A METHOD FOR IMPROVING THE MEASUREMENT OF LOW-FIELD MAGNETIC SUSCEPTIBILITY ANISOTROPY IN WEAK SAMPLES

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The final version of this article can be downloaded from the Journal of Applied Geophysics webpage, DOI: 10.1016/j.jappgeo.2012.10.008

Abstract

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.

Keywords: Magnetic susceptibility anisotropy, mineral magnetic fabric, susceptibility bridge, single crystal anisotropy, weak samples

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; Kligfield et al., 1981; Hrouda, 1982), 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 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.

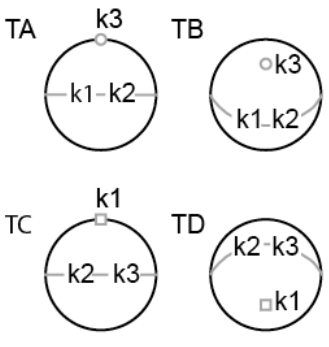
In general, if a sample has a high susceptibility and is strongly anisotropic, measurements with any of the above methods are reproducible within small measurement errors. However, for samples with a low susceptibility or a weak anisotropy the noise level of the measurement may be on the order of the 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 degree, shape and principal directions are defined by the AMS data. In order to understand the variation of the susceptibility parameters for weak samples, model calculations are performed for synthetic data with different degrees and shapes of anisotropy. This part of the study leads to a way of assessing the quality of AMS measurements. Finally, the method is applied to real samples with a range of bulk susceptibilities and anisotropies.

2. Synthetic data

Four AMS tensors have been investigated by analysis of synthetic data (Fig. 1): two rotationally *oblate* ellipsoids, with either horizontal or tilted k_3 (minimum) axes (TA and TB, respectively) and two rotationally *prolate* ellipsoids with horizontal or tilted k_1 (maximum) axes (TC and TD, respectively). For each of these tensors, anisotropy degrees of P = 1.01, 1.05 and 1.10 were analyzed. These synthetic datasets correspond to the typical anisotropies for the amphibole and clinopyroxene mineral groups. The directional values for the susceptibility that are usually measured were computed for each of these cases.



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

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

In weakly magnetic samples the signal of the sample holder may be similar to, or greater than, that of the sample and must be compensated. In order to obtain an idea of the noise distribution of the MFK1 instrument, the empty holder was measured 300 times and the standard correction for the holder made each time. As expected, the measurements cluster about a value of zero. Figure 2 shows that we can assume a normal distribution for the noise. The noise measurements were compared to typical mean susceptibilities for different samples of amphiboles, pyroxenes or feldspars. This comparison shows that the instrumental noise levels is commonly up to 20% of the mean susceptibility, while for certain feldspar crystals they can amount to as much as 300% of the mean susceptibility.

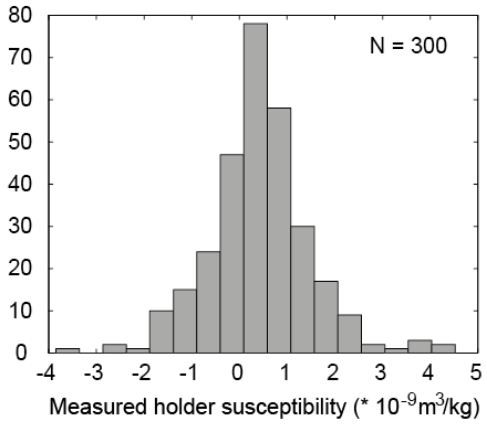


Figure 2: Susceptibility values of 300 holder measurements after correction for the holder susceptibility. The data correspond to the noise distribution of the MFK1 and follow a normal distribution.

In order to simulate noisy data from our synthetic tensors, we first computed directional susceptibilities for the 15 positions that are routinely measured. Noise was simulated by selecting random numbers from a normal distribution with zero mean-value whose standard deviation was successively set equal to different values between 1% and 100% of the mean susceptibility of the synthetic sample. Defining noise as a percentage of the mean susceptibility has the advantage that our results are valid for arbitrary mean susceptibilities. The computed noise was added to the directional data. Ten datasets were generated, each consisting of 3, 5, 7 or 10 values for each of the 15 measurement positions. This was repeated for every combination of susceptibility tensor, AMS degree, and noise level. In addition, 20 isotropic datasets were generated with the same noise distribution as in the anisotropic data. The repeated values at each measurement position were then averaged. In this way, statistical noise is cancelled whereas the signal due to the magnetic susceptibility anisotropy is enhanced. For comparison, individual AMS ellipsoids were also determined from all of the first, second, … and fifteenth values at each position.

The AMS ellipsoid was computed by performing a least-squares-fit for each averaged or individual dataset. From this, one obtains the magnitudes and directions of the principal susceptibilities. The shape and degree of the anisotropy ellipsoid for each of the individual datasets can then be compared to the same anisotropy parameters of the averaged dataset. The anisotropy ellipsoid is characterized from the AMS data by its degree, $P = k_1/k_3$ (Nagata, 1961) and by its shape $U = (2k_2 - k_1 - k_3)/(k_1 - k_3)$ (Jelinek, 1981). *P* is equal to 1 in the isotropic case and increases with increasing anisotropy. The parameter *U* can have values between -1, for rotationally *prolate* ellipsoids, and +1, for rotationally *oblate* ellipsoids.

Data quality and significance of the anisotropy are evaluated by comparing the deviation of the ellipsoid from a sphere to the amount of noise. Two estimates for a noise parameter were investigated for the stacked datasets: $var_1 = \left(\sum_{i=1}^{15} \Delta a_i{}^2\right)/\left(\sum_{i=1}^{15} \bar{a}_i{}^2\right)$ and $var_2 = \sum_{i=1}^{15}(\Delta a_i/\bar{a}_i)^2$ where $\Delta a_i{}^2 = \frac{1}{10}\sum_{j=1}^{10}(a_{ij} - \bar{a}_i)^2$, $\bar{a}_i = \frac{1}{10}\sum_{j=1}^{10} a_{ij}$ and a_{ij} is the jth measurement in the ith position. The parameters var_1 and var_2 have the same values for small noise levels. For most datasets, the two parameters vary proportionally to each other (Fig. 3). However, if the noise is comparable to the signal

and the mean value in one direction is close to zero, var_2 will increase dramatically, whereas var_1 will remain stable (Fig. 3, inset). For this reason only var_1 will be considered further.

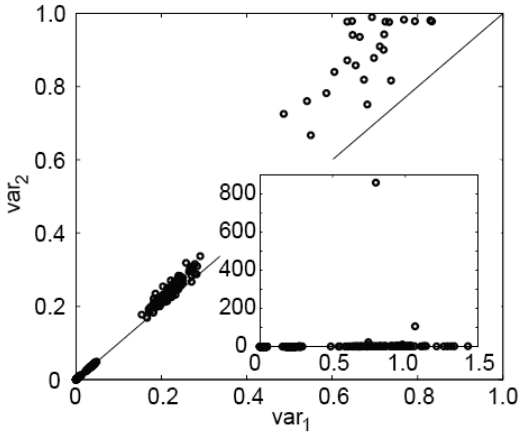


Figure 3: A comparison of var_1 and var_2 of all anisotropic synthetic datasets shows that var_2 increases strongly for certain datasets, whereas the variation in var_1 is smaller. Inset: Effect of near-zero mean value on parameter var_2.

The deviation of the ellipsoid from a sphere, *dev*, is described by Jelinek (1977) as $dev = (k_1^2+k_2^2+k_3^2-3k_{mean}^2)/((N-1)k_{mean}^2)$, where $N = 6$ is the number of independent elements in the susceptibility tensor and k_{mean} is the mean susceptibility.

The parameter that we have used to assess the significance of the AMS is $R_1 = \sqrt{dev/var_1}$. The larger this parameter, the better defined is the anisotropy compared to the noise level. The largest value obtained with isotropic data is used to define the lower threshold for assessing whether or not the sample is anisotropic. All samples that are below this threshold are considered not to exhibit a significant anisotropy.

2.1 Results for isotropic data

Analysis of isotropic synthetic datasets allows us to estimate a threshold of significance for the anisotropy determined from a given dataset – synthetic or measured. Synthetic datasets were computed for isotropic samples assuming the different noise levels described in the previous section. A set of 20

datasets was generated for each noise level. The parameter R_1 depends on the number of values that are averaged; it is generally smaller and shows less variation when the number of datasets that are averaged increases (Fig. 4). Basing the stacking of data on 10 (measured or synthetic) values gives slightly more consistent results than using N = 7 data, and significantly lower noise parameters than using N = 3 or 5. For a stack of ten isotropic datasets, the ratio R_1 was found to be less than 0.4, independently of the noise level. Thus, AMS data for samples with a ratio of less than 0.4 should be rejected, as their anisotropy is not significant.

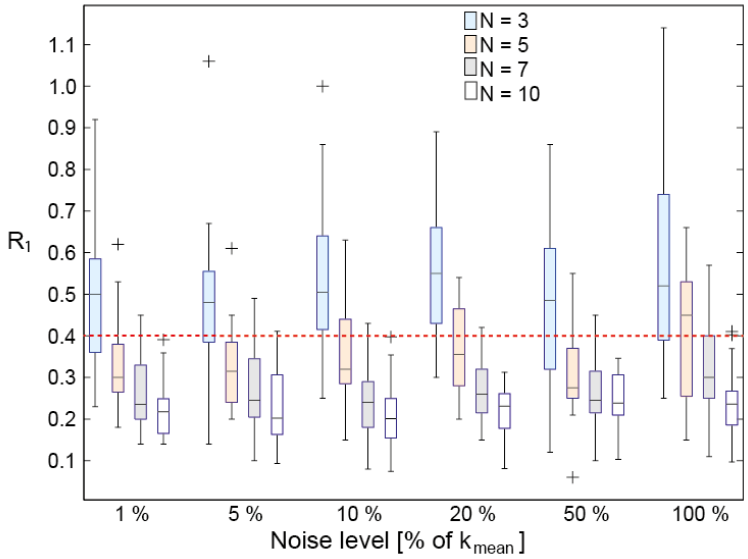


Figure 4: Results for isotropic synthetic data with different noise levels and sizes of datasets (N = 3, 5, 7 and 10 repeated measurements per position). R_1 decreases with increasing N, independently of the noise level. The line represents the median of the data, the box extends from the 25th to the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

The degree of anisotropy, P, should equal 1.00, because the input data are isotropic. However, P is seen to increase strongly with increasing noise level. This increase is less pronounced in the stacked data than for the individual datasets (Fig. 5). Therefore, a large P does not necessarily correspond to strong anisotropy, but could merely be an indication of poor data quality. This is especially the case when a large P is associated with a large variation in the repeated measurements. Principal directions are random in this situation, which indicates that no preferential direction is

introduced by the data processing. The only parameter that remains well-defined, independent of noise level, is the mean susceptibility (Tab. 1).

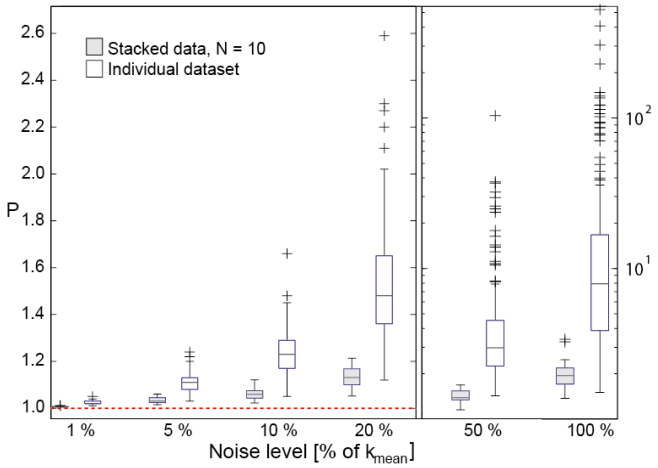


Figure 5: The anisotropy degree *P* for isotropic synthetic data. *P* should equal 1, however it increases with increasing noise level. This effect is less pronounced for the stacked than for the individual datasets. Note the change of vertical scale: on the left the scale is linear, on the right it is logarithmic.

2.2 Results for anisotropic data

Results for the synthetic anisotropic data are summarized in Table 2 (electronic supplementary material). Again, we generated data with P = 1.01, 1.05 and 1.10 and noise levels of 1% to 100% of the mean susceptibility for the four tensors. The isotropic data show that best results are achieved with stacking 10 measurements at each position. Therefore, N = 10 was used for further analysis. Tensor TA (Fig. 6 and 7) illustrates how ellipsoid shape and axial directions vary with the degree of anisotropy and the noise level. As with the isotropic data, P increases when the noise increases. Furthermore, the variation in U increases with the amount of noise. For the individual measurements, the shape already varies from oblate to prolate and is not reliable when P = 1.10 and the noise level is 5%. Even for 1% noise, the U values indicate the correct region – oblate or prolate – but show large variations between individual datasets. The increase of the AMS degree P to unrealistically high values is much more pronounced in the individual datasets than for the stacked data. The directions of the stacked datasets agree reasonably well with the true directions, even when the noise level is

slightly larger than the degree of AMS. This is even the case when the directional data of the individual measurements appear to be nearly randomly distributed and both *U* and *P* show large variations.

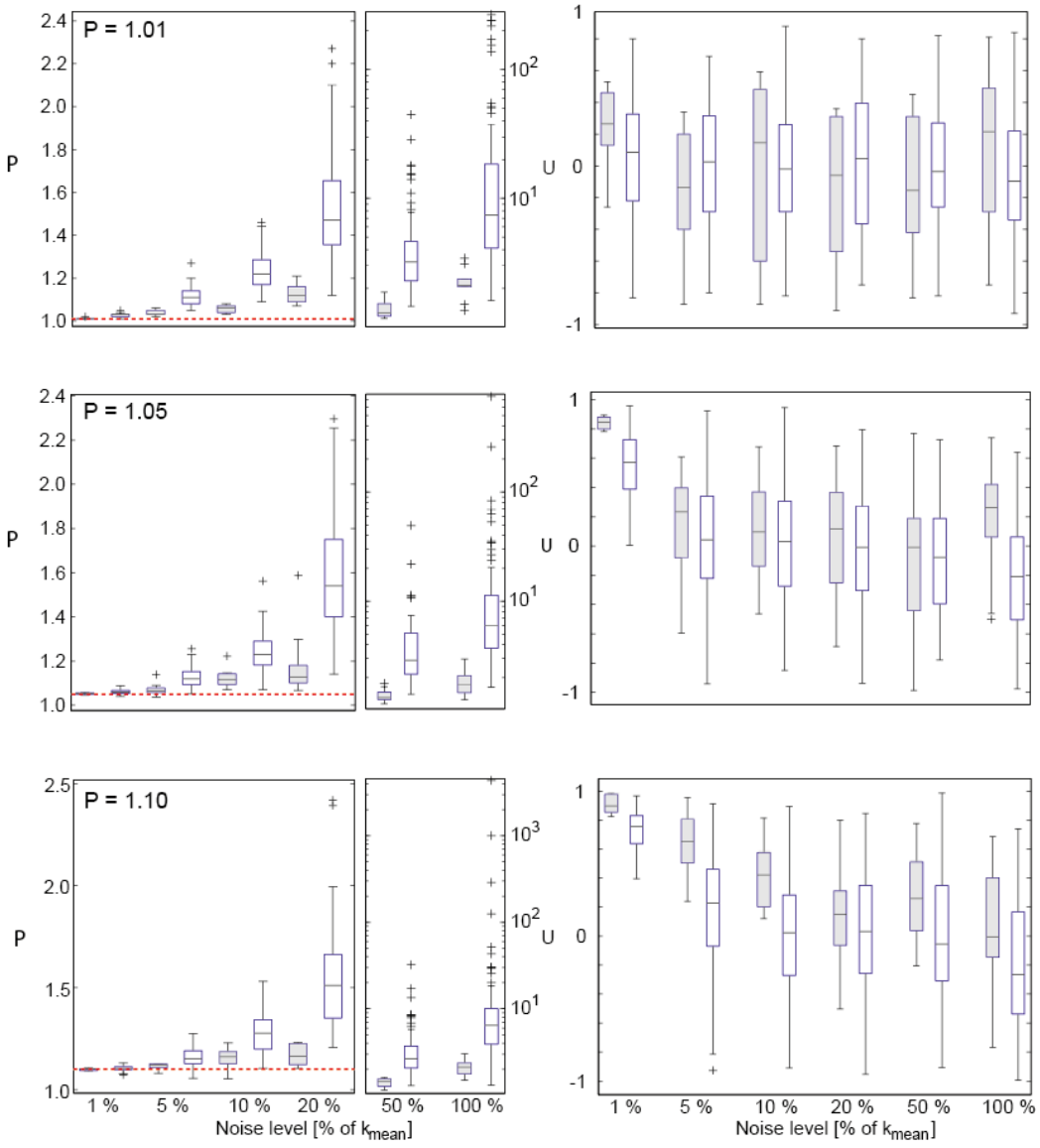


Figure 6: *P* and *U* computed from synthetic datasets with oblate shape and (a) 1%, (b) 5% and (c) 10% anisotropy. The green line shows the expected anisotropy degree *P* for these cases. The shape parameter *U* should be equal to one.

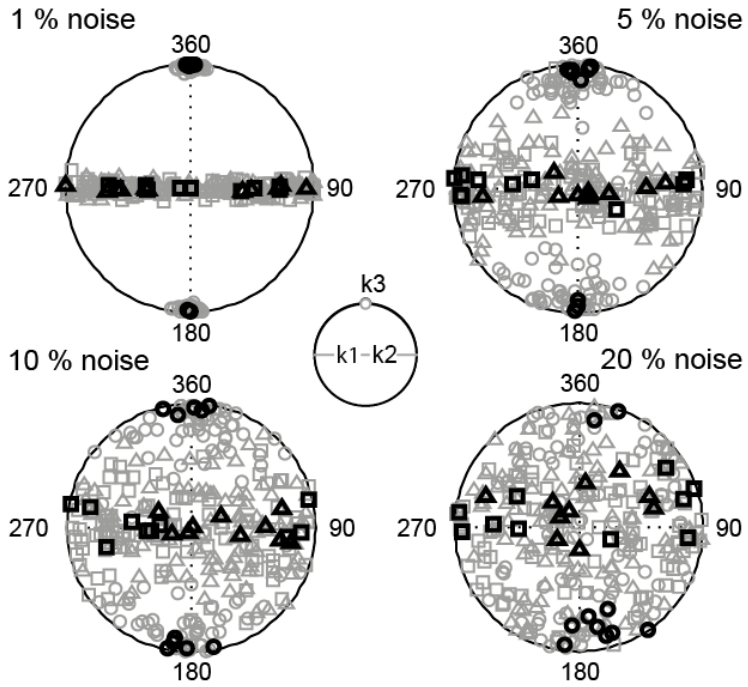


Figure 7: Principal susceptibility directions for an oblate ellipsoid with 10% AMS and different noise levels. The expected solution is a cluster of k_3 axes at 360° and a girdle of $k_1 = k_2$ axes in a plane perpendicular to k_3, as suggested in the small central plot. Minimum directions are grouped around the true direction even when the noise level is 20% and thus twice the anisotropy. In these equal-area, lower hemisphere stereoplots squares, triangles and circles refer to the maximum, intermediate and minimum principal susceptibility, respectively. Grey symbols represent individual data and dark symbols represent the stacked values in this and subsequent figures.

The usefulness of R_1 as an indicator of data quality is illustrated in Figure 8. For example, for an anisotropy degree of 1.10 and noise of 1%, R_1 is nearly an order of magnitude larger than the threshold of 0.4, and the principal directions, shape and degree of the AMS ellipsoid coincide with the input parameters. However, if $P = 1.10$ and the noise is 5%, the values for R_1 are between 0.5 and 1, only slightly above the 0.4 limit. In this case, the directions and the degree of the ellipsoid can be well resolved, but the shape shows a large variation between the individual data stacks. If the anisotropy degree is $P = 1.10$ and the noise is 10%, the directions of the ellipsoid principal axes are reasonably well resolved, but the data for the AMS shape are no longer reliable and the AMS degree is too large.

In summary, the anisotropy ellipsoid can be recovered well from the stacked values, provided the noise level of the measurements does not exceed the degree of anisotropy of the sample. The directions are defined better than the degree of anisotropy and the ellipsoid shapes. When the noise

level is less than the anisotropy, the anisotropy degree and shape are well defined, but when the noise level is larger than the AMS, *P* increases to unrealistically high values and *U* covers the whole range from prolate to oblate ellipsoids. The known input values are recovered better by the stacked data than by the individual datasets. For weak samples, where the anisotropy is on the order of the noise level, stacking makes it possible to obtain reliable data that otherwise could not be derived. *P* and especially *U* may not be recovered when the anisotropy is on the order of – or smaller than – the noise level. However, even then it is possible to determine the principal directions. For example, directional data of the individual datasets appear to be random when the noise level is above the degree of anisotropy, yet the stacked datasets still cluster along the true directions, as shown in Figure 7.

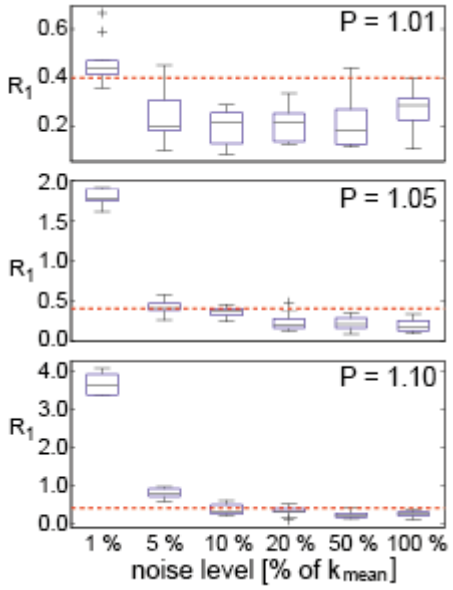


Figure 8: Ratio R_1 for the synthetic oblate amphibole datasets shown in Figure 3. Where R_1 is below 0.4, the AMS data are not significant. Dotted line shows R_1 = 0.4.

3. Rock samples

3.1 Method

Low-field AMS was analyzed for a collection of single crystals of amphiboles and pyroxenes. Samples were measured on an AGICO MFK1-FA Kappabridge in a field of 200 A/m. Each position was recorded ten times and weak samples were remeasured in a 500 A/m field to enhance the signal/noise ratio. As for the synthetic data, individual as well as stacked datasets were analyzed.

Sample and background were remeasured in the same position 10 times and averaged to obtain the stacked dataset. It is assumed that these repeated measurements give independent estimates of the susceptibility value in each sample direction. Repeated measurements of the same position were plotted against time to check for instrumental drift, which was negligible in all samples. Samples were chosen so as to cover a wide range of susceptibilities within the same mineral group. If the AMS correlates with the crystallographic structure of the mineral, the ellipsoid shape and its principal directions should be comparable for a range of chemical compositions.

3.2 Results

For samples with strong susceptibility and/or a large degree of anisotropy, the noise is very small compared to the signal and stacking brings no advantage, as can be seen for the actinolites (samples Akt1 and FAkt3, Fig. 9) and augites (T3 and T17, Fig. 10). The individual measurements coincide with each other. The agreement of the directions is, however, more consistent than the agreement of the degree and shape of the anisotropy ellipsoid.

In the case of samples that have a low susceptibility, or those with a weak anisotropy, the noise is comparable to the signal (e.g. Trem2, Trem3 and Di2). In this case, stacking substantially improves the signal quality. The noise parameter for Trem2 is below the threshold of 0.4, and thus the anisotropy of Trem2 is considered not to be significant. Sample Di2 has a value of R_1 slightly above the threshold; whereas the individual measurements show a large variation, the minimum direction of the stacked dataset is very close to that expected from results in the other diopsides. Compared to the other diopsides the discrepancy is larger for the directions of the maximum and intermediate principal axes, because diopside possesses an oblate-shaped AMS ellipsoid. The anisotropy parameters U and P show large variations for the individual datasets of Di2, but the stacked values are similar to the expected values as determined from Di3 and Di4. Similarly, Trem3 displays a large variation in the individual datasets, but the stacked values agree well with the better-defined AMS parameters of samples with higher susceptibility or stronger degree of anisotropy. Trem2, Trem3, Trem4 and Di2 display negative susceptibilities in all directions and thus all principal susceptibilities are negative. For these samples, AMS parameters were defined in terms of the absolute values of the principal

susceptibilities. This convention causes problems in samples that have positive susceptibilities in some directions and negative in others, e.g. when $k_1 > 0$ and $k_3 < 0$. On the other hand, it allows direct comparison with high-field torque data, as the torque signal is indifferent to whether the magnetization is parallel (in the paramagnetic case) or antiparallel (in the diamagnetic case) to the magnetic field, but depends on the angle between the easy magnetization axis and the magnetic field direction. The most negative susceptibility, i.e. highest absolute value, in a diamagnetic sample corresponds to the easy axis of magnetization.

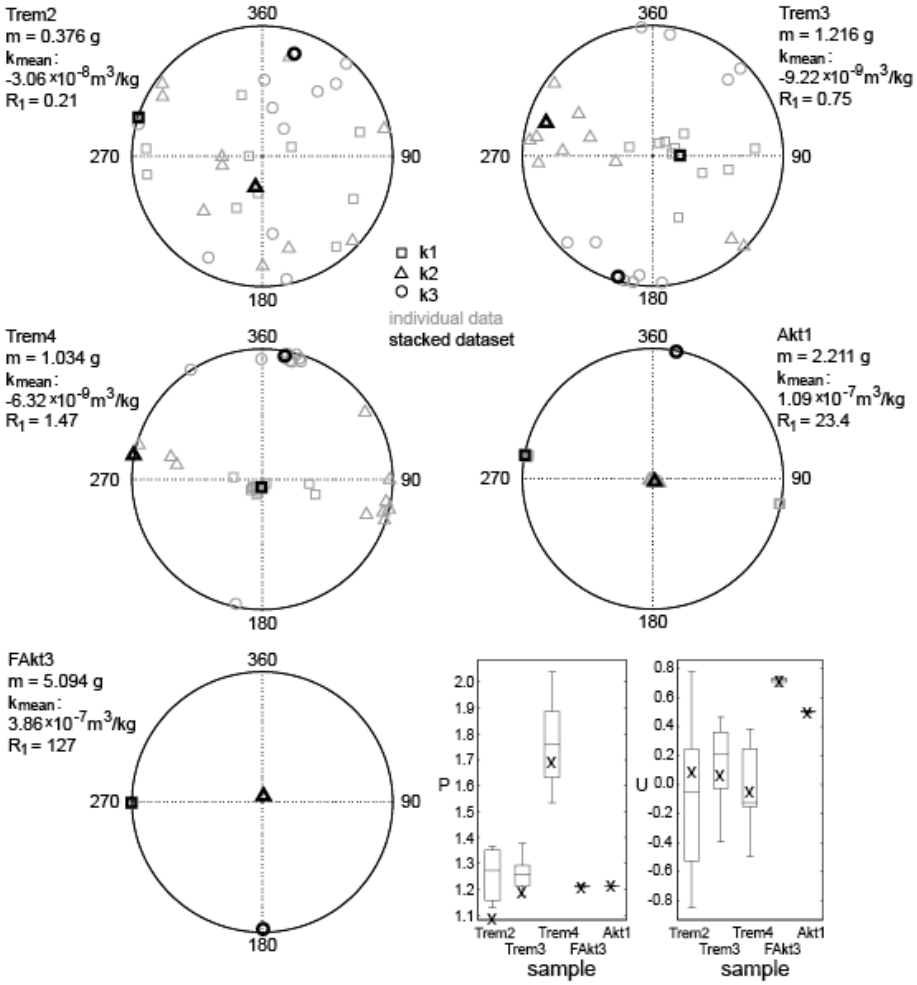
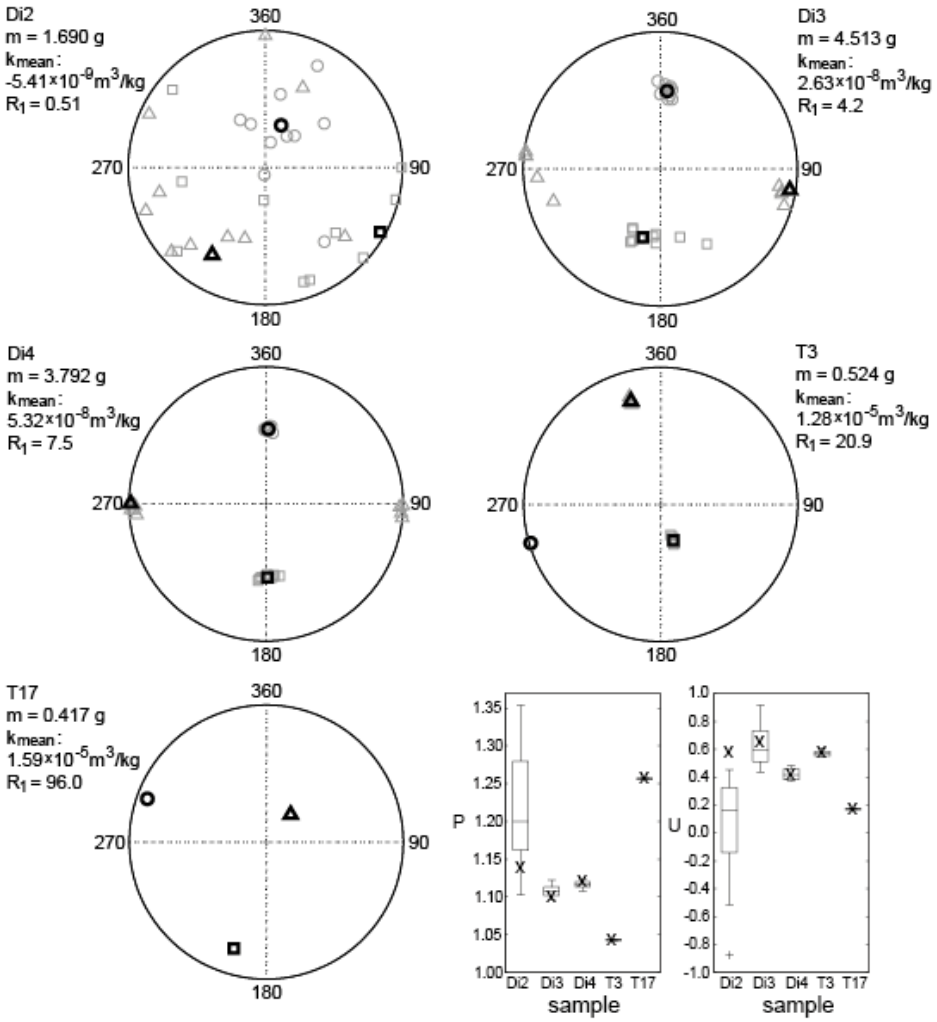


Figure 9: Principal directions, shape and degree of AMS for amphiboles with different data quality. The larger R_1, the better defined are the data. Directions are close to the expected values even when R_1 is slightly less than 0.4. Good data can also be obtained with individual datasets for $R_1 > 10$. For Trem4, directional data are consistent within reasonable errors, whereas there is a large spread of both *P* and *U*. In this case, stacking leads to a significant improvement in the results. For Trem3, this also applies to the directional results.



310

311 Figure 10: AMS results for a selection of clinopyroxenes. Augites T3 and T17 show different directions
312 than diopsides Di2, Di3 and Di4 because the low-field AMS of the augites is dominated by magnetite
313 inclusions.

314

315 Diamagnetic and paramagnetic contributions to the AMS are related to atomic positions in the
316 silicate lattice, thus it is reasonable to assume that all diopsides or all tremolites, respectively, exhibit a
317 similar AMS ellipsoid. However, this is not true for very strong samples, like T3 and T17, whose
318 AMS is dominated by the signal of ferromagnetic inclusions. For R_1 between 1 and 10 (Trem3, Di3,
319 Di4), a clustering of directions already appears in the individual datasets; the larger R_1, the better the
320 grouping of directions. In these cases, stacking significantly improves the estimates for anisotropy
321 degree and shape, whereas the improvement in the directional data is smaller. If R_1 is larger than 10,
322 stacking is not essential, but it enables an assessment of the data quality.

323 Directions of individual measurements can show a large variation, but when measuring several
324 samples of the same mineral, the stacked directions coincide reasonably well. As is the case for the
325 synthetic data, it appears that for the minerals, as for the synthetic data, the data quality is poor (or the
326 anisotropy not significant) if the factor R_1 is less than 0.4.

327 It is of interest to compare results obtained with the MFK1 instrument in both the static and
328 spinning modes of measurement. A summary of the spinning mode data is shown in Table 3
329 (electronic supplementary material). Figure 11 shows AMS of the same samples as in Figure 9, but
330 measured in the spinning specimen mode. For comparison, the spinned measurements were repeated
331 ten times. The directions of the weak samples (Trem2, Trem3 and Trem4) show a large scatter and
332 appear to be influenced more strongly by the holder signal – even though this is subtracted – than by
333 the anisotropy of the crystal itself. A superposition of signals due to the crystal anisotropy and
334 remaining holder signal is measured, the holder having a positive susceptibility and the crystals a
335 negative susceptibility. Thus, the remaining holder signal is effectively subtracted, which explains
336 why k_1 of the holder relates to k_3 in the tremolite samples. For the stronger samples Akt1 and FAkt3
337 the results are consistent and agree with those from the static mode. The scatter is larger for repeated
338 measurements in the spinning mode. According to F-values and confidence angles that are computed
339 when measuring in the spinning mode, AMS is not significant for Trem2, Trem3 or Trem4 at the 95%
340 level of significance. However, the static measurements show a good grouping about the correct mean
341 direction for Trem4 and, to a lesser extent, Trem3. Only the R_1 value of Trem2 indicates that its AMS
342 is not significant. Thus, a significant improvement with respect to the spinning mode can be achieved
343 by stacking AMS data measured in the static mode.

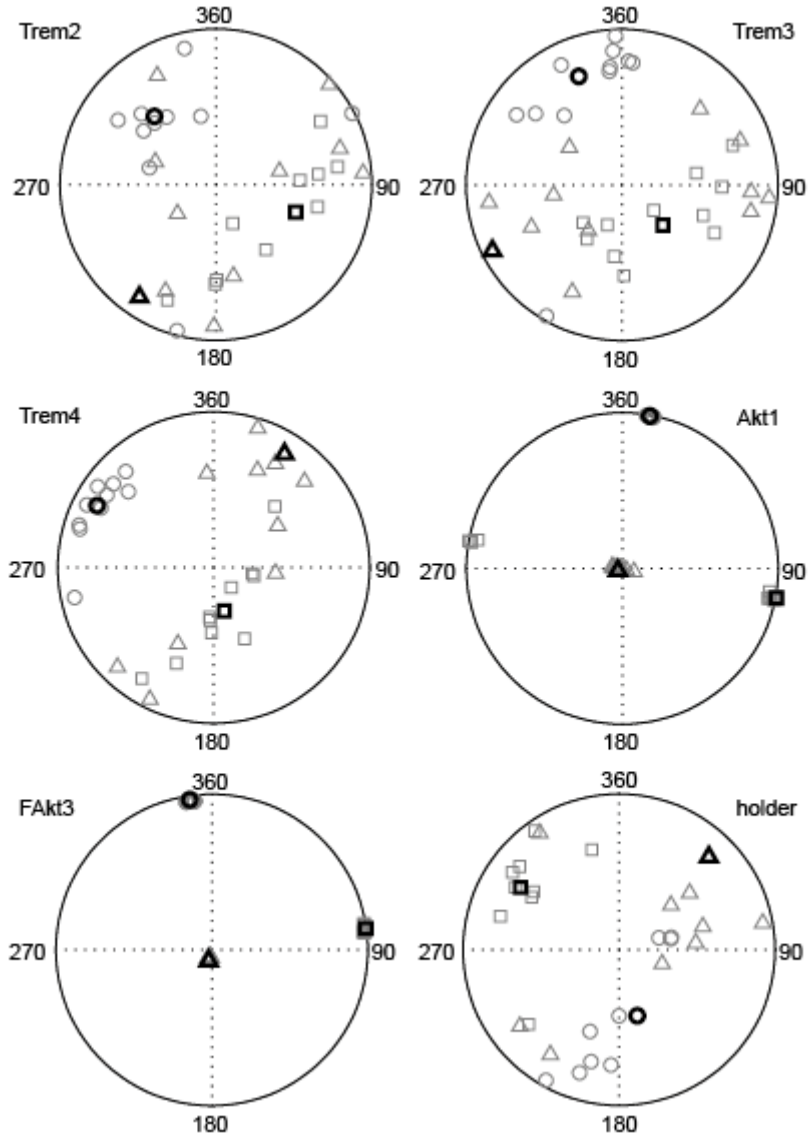


Figure 11: AMS results for the same samples as in Figure 9, measured in the spinning specimen mode of the MFK1. The results of the weak samples (Trem2, Trem3 and Trem4) are strongly influenced by the anisotropic signal of the holder. Results for the stronger samples (Akt1 and FAkt3) are similar to those determined in the static mode, but show a larger variation in directions.

4. Discussion and conclusions

There is a strong interest in using AMS to define preferential grain orientation in rocks or sediments with weak mineral fabrics. These may represent flow directions in the case of lavas or river deposits, or strain fabrics in the case of deformed rocks. Especially for weak samples it may be the case that a large spread in individual directions reflects the influence of noise rather than a true variation in directions. This would explain why Kligfield et al. (1981), in a study of AMS in deformed

356 Permian redbeds, found that, although the anisotropies of redbed specimens displayed a high scatter,
357 the average AMS ellipsoid correlated with the strain ellipsoid.

358 Hrouda (1986; 2004) observed that quartzite, whose bulk susceptibility is close to zero,
359 displays an unrealistically high degree of AMS. He proposed that AMS parameters obtained from
360 samples with bulk susceptibilities between -5×10^{-6} and $+5\times10^{-6}$ (SI) should not be used to infer
361 mineral fabric. For low-susceptibility samples, noise contributes significantly more to the
362 measurement than for those with high susceptibility, which probably explains these earlier
363 observations. We have shown that a high noise level causes a large increase in the calculated
364 anisotropy degree. This effect can be reduced by stacking, which yields reliable data for samples with
365 low mean susceptibility.

366 The AGICO susceptibility bridges are highly sensitive, but like any instrument they have a
367 detection limit. The signal generated by the anisotropy of many rocks or minerals may be comparable
368 to instrumental drift (Gee *et al.*, 2008). For this reason, a linear trend is removed from the values
369 measured on AGICO's MFK1 Kappabridge. However, drift is not necessarily linear, and its variability
370 may be an additional source of error. Measuring the deviatoric susceptibility often leads to better
371 precision and higher sensitivity (Jelinek, 1996). However, the present study has shown that, although
372 the stacking of static measurements requires considerably more time to acquire data, it is more
373 effective in determining directional data for very weakly anisotropic samples than the spinning mode
374 of measurement. Magnitudes of principal susceptibilities are more sensitive to measurement noise;
375 however, stacking also improves the definition of the degree of anisotropy and the shape of the AMS
376 ellipsoid. At the same time, stacking allows an assessment of the data quality by means of a simple
377 ratio, and allows definition of a measure of the significance of the AMS. The anisotropy degree P is
378 generally smaller and shows less variation for stacked data. Since P not only increases as a function of
379 anisotropy, but also with increasing noise, this indicates that the signal-to-noise ratio has been
380 enhanced.

381 In particular we have shown for weak samples, for which no reasonable results would be
382 obtained with the standard measurement procedure, that the stacking procedure makes it possible to

obtain reasonable results. Therefore, when very exact measurements are needed, as for example to determine the magnetic anisotropy of single crystals, the method of stacking repeated static measurements is recommended.

Acknowledgements

A. Stucki (siber+siber AG, Zurich), S.A. Bosshard and P. Brack (ETH Zurich) are thanked for providing samples. We thank Bernard Henry for his constructive review. This study was funded by the Swiss National Science Foundation (SNF) under project 129806.

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