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A method for improving the measurement of low-field magnetic susceptibility anisotropy in weak samples

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A R T I C L E I N F O

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A B S T R A C T

Many minerals and rocks have low susceptibilities and magnetic anisotropies on the order of the noise level of the measuring instrument. Anisotropy is often not significant in these samples when using the standard measurement procedure. We propose a method that uses stacking of data to improve the signal-to-noise ratio, thus extending the dynamic range for measurement and allowing for assessment of the data quality. The method makes it possible to obtain consistent directions of the principal axes for samples with an anisotropy on the order of, or even slightly below, the noise level of the instrument. For noisy datasets, the stacking procedure makes it easier to recover correct directions. However, the degree P and shape U of the anisotropy ellipsoid show large variations. Large values of P, in combination with a badly defined U, may indicate noisy data rather than a large anisotropy. The stacking procedure is especially useful for determining the magnetic anisotropy of single crystals that often have a low susceptibility but must be measured with high accuracy.

1. Introduction

During the formation or deformation of a rock or sediment the mineral grains may experience partial alignment, which causes physical properties to be anisotropic. In this case the magnetic susceptibility can be described mathematically by a second-order symmetric tensor and represented geometrically by an ellipsoid. The principal axes of this ellipsoid, $k_1 \geq k_2 \geq k_3$, have lengths corresponding to the eigenvalues of the tensor. The mean susceptibility is defined as the average of the eigenvalues: $k_{mean} = \frac{1}{3}(k_1 + k_2 + k_3)$.

The potential usefulness of the anisotropy of magnetic susceptibility (AMS) as a petrofabric indicator was first indicated by Graham (1954), but was not investigated widely for many years. An early use of AMS was made in the investigation of the deflection of remanent magnetization away from the applied field direction by rock magnetic fabric (Fuller, 1960, 1963). This could result in errors of interpretation in studies of the paleomagnetic field, and might also cause inaccuracies in total-field magnetic anomaly studies. AMS was investigated as a means of correcting for these effects. Many studies of the relationship between AMS and mineral fabric have established the usefulness of AMS as a proxy for current directions in sediments (Hamilton and Rees, 1970), deformation or strain in deformed rocks (Graham, 1966; Hrouda, 1982; Kligfield et al., 1981), and flow directions in igneous rocks (Stacey, 1960). Comprehensive reviews of these applications of AMS have been made by Borradaile and Henry (1997), Borradaile and Jackson (2010) and Tarling and Hrouda (1993).

In order to relate AMS to the mineral fabric, it is important to understand which mineral carries the anisotropy. This is not necessarily the mineral with the highest intrinsic susceptibility (such as magnetite or pyrrhotite), which may only be present in trace amounts. Many common rock-forming minerals (such as quartz, feldspars, calcites) have a low susceptibility and/or a weak anisotropy. In addition, mineral groups such as amphiboles or pyroxenes can also have very low susceptibilities, depending on their chemical composition. When AMS is used as an indicator for mineral fabric in rocks whose constituent minerals are made up largely of these phases, it is difficult to extract the useful signal from the measurement noise, even with instruments of high sensitivity.

Two methods are commonly used to measure magnetic anisotropy. The first consists of determining the full susceptibility tensor, whereas the second measures the deviatoric susceptibility tensor. The full tensor can be obtained by measuring the susceptibility in specified directions relative to sample coordinates. This static technique can be used with susceptibility bridges, such as the AGICO KLY or the MFK1. The measurement scheme requires the determination of at least 6 directional susceptibilities to compute the 6 independent elements of the symmetric (3×3) susceptibility tensor. The AMS ellipsoid is estimated by a least-squares fit to the directional data. If more than the minimum number of measurements are made, the ellipsoid is over-defined and the error of fitting can be determined. For example, with the AGICO instruments the susceptibility is measured in 15 directions, so the data quality and significance of the AMS can be estimated (Jelinek, 1977). Another way to determine the full susceptibility tensor utilizes the high-field slopes of hysteresis loops (Kelso et al., 2002). This method uses 24

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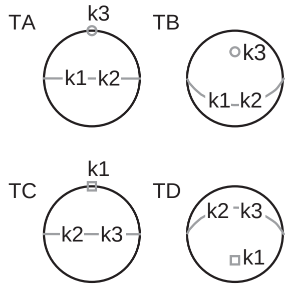

TA, TB: U = 1

	k1 = k2	k3
P = 1.01	1.003	0.993
P = 1.05	1.016	0.968
P = 1.10	1.031	0.938

TC, TD: U = -1

	k1	k2 = k3
P = 1.01	1.007	0.997
P = 1.05	1.033	0.984
P = 1.10	1.065	0.968

Fig. 1. Directions of principal axes of the susceptibility tensors from which the synthetic data were calculated.

different orientations of the sample to the field direction and yields the paramagnetic component of the anisotropy.

The second method of determining AMS measures the deviatoric susceptibility tensor. This is generally done by rotating the sample in a magnetic field successively in three mutually orthogonal planes. Such measurements can be made with a spinner magnetometer or with a susceptibility bridge. They can also be made with a torque magnetometer, in which a sample is suspended in an applied field and the torque which the sample experiences due to its anisotropy is measured as a function of applied field in the three orthogonal planes. Used in strong fields this method can be used to separate the fabrics of ferromagnetic (s.l.) and paramagnetic mineral fractions in a rock. In low applied fields the rotational technique forms the basis of anisotropy analysis with spinner magnetometers, such as the AGICO KLY-3S, KLY-4S and MFK1, and the Digico and MiniSpin instruments. The signal of the rotating sample is a sine curve whose frequency is twice that of the rotation. In principle, half a revolution in each of the three planes would be enough to determine the signal. In practice, the signal is measured over a full revolution in the high-field torque magnetometer and is averaged over many cycles in the spinner magnetometers. The absolute tensor can be calculated by measuring the susceptibility in a specific direction and adding this to the deviatoric tensor.

According to Jelinek (1996), the deviatoric tensor can be measured with higher precision and better sensitivity than the full tensor. For example, the KLY-4S instrument has a higher sensitivity (2×10^{-8} SI) for anisotropy measurements than for bulk susceptibility (3×10^{-8} SI). Instrument development has led to ever-increasing sensitivity; the MFK1 susceptibility bridges have a sensitivity level of 2×10^{-8} SI at a frequency of 976 Hz and in a field of 400 A/m.

In general, if a sample has a high susceptibility and is strongly anisotropic, measurements with any of the above methods are

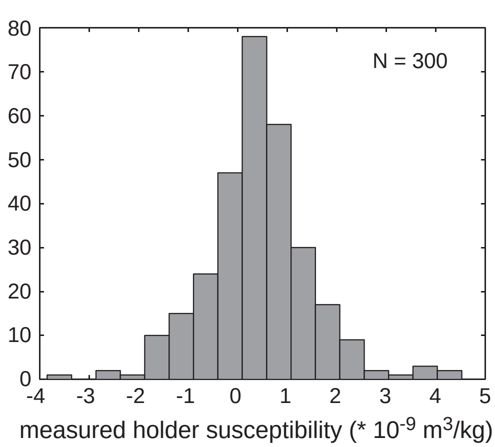

Fig. 2. Susceptibility values of 300 holder measurements after correction for the holder susceptibility. The data correspond to the noise distribution of the MFK1 and follow a normal distribution.

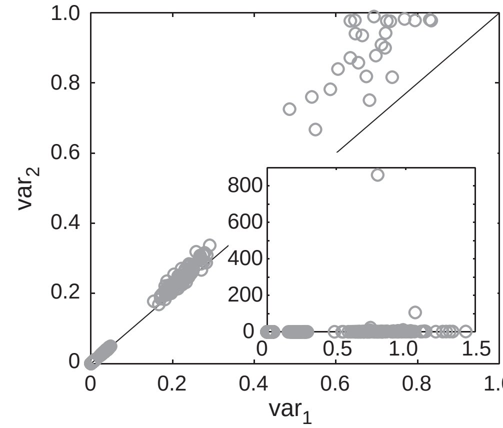

Fig. 3. A comparison of var_1 and var_2 of all anisotropic synthetic datasets shows that var_2 increases strongly for certain datasets, whereas the variation in var_1 is smaller. Inset: Effect of near-zero mean value on parameter var_2.

reproducible within small measurement errors. However, for samples with a low susceptibility or a weak anisotropy the noise level of the measurement may be on the order of the anisotropy of the sample. Consequently, subsequent measurements of the same specimen can give strongly different results in terms of the degree, shape and principal directions of the anisotropy ellipsoid.

Our interest in increasing the resolution of AMS measurements stems from the goal of determining the fundamental anisotropy of single crystals of rock-forming minerals, which is related to the crystallographic axes. This requires measurements that are accurate and precise, because minerals with low iron-content (e.g. tremolite, diopside or feldspars) have bulk susceptibilities that can be weakly paramagnetic or diamagnetic. The anisotropies of these minerals can be difficult to measure reliably.

In this report we evaluate a method to extend the instrumental resolution and obtain significant results for samples and crystals with very weak anisotropies. The measurements for this study were made with the MFK1-FA in the static operational mode. Further comparison is made with the same instrument in spinning mode. With the data from the static mode, we define a measure for (1) determining if the sample is significantly anisotropic, and (2) evaluating how well the

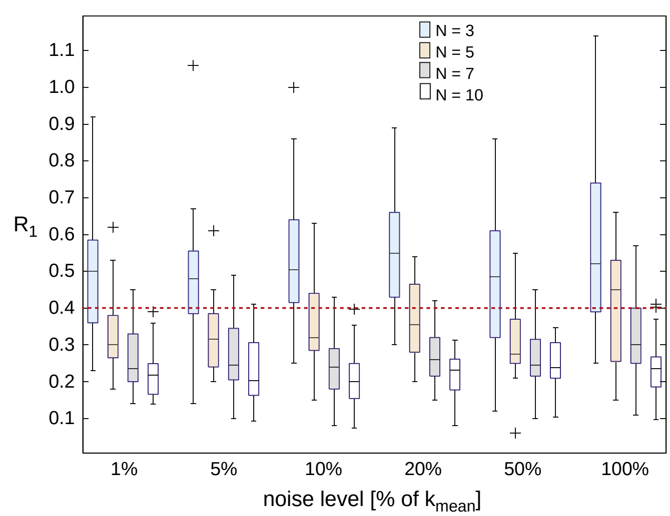

Fig. 4. Results for isotropic synthetic data with different noise levels and sizes of datasets ($N = 3$, 5, 7 and 10 repeated measurements per position). R_1 decreases with increasing N, independently of the noise level. The line represents the median of the data, the box extends from the 25th to the 75th percentile and the whiskers can be interpreted as the 1st and 99th percentiles. Crosses represent values considered as outliers. Dashed line shows R_1-value used to distinguish if the sample is anisotropic.