error (RMS/Mean) is in all cases about 0.002 (0.2 %), Dmax is less than 1%.

Excellent Reproducibility. Demag does not improve it.

Experiments, 2nd Set

Purpose: Testing whether specimen remagnetization after changing direction is complete.
Material: Artificial Magnetite disseminated in Plaster of Paris, the same as in the 1st Set.
Tumble demag to10^{-3} A/m was made before each experiment, not between the experiments.



In all experiments, 3 impulse magnetization.

Exp. 4: magnetization parallel to –*Z* axis.
Exp. 5: magnetization parallel to +*Y* axis.
Exp. 6: magnetization parallel to –*Z* axis.
Exp. 7: magnetization parallel to –*Y* axis.
Exp. 8: magnetization parallel to +X axis.

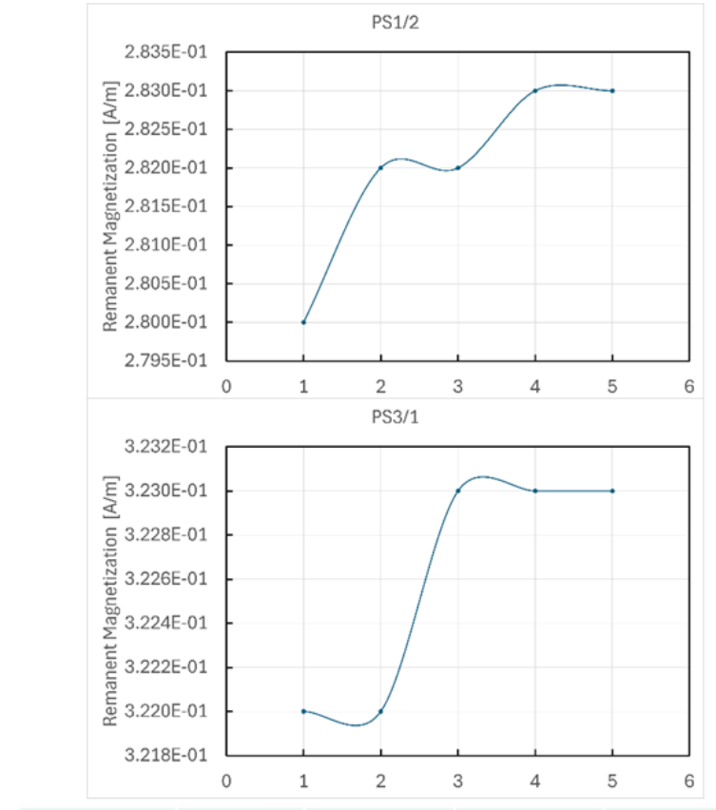
Experiment	Mean A/m	RMS Error A/m	RMS/Mean percentage	Dmax A/m
Exp. 4	-70.96	0.0894	0.0013	0.0028
Exp. 5	71.5	0.6301	0.0088	0.0056
Exp. 6	71.06	0.1140	0.0016	0.0042
Exp. 7	71.96	0.0894	0.0012	0.0042
Exp. 8	71.94	0.1140	0.0016	0.0042

Relative Error (RMS/Mean) is mostly (except Exp. 5) less than 0.002 (0.2 %), Dmax is about 0.5%.

Virtually Complete Remagnetization.

Experiments, 3rd Set

Purpose: Testing specimens with natural magnetite.
Material: Natural Magnetite (Kiruna) disseminated in Plaster of Paris.
Tumble AF demag with 100 mT was made before measuring each specimen.



In both experiments, 3 impulse magnetization.

Exp. 9: specimen PS1/2, magnetization parallel to *Z* axis.

Exp. 10: specimen, PS3/1, magnetization parallel to Z axis.

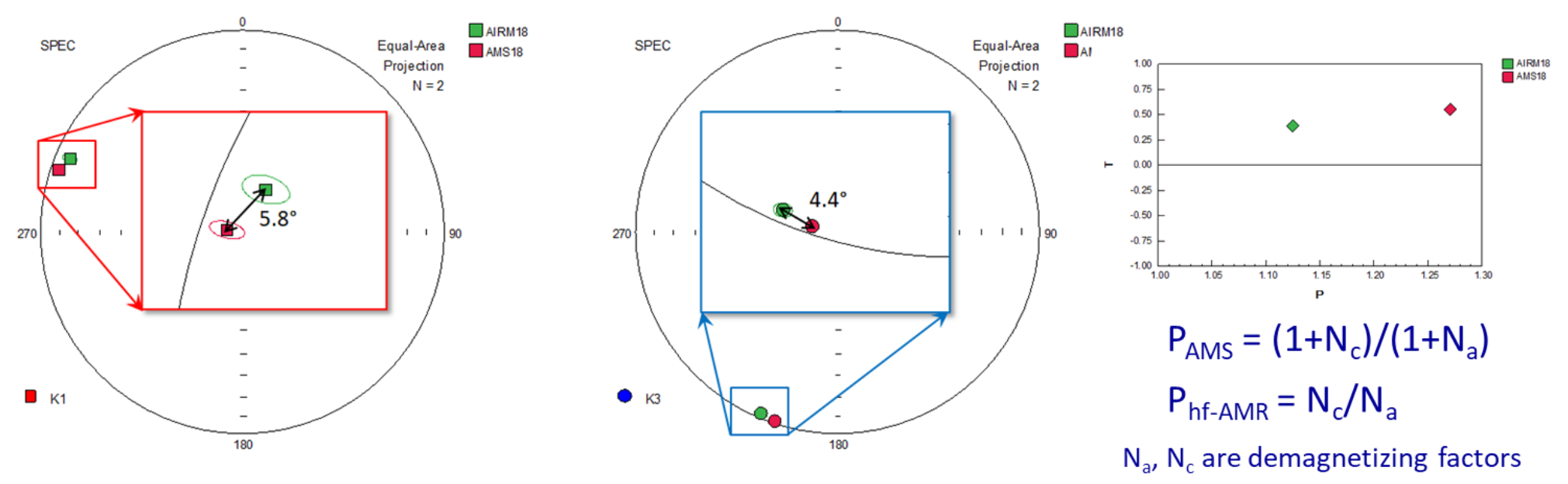
Experiment	Mean A/m	RMS Error A/m	RMS/Mean percentage	Dmax A/m
Exp. 9	0.282	0.0012	0.0043	0.0106
Exp. 10	0.3226	0.0005	0.0017	0.0031

Relative Error (RMS/Mean) is less than 0.005 (0.5 %), Dmax is 1 % and 0.3%.

Reasonable Reproducibility.

Comparison of hf-AMR and AMS

Even though remanence and susceptibility are different physical entities, it would be useful to compare hf-AMR to AMS to reveal whether they differ mildly or dramatically. A specimen whose magnetism is carried by only one mineral (magnetite) is used for this purpose.



$P_{AMS} = (1+N_c)/(1+N_a)$

$P_{hf\text{-}AMR} = N_c/N_a$

N_a, N_c are demagnetizing factors

Principal directions obtained by both techniques are very similar. This is expectable because in magnetite both AMR and AMS are controlled by the demagnetizing factor (grain shape). Larger differences are in the degree of anisotropy. This is also expectable because the control by the demagnetizing factor slightly differs in both cases.

AGICO 18 vs. Girdler 9 Measuring Designs

Manual measurement of hf-AMR is rather laborious (automatic one has not been developed), measurement of one specimen takes about an hour using Agico 18 directions design. Girdler design of 9 directions is much faster (about half an hour) but provides us theoretically with less precise results. For more detail analysis we used the two specimens described in Experiments, 3rd set, and measured them in Agico 18 design. From these measurements we also separated two data sets by 9 directions and denoted them as Girdler 9-1 and Girdler 9-2. The results are in the attached Table.

Specimen	Design	Km	Std Error	Rel Std E	Fitting Error	Rel Fitt E	Conf. E12	Conf. E23	Conf. E13
PS1/2	U18	2.68E-01	0.00079	0.00297	0.00065	0.00242	8.9	2.3	1.8
	G9	2.68E-01	0.00092	0.00342	0.00053	0.00198	13.5	4.2	3.2
	E9	2.68E-01	0.00059	0.00220	0.00034	0.00127	12.5	2.6	2.2
PS3/1	U18	3.16E-01	0.00056	0.00177	0.00032	0.00102	3.8	1.8	1.2
	G9	3.16E-01	0.00050	0.00016	0.00029	0.00091	5.6	2.4	1.7
	E9	3.16E-01	0.00029	0.00093	0.00017	0.00054	3.0	1.5	1.0

Fitting Error

$$FE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Rm_i - Rf_i)^2}$$

Surprisingly, all the errors are larger in Agico 18 design than in Girdler 9 design. On the other hand, confidence angles are larger in 9 directions design.

One can preliminarily conclude that the 9 directions design, which saves much time, would be convenient from the practical point of view.

Conclusions

- ✓ The measurement of hf-AMR is a rather complex procedure, consisting of initial demagnetization, impulse magnetization, measurement of remanent magnetization, processing of measurement, theoretically implying much less precision than the simple measurement (in one step) of standard AMS.
- ✓ Our investigations have shown that in spite of this, the accuracy in determination of directional remanebility can be comparable to that of directional susceptibility provided that one disposes a high-field magnetizer equipped with precise and repeatable field adjustment and producing relatively homogeneous magnetic field within sample holder. In addition, the remanence must be measured with high accuracy instrument.
- ✓ Our investigations have shown that repeated magnetizing and consequent measurement of remanence gives only very weakly variable results. This indicates virtually complete remagnetization by high field.
- ✓ Using 18 directions and 9 directions measuring designs provides us with similar results in determination of hf-AMR tensor, only confidence intervals in anisotropy parameters and angles are substantially narrower in the former case than in the latter. This results from different degrees of freedom of both designs.

Potential Rock Fabric Implications

In many rock types, such as slates and low-susceptibility metamorphic rocks, the standard AMS is often predominantly controlled by paramagnetic minerals despite the ferro-magnetic minerals are also present (in very low amounts). In addition, the latter minerals may have undergone slightly different geological history (e.g., pre-deformational or post-deformational origin) than the former minerals and may therefore show different magnetic sub-fabric. As the AMR indicates only the ferromagnetic mineral sub-fabric, it can discover the processes forming this sub-fabric. As the hf-AMR is measured in an order-of-magnitude stronger fields than those used in standard AMR, it may show more convenient to this purpose.

As known from acquisition magnetization curves, massively used in the identification of magnetic minerals in palaeomagnetism, the magnetite acquisition curve initially increases rapidly, but after the field reaches a certain value, it saturates and remains constant even with increasing field. The curves of hematite and partially also pyrrhotite on the other hand steadily increase with increasing field. Through measurement of the hf-AMR in the fields stronger than is the saturation field of magnetite one will be able to separate the component due to magnetite from that due to the mineral with remanence increasing with field. This will be applicable to ultramafic rocks, which often contain both magnetite and pyrrhotite and both mineral fabrics can be coaxial and/or non-coaxial depending on the rock genesis.

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