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Origin of magnetic fabrics in ultramafic rocks

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Abstract. The magnetic fabric of a rock, defined by the anisotropy of magnetic susceptibility (AMS), is often used as a tectonic indicator. In order to establish a quantitative relationship between AMS and mineral texture, it is important to understand the single crystal intrinsic AMS of each mineral that contributes to the AMS of the rock. The AMS and crystallographic preferred orientation (CPO) of amphiboles, olivine and pyroxenes has been analyzed in a series of amphibolites, peridotites and pyroxenites that do show preferred mineral alignment. The CPO of each mineral phase was determined based on electron backscatter diffraction (EBSD). Whole-rock AMS was computed based on the CPO and single crystal AMS of the respective minerals. A comparison between measured and modelled magnetic anisotropy shows that the directions of the principal susceptibility axes agree well in amphibolite and peridotite. Pyroxenite is a good example for competing AMS fabrics in polyphase rocks.

1. Introduction

Anisotropy of magnetic susceptibility (AMS) is often used as a proxy for mineral texture in geologic applications, e.g. to gain information on deformation processes in metamorphic rocks or emplacement and flow processes in igneous rocks [1-3]. Magnetic susceptibility is a second-order symmetric tensor and typically relates to the arrangement of iron in the crystal lattice. Therefore, AMS in a rock can yield information on the preferred mineral alignment, given that (1) the minerals that carry the AMS can be identified, and (2) their intrinsic AMS is known. Rock texture is usually carried by the abundant paramagnetic minerals, e.g. silicates, while even small amounts of ferromagnetic grains, e.g. iron oxides, often dominate the magnetic susceptibility. Hence it is important to isolate the paramagnetic component of the AMS [4]. Ultramafic minerals, such as amphiboles, pyroxenes and olivine, often control the paramagnetic AMS and texture in mafic and ultramafic rocks [5-8].

Electron backscatter diffraction (EBSD) is a powerful technique that determines mineral phases and their CPO on large areas of a sample [9]. The CPO can then be correlated with the anisotropy of physical properties, most often for seismic (elastic) anisotropy. EBSD has also served to better understand what minerals carry the AMS in polyphase mafic rocks and how CPO and AMS relate qualitatively. For example, in the La Palisse lava flow in the French Massif Central, a correlation was found between plagioclase and clinopyroxene preferred orientation and the orientation of the principal susceptibility axes [10].

The aim of this study is to test how mathematical models that combine the EBSD-derived CPO with the single-crystal AMS of the constituent minerals compare to measured AMS in ultramafic rocks. For this, a series of deformed mono- and polyphase rocks like amphibolite, peridotite and pyroxenite are investigated through EBSD and AMS measurements. The results from this study allow using AMS as qualitative and possibly quantitative proxy for mono- or polyphase mineral texture, and as such as a tectonic marker.

2. Material and methods

2.1. Sample description

After carefully performed pre-inspection by standard petrographic techniques, four samples each were selected from three different rock types: amphibolite, peridotite and pyroxenite. Two amphibolite samples were drilled in the Ivrea Zone, Northern Italy, and consist of hornblende, quartz and feldspar. The other two amphibolite samples were taken from the Møre-Trøndelag Fault Zone, Norway, and contain hornblende, biotite, quartz and feldspar. The four peridotite samples come from the Ivrea Zone and are made up mainly of olivine, with minor components of hornblende, clinopyroxene and an opaque mineral, probably magnetite. The pyroxenite samples are from Oman, consist of clinopyroxene, orthopyroxene and hornblende and are strongly serpentinized. One pyroxenite sample contains large grains, so that is was not possible to obtain a representative CPO. Deformed rocks were chosen in order to ensure that they possess a CPO and magnetic fabric. The lineation and foliation were determined if possible from macroscopic and thin section evidence.

2.2 Determination of AMS
Cores of 2.5 cm diameter and 2.2 cm length or 1.7 cm diameter and 1.6 cm length were drilled from each rock in its geographic reference system. AMS was measured on a torque magnetometer. Measurements were performed in high fields between 1.0 and 1.5 T in order to isolate the paramagnetic component of the AMS. The measured AMS is described in Fig. 1 by the orientation of the principal axes, i.e. the eigenvectors, of the susceptibility tensor.

2.2 Determination of CPO
The core surfaces were ground, polished, and lapped with colloidal silica in order to obtain a smooth surface low in defect content and thus suitable for EBSD measurements. The sides of each core were covered with silver paint to reduce charging problems, but no surface coating was applied. EBSD data were acquired on a SEM EOscan (Tescan, Brno CZ), equipped with a Pegasus OIM version 6.2 EBSD+EDS system by Ametek-Edax (Mahway, NJ, USA). EBSD patterns and EDS counts of specific elements were mapped simultaneously with a beam current of 3-5 nA and 20 kV acceleration voltage. Only one high-symmetry phase was indexed online to increase acquisition speed. The data were later reprocessed using the ChiScan routine of OIM Data Collection to re-index all relevant mineral phases filtered by user-defined windows for EDS counts. The measured CPO is presented in Fig. 1 by contoured pole figures of three mutually perpendicular crystal axes.

2.3 Modelling of rock AMS
AMS was modelled based on the CPO and single crystal susceptibility tensors [11]. Model calculations of Hill averages [12] were performed using MTex [13]. Separate models were made for (1) each relevant phase, and (2) a combination of all phases according to their modal composition for each rock. The modelled susceptibility ellipsoid is displayed in Fig. 1 by colored isolevel stereoplots and by the orientation of the corresponding principal axes.

3. Results
A summary of CPOs and comparison between measured and modelled AMS of selected cores is given in Fig. 1. Modelled principal susceptibility directions agree well with observations for all amphibolites, both from the Ivrea Zone and the Møre-Trøndelag Fault Zone. These samples are clearly dominated by the hornblende fabric, as quartz and plagioclase (1) possess weak CPOs and (2) have weak susceptibilities. The biotite fraction in the amphibolite from the Møre-Trøndelag Fault Zone is less than 5 vol%. Thus, the magnetic fabric of the amphibolites can be considered as monomineralic.

For the peridotite, AMS was modelled for each phase – olivine, clinopyroxene and hornblende – and the combination of phases, weighted according to the modal composition. As can be seen in Fig. 1c, olivine predominates the total AMS signal. The hornblende AMS competes with the olivine AMS. However, because olivine composes >93% of these samples, both hornblende and clinopyroxene AMS only add minor contributions to the total AMS. The principal directions match well between observed and modelled AMS both if (1) the AMS is calculated exclusively for olivine, and (2) the AMS is computed for the combination of phases.

In the pyroxenite samples, the measured maximum susceptibility coincides with that modelled for clinopyroxene, which is the main phase (Fig. 1d). The orientation of the minimum axes of measured and whole-rock modelled AMS agree. The latter is strongly influenced by the orthopyroxene component, which makes up only 14% of the rock.

4. Discussion
The orientation of principal susceptibility axes has been successfully modelled in rocks whose AMS is dominated by a single mineral phase, e.g. by phyllosilicates [14]. This study confirms these results for ultramafic and mafic rocks. In the case of amphibolite, the orientations of the maximum and minimum axes of the modelled AMS based on hornblende

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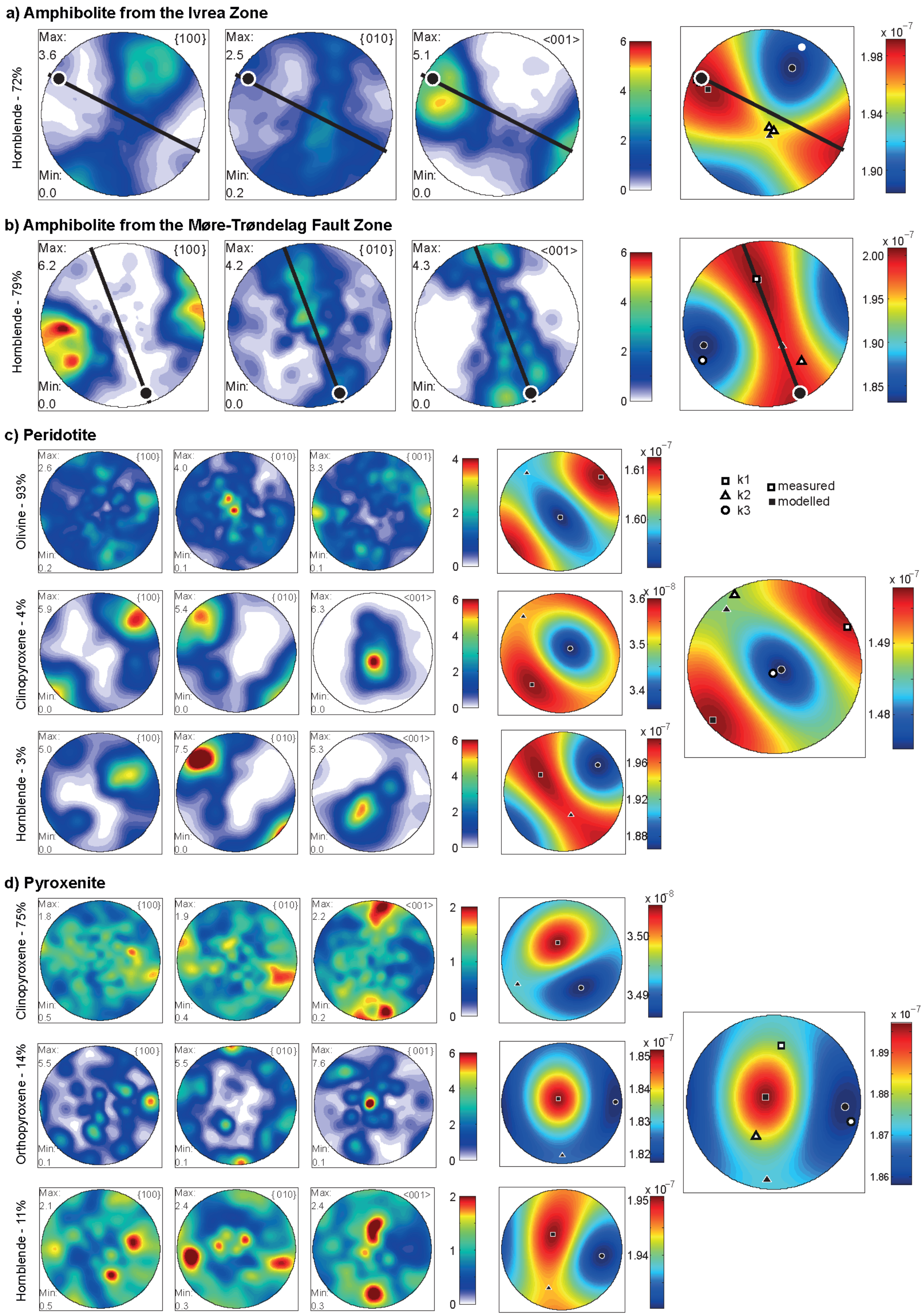

Figure 1: CPO of relevant phases, modelled and measured AMS for amphibolite (a,b), peridotite (c), and pyroxenite (d). The AMS contribution of each phase and the combination is shown separately for the peridotite and pyroxenite. Black lines and circles indicate foliation and lineation directions if visible.

CPO are in good agreement with the measured AMS. The orientation of the principal susceptibility axes with respect to macroscopic lineation will depend on the hornblende texture. The intrinsic maximum susceptibility of hornblende is parallel to the crystallographic *b*-axis, the minimum is parallel to *a**, and the intermediate susceptibility, which is parallel to *c*, has a value close to the maximum susceptibility. The girdle distribution of the *a** and *b*-axes of hornblende in the Ivrea samples forces the maximum susceptibility to align with the macroscopic lineation. In contrast, the crystallographic axes in the samples from the Møre-Trøndelag Fault Zone show a point distribution and the maximum susceptibility is sub-parallel the concentration of crystallographic *b*-axes. Therefore, the maximum principal susceptibility, i.e. the magnetic lineation, coincides with the mineral lineation for a fiber texture with *c*-axes parallel lineation. If the *b*-axes are grouped, it will flip and follow the *b*-axes maximum, which is typically formed perpendicular to the rock lineation. This transition in AMS related to variation of CPO was verified by modelling (not shown here) using the Bingham distribution [15] implemented in MTex [13].

Olivine dominates the magnetic fabric of the peridotite samples. There is a good agreement between the modelled and measured AMS. The intrinsic AMS for olivine has the maximum susceptibility along the *c*-axis, and the minimum along the *b*-axis for Fe concentrations >6 wt% FeO. A comparison between olivine CPO and measured AMS shows that the olivine in the peridotites contains >6 wt% FeO.

The pyroxenite samples display a complex relationship between the measured and modelled AMS, which is related to the competing magnetic fabrics of clinopyroxene, orthopyroxene and hornblende. The measured AMS does not agree with any modelled single crystal anisotropy; the measured maximum susceptibility is near the predicted orientation for clinopyroxene, but the minimum axis is closer to what is expected for orthopyroxene or hornblende.

5. Conclusions

This study is a further demonstration of modelling magnetic fabrics based on the modal composition and CPO of relevant phases in a rock [cf. 14]. A good agreement has been found between measured and modelled AMS in particular for amphibolite and peridotite, where the AMS is dominated by a single mineral. The magnetic fabric, even though clearly related to the CPO, is not necessarily coaxial with the mineral fabric. Pyroxenite is a good example for a composite fabric from minerals whose individual magnetic fabrics compete with one another. When modelling AMS from CPO it is important: (1) to have enough grains to allow for reliable orientation statistics in the EBSD data; (2) to use a sample surface that is representative for the whole sample; and (3) to know the intrinsic AMS of minerals responsible for the magnetic fabric. This study demonstrates, newly also for mafic and ultramafic rocks, that AMS can be applied as proxy for rock texture in geologic applications, in particular when it is dominated by a single mineral.

References

[1] Borradaile GJ and Henry B 1997 *Earth-Science Reviews* **42** 49-93
[2] Borradaile GJ and Jackson M 2010 *Journal of Structural Geology* **32** 1519-1551
[3] Hrouda, F 1982 *Geophysical Surveys* **5** 37-82
[4] Martín-Hernández F and Ferré EC 2007 *Journal of Geophysical Research* **112** B03105
[5] Archanjo CJ et al 1994 *Journal of Structural Geology* **16** 323-335
[6] Borradaile GJ, Steward RA and Werner T 1993 *Tectonophysics* **227** 1-15
[7] Schulmann K and Ježek J 2011 *International Journal of Earth Sciences* **101** 705-714
[8] Zak J, Verner K and Tycova P 2008 *Geological Magazine* **145** 537-551
[9] Prior DJ et al 1999 *American Mineralogist* **84** 1741-1759
[10] Boiron T et al 2013 *Geophysical Journal International* **193** 585-602
[11] Biedermann AR 2014 *PhD Thesis 21989* ETH Zurich (Zurich, Switzerland)
[12] Hill R 1952 *Proceedings of the Physical Society A* **65** 349-354
[13] Mainprice D, Hielscher R and Schaeben H 2011 *The Geological Society Special Publications* **360** 175-192
[14] Martín-Hernández F et al 2005 *Journal of Geophysical Research* **110** B06102
[15] Kunze K and Schaeben H 2004 *Mathematical Geology* **36** 917-943