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SHORT NOTE

The quantification of crystallographic preferred orientation using magnetic anisotropy

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Abstract—Magnetic anisotropy analysis presents an alternative and fast method for obtaining and quantifying crystallographic preferred orientations in rocks, using relatively simple equipment. Two natural examples and numerical modeling demonstrate that magnetic anisotropy increases with increasing degree of crystallographic preferred orientation. The normalized magnetic parameters $M_i = \ln (k_i/(k_{max} * k_{int} * k_{min})^{1/3})$ ($k_{max} \geq k_{int} \geq k_{min}$ are the principal magnetic susceptibilities) correlate directly with March 'strains' obtained from X-ray texture goniometry. The additional advantage of our method is that the preferred fabrics are determined from large sample volumes (typically about 11 cm^3) rather than the essentially two-dimensional slice used in optical and X-ray methods. Thus, magnetic anisotropy provides a reliable measure of bulk crystallographic preferred orientation in rocks.

INTRODUCTION

THE relationships between magnetic fabrics (mainly the anisotropy of magnetic susceptibility, AMS) and rock fabrics have been studied for more than 30 years. However, the interpretation of magnetic fabrics has been problematic (see reviews by Hrouda 1982, Borradaile 1988). A quantitative relationship between finite strain and the AMS ellipsoid was proposed (e.g. Rathore 1979) and empirically established in a number of case studies (review by Borradaile 1991). Recent investigations, however, have demonstrated the strong dependence of the AMS tensor on the mineral composition. For example, Borradaile (1987), using a calculation based on single-mineral AMS data, demonstrated the dependence of the AMS ellipsoid shape on the mineral composition. Moreover, slight variations in the concentration of the ferri(o)magnetic trace minerals strongly influence the shape and magnitude of the AMS ellipsoid. In many cases these composition-dependent variations can be much more pronounced than changes due to strain.

On the other hand, magnetic fabrics may allow quantification of the preferred orientation of mineral lattice planes in rocks. Crystallographic orientation data are usually obtained with very time-consuming procedures, such as optical methods (U-stage) or X-ray texture goniometry. A further disadvantage of such methods is that only a thin section or the surface of the rock is measured. The magnetic anisotropy method, in contrast, integrates crystallographic preferred fabrics over a sample volume of typically about 11 cm^3. The basic requirement for the applicability of this method is that the AMS is dominated by the mineral of interest or that it is possible to correct for the magnetic contribution of other minerals. Of particular significance in geologic materials are white mica, biotite and chlorite.

We emphasize that the method is only applicable if the mineral under consideration is demonstrated to be the major source of AMS. Modern methods in rock magnetism provide tools for a separation of the ferro- and paramagnetic contributions to the susceptibility tensor and an approximation of single mineral anisotropies can be obtained by a technique described in Borradaile *et al.* (1987). Moreover, our method does not provide a measure of finite strain unless the specific assumptions of the March model are met. The aim of this short paper is to demonstrate the applicability of magnetic fabric data as a powerful method to obtain crystallographic preferred orientation data.

THE RELATIONSHIP BETWEEN MAGNETIC FABRICS AND CRYSTALLOGRAPHIC PREFERRED ORIENTATIONS

The physical properties of paramagnetic minerals are directly related to the symmetry of the crystallographic lattice (Nye 1985). For example, the minimum susceptibility axis of pseudohexagonal mica is sub-parallel to the crystallographic *c*-axis (Fig. 1). The intermediate and maximum axes lie in the basal plane; their relationship

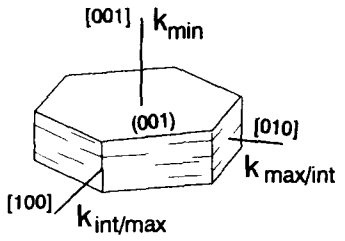

Fig. 1. The relationship between principal susceptibility axes and crystallographic axes in a single mica crystal. The minimum susceptibility is parallel to the crystallographic *c*-axis; the relationship between the maximum/intermediate axes and the crystallographic *a* and *b* directions varies for different micas.

to the crystallographic *a*- and *b*-axes varies with the mica species. The degree of anisotropy $P = k_{max}/k_{min}$ ($k_{max} \geq k_{int} \geq k_{min}$ are the principal susceptibilities) varies typically between 1.15 and 1.75 for chlorite, 1.29 and 1.85 for biotite, and is 1.41 for muscovite (Borradaile *et al.* 1987). A multiparticle system consisting of muscovite flakes, for example, can show an anisotropy that ranges from $P = 1.0$ for randomly distributed aggregates to $P = 1.41$ for a perfect preferred orientation of all particles. The relationship between anisotropy and preferred mineral orientation can be modeled with basic tensor operations, assuming that the shape of the single particle anisotropy of mica is represented by an oblate ellipsoid of revolution (Owens 1974, Richter in press). The total anisotropy of the system $[k_{ij}]_{tot}$ is obtained by the summation of all single mineral tensors $[k_{ij}]_s$:

$$[k_{ij}]_{tot} = \sum_{s=1}^{n} [k_{ij}]_s \qquad (1)$$

($i, j = 1, 2, 3$; n = number of grains)

neglecting any physical interactions between the single grains, an assumption that is appropriate in the case of mica.

A method to obtain multiparticle systems with different degrees of preferred orientations is to apply March's (1932) model to an initially uniformly distributed system (Ramsay & Huber 1983, Richter in press). Figures 2(a) & (b) show the result of 102 simulations, where we applied March strains to an initially uniform distribution of four different micas with degrees of anisotropy in the range of natural minerals ($P = 1.2$, 1.4, 1.6 and 1.8) and calculated the corresponding magnetic fabric. To test the effects of different strain geometries, we applied plane strain under co-axial conditions ($X > Y = 1 > Z$), pure flattening ($X = Y > Z$) and uniaxial constriction ($X > Y = Z$); constant volume deformations were assumed in all cases. The first two are most likely to occur in natural mudstones or slates. The applied natural strain $\varepsilon_i = \ln(1 + e_i)$ is plotted in Fig. 2 vs a corresponding magnetic parameter

$$M_i = \ln(k_i/(k_{max} * k_{int} * k_{min})^{1/3}). \qquad (2)$$

Figure 2(a) shows that the magnetic anisotropy M_i increases with increasing crystallographic preferred orientation and that it reaches a saturation value that is

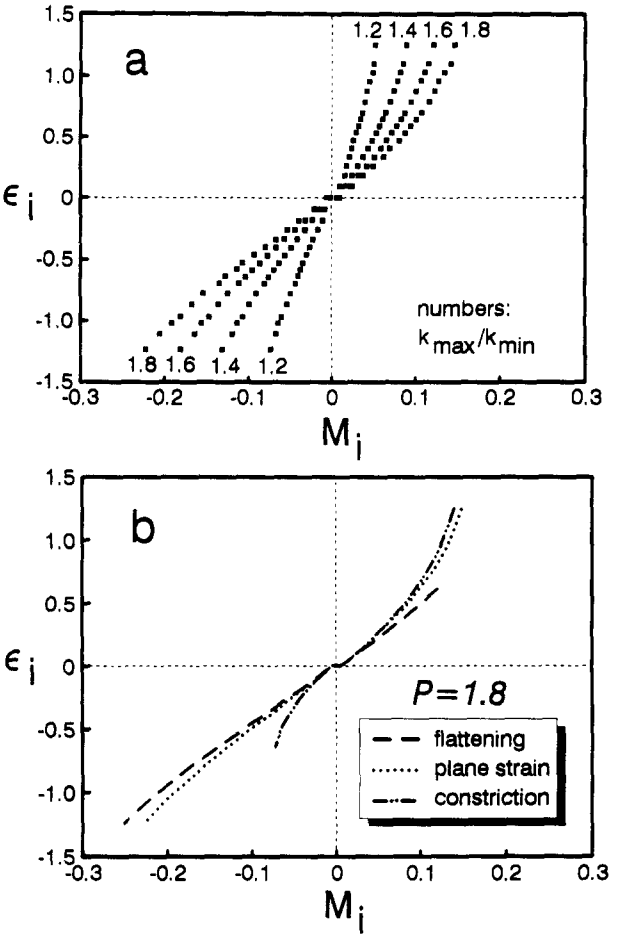

Fig. 2. (a) Theoretically obtained correlation between the logarithmic March strains ε_i and $M_i = \ln(k_i/(k_{max} * k_{int} * k_{min})^{1/3})$ for various single mineral anisotropies ($P = k_{max}/k_{min} = 1.2$, 1.4, 1.6 and 1.8). (b) The effect of different strain geometries (pure flattening, plane strain and pure constriction) on an initially uniformly distributed mica ($P = 1.8$) aggregate; constant volume deformation.

defined by the single mineral anisotropy. For aggregates of perfectly oblate particles the saturation anisotropy is reached twice as fast for the maximum axes than for the minimum axes. Therefore, the minimum axes are a better indicator of the degree of crystallographic preferred orientation than the maximum axes. The slope of the correlation line is a function of the single particle anisotropy and therefore characteristic of a specific mineral. Figure 2(b) demonstrates that in practice the correlations are almost independent of the strain regime under which the preferred orientation was acquired.

March strains can be obtained without much mathematical/statistical effort from natural samples (see Oertel 1983 for discussion). They directly represent rock strain if a sediment with an initially random distribution, for example of mica flakes, is weakly deformed. March strains are particularly easy to determine from X-ray texture goniometer analysis of slates (e.g. Wood *et al.* 1976) and are a measure of the degree and the geometry of mica preferred orientation.

Magnetic anisotropy also measures the degree of crystallographic preferred orientation. The advantage over X-ray and optical methods is, in addition to the speed of anisotropy measurements, that a rock volume of up to *ca* 11 cm^3 is analyzed. The measuring procedure

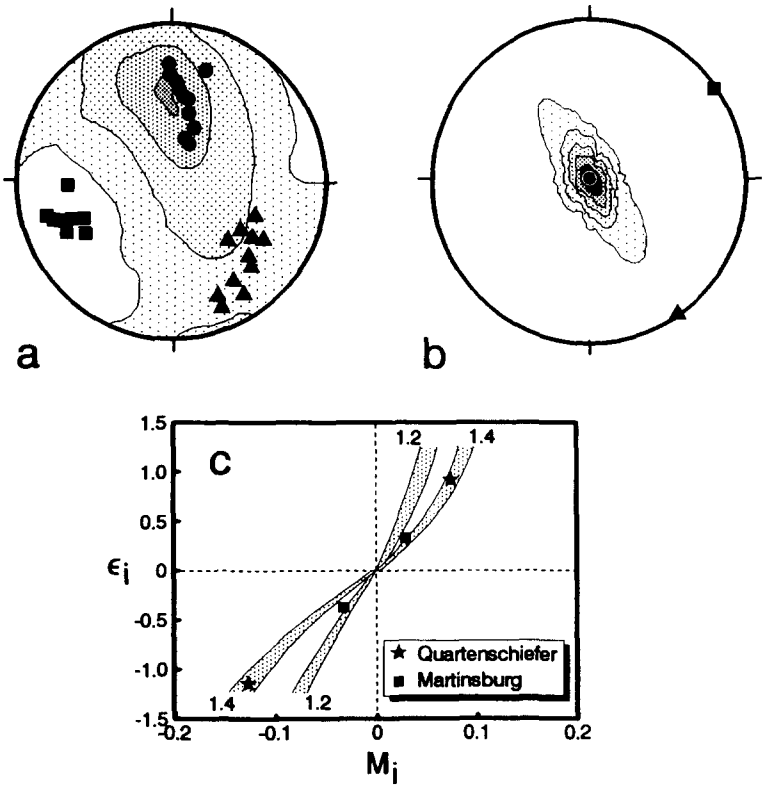

Fig. 3. X-ray textures and principal susceptibility orientations for (a) a chlorite dominated specimen (Martinsburg Formation) and (b) a mica dominated sample (Quartenschiefer Formation) in lower-hemisphere, equal-area projections. X-ray texture data for (a) from Holeywell & Tullis (1975) rotated into geographic co-ordinates; (b) in specimen co-ordinates. The maximum density of mica–chlorite basal planes is parallel to the minimum susceptibility pole. (c) March strains calculated from the X-ray textures are plotted vs magnetic anisotropy. The measured March 'strains' and magnetic 'strains' show perfect agreement with the appropriate theoretical curves of Fig. 2.

with a susceptibility device is easy and, because of the large volume involved, the sample preparation does not affect the measurement. The bulk crystallographic fabric, hence, is better represented with magnetic fabric analysis than with the thin surface slice measured in conventional methods.

TWO APPLICATIONS

A comparison between the orientations of the principal magnetic axes and the density distributions of mineral lattice planes obtained by X-ray measurements is used to demonstrate the reliability of our method. The first example is from the Quartenschiefer Formation (Swiss Alps). Rock magnetic investigations, low temperature susceptibility analysis and hysteresis experiments, demonstrate that paramagnetic minerals (mainly white mica) dominate the magnetic susceptibility of our specimen. The second sample is from the Martinsburg Formation (Pennsylvania) where rock magnetic investigations prove that the susceptibility is dominated by chlorite (AMS from Housen & van der Pluijm 1990, X-ray textures from Holeywell & Tullis 1975). In both cases the maximum densities from X-ray goniometry are perfectly reflected by the poles of the minimum susceptibility axes (Figs. 3a & b). This indicates that the mica fabrics (Quartenschiefer) and the chlorite fabrics (Martinsburg) are equally well characterized by both X-ray and magnetic fabric analysis. Such qualitative relationships between magnetic fabrics and X-ray textures have been reported before (Ihmlé *et al.* 1989, Richter *et al.* 1991), but a quantification of the magnetic fabric has not been offered.

March (1932) derived a formula relating the final pole densities in the principal strain directions (ρ_i) to an original unitary and uniform density, $e_i = \rho_i^{-1/3} - 1$, where ρ_i is obtained by the normalization of the principal pole densities to the average pole density for all orientations and e_i is the elongation. The interpretation of March values as finite strains is debatable (Oertel 1983). We use them as an expression for the pole density in the three principal directions. The March 'strains' of our examples (as natural strains) are plotted against the normalized magnetic fabric magnitudes in Fig. 3(c). The actual single mineral anisotropies were estimated for our Quartenschiefer sample to be $P = 1.4$ and for the Martinsburg sample to be $P = 1.2$–1.3 based on chemical composition (Wintsch *et al.* 1991) and data from Borradaile *et al.* (1987). The modeled (stippled thick lines in Fig. 3c) and the natural data show excellent agreement and lie well within experimental precision.

In conclusion, magnetic anisotropy is a fast and easy method to obtain the geometry and magnitude of crystallographic preferred orientations. March strains can be obtained from the modeled relationship in Fig. 2(a). The precision is sufficiently high to discriminate among various strain states provided that the dominant mag-

netic phase is characterized. In fact, the relative ease, speed and greater volume analyzed suggest that magnetic fabric analysis may be a superior method in many cases.

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