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Evaluating quartz crystallographic preferred orientations and the role of deformation partitioning using EBSD and fabric analyser techniques

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ABSTRACT

Quartz crystallographic preferred orientations (CPO) from three distinct orthogneisses using both the Electron Back Scatter Diffraction (EBSD) and Fabric Analyser (FA) techniques reveal a clear trend from basal <a> and rhomb <a + c> slip for high P–T conditions (670 ± 20 °C/9 kbar), rhomb <a + c> and basal <a> slip for medium P–T (590 ± 15 °C/6 kbar) and a dominance of prism <a> slip for lower P–T conditions (<570 °C/4–5 kbar). The textural variations are interpreted in terms of a temperature field gradient and microscale strain partitioning controlled by a weak feldspar matrix that can locally invert the expected slip system sequences. Locally quartz CPOs are different within one thin section, and in comparison to bulk orientation measurements both, EBSD and the Fabric Analyser techniques are ideal to determine such textural heterogeneities. While the EBSD is a powerful technique to determine the full CPO, measurements from similar locations inside several quartz grains from the orthogneisses and an annealed and undeformed quartzite show that the FA is an accurate tool to determine CPOs of *c*-axis orientations in uniaxial materials. In a CPO focussed study the FA is a cheap alternative to EBSD as the analysis of whole thin section can be accomplished in a very short time, with minimal sample preparation. With the FA it is possible to evaluate the CPOs of several samples quickly with an accuracy that allows identification of the main slip systems and their homogeneity.

1. Introduction

Crystallographic Preferred Orientation (CPO) measurement in deformed rocks is a common procedure introduced into classical structural analysis (e.g. Sander, 1930; Fairbairn, 1949; Turner and Weiss, 1963). A CPO analysis is crucial in order to decipher observed microstructures and/or deformation mechanisms (e.g. Prior and Wheeler, 1999), model other physical anisotropies of rocks (e.g. Ji and Mainprice, 1988; Bascou et al., 2001) and to understand and quantify sedimentary, metamorphic and magmatic processes (e.g. Mørk and Moen, 2007; Romeo et al., 2007; Hasalová et al., 2008).

Quartz is one of the most common minerals in the Earth's crust and therefore understanding its deformational behaviour is important. There are many studies of experimentally and naturally deformed quartz-rich rocks that provide some insight in understanding of quartz deformational behaviour and development of its CPO (Hobbs, 1968; Tullis, 1977; Blumenfeld et al., 1986; Schmid and Casey, 1986; Dell'Angelo and Tullis, 1989; Gleason et al., 1993; Stipp et al., 2002; Vernooij et al., 2006; Menegon et al., 2008; Stipp and Kunze, 2008). Quartz CPO is controlled by temperature, strain rate, differential stress and fluid content (e.g. Stipp et al., 2002; Menegon et al., 2008). Therefore deformed quartz has distinctive CPOs that can be related to specific conditions of formation (e.g. Tullis, 1977; Schmid and Casey, 1986; Stipp et al., 2002).

A CPO can be obtained either by single grain measurements or by statistical diffraction experiments (volume texture measurements). The latter includes methods such as X-ray diffraction or neutron diffraction (Wenk et al., 1984, 1986). Single grain measurements are based on the determination of the orientation of selected lattice directions, or the complete orientation of individual crystals in a sample (Ullemeyer et al., 2000). The Electron Back Scatter Diffraction (EBSD) method adapted to a Scanning Electron Microscope (e.g. Lloyd et al., 1991; Adams et al., 1993; Prior et al., 1999) is a commonly used method. Other methods are based on optical microscopy using the universal stage (Berek, 1924;

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Reinhard, 1931; Turner and Weiss, 1963) or computer assisted microscope stages (Heilbronner and Pauli, 1993; Fueten, 1997; Fueten and Goodchild, 2001; Wilson et al., 2003, 2007). All of these methods have specific advantages and restrictions. The choice of technique depends on the problem being investigated, e.g. which minerals are measured, grain size, whether a thin section or hand specimen is analysed, if the rock is mono- or polymineralic and if it is important to link crystallographic orientations to the exact microstructural position.

The EBSD method provides the easiest way of acquiring large numbers of complete CPO data from individual rock forming minerals with a spatial resolution of <1 μm with a simultaneous knowledge of the microstructure. As in a Scanning Electron Microscope the electron beam creates a source of scattered electrons within a specimen, diffraction of these electrons will occur simultaneously on all lattice planes in a polygrained sample and the back-scattered electrons will form a diffraction pattern and provide the orientation of individual grains (for details see Prior et al., 1999). The newest 'High-speed EBSD' technique can acquire more than 1000 images per second, while the mineral indexing is performed offline (Schwarzer and Hjelen, 2010). Nevertheless, 'High-speed EBSD' can only be applied on suitable materials such as aluminium or nickel and therefore, is not usable for rock and mineral samples (Schwarzer and Hjelen, 2010). The speed of automatic EBSD data collection for minerals including quartz is less than 20 points per second (Prior, 2009).

In summary, advantages of the EBSD method are its high spatial and angular resolution, automatic recognition of mineral phases and that the complete crystallographic orientation including all crystallographic axes, i.e. including Dauphiné twins, can be determined. On the other hand, some extra sample preparation is needed and even with directed automatic EBSD data acquisition the analysis of larger areas, i.e. whole thin section will in general take longer and therefore makes this technique in comparison to the fabric analysis technique described in this paper more expensive.

As an alternative, the optical technique such as the FA (Wilson et al., 2003, 2007) is a fast and a sufficiently accurate tool to determine individual *c*-axis orientation of uniaxial minerals such a quartz, calcite or apatite. Samples can be analysed with a resolution of ~2.8μm/pixel and no special sample preparation is needed. Covered, uncovered, polished, coated or stained thin sections as well as mounts for fission track analysis can be analysed (Peternell et al., 2009). The biggest advantages of the FA are its ability to measure up to 10×10 cm sized samples and its speed and ease of operation. With the standard setting used in this study approximately 90 000 pixels per second can be acquired. Nevertheless, because of the used 2 Ghz desktop computer for image processing, the real-time analysis for a whole thin section ($\sim 4 \times 2.5$ cm) is slowed down to <45 min with 50 μm/pixel, <2 h with 5 μm/pixel and <8 h with 2.8 μm/pixel resolution. The result of the analysis is presented as an axial-distribution (AVA) image of the *c*-axis orientation for each pixel (Heilbronner and Pauli, 1993; Fueten, 1997; Fueten and Goodchild, 2001; Wilson et al., 2003, 2007, 2009). Disadvantages of the method are its limitation to analyse not the full crystallographic orientation, its current restriction to hexagonal and trigonal minerals, and lower spatial and angular resolution in comparison to the EBSD. In summary, FA and EBSD are very valuable alternatives for specific questions as the type of data and sample preparations are different.

The aim of this work is (i) to evaluate the accuracy of quartz CPO data obtained from the FA by comparing results to EBSD analysis (using both the HKL and the TSL systems) and (ii) to discuss the role of deformation partitioning in the development of quartz CPOs.

Wilson et al. (2007) conducted on one sample a first comparison between CPO data obtained by EBSD and FA. However, this was done using an earlier version of the FA and no single point comparison, crystal mapping or *c*-axis distribution within a single thin section was performed. In this study we perform a more rigorous evaluation of the accuracy of FA data by analysing an undeformed Appin Quartzite from the Ballachulish contact aureole, Scotland and a deformed medium-high grade orthogneisses from the Thaya dome in the Bohemian Massif (Czech Republic). The quartz CPOs were measured in four different ways: (i) Single crystal orientation maps, (ii) point orientations within individual quartz crystals, (iii) bulk *c*-axis orientations and (iv) distribution of *c*-axes orientations on the thin section scale. Advantages and disadvantages of both techniques will be discussed in detail, as well as the problem of texture heterogeneity determination on a thin section scale.

Results show that Thaya samples show different quartz CPOs as a result of different deformation and metamorphic conditions. The peak P–T conditions change from c. 670 ± 20 °C/9 kbar to 570 °C/4–5 kbar. Quartz *c*-axis orientations in the distinct orthogneiss samples will be discussed in relation to deformation and metamorphic conditions they underwent. Finally, results will be linked to their implication for microstructural development on the regional scale.

2. Geological setting of the Thaya Dome

The Thaya Dome (or so-called Thaya tectonic window) is situated at the southeast margin of the Bohemian Massif (Fig. 1a) and consists of par-autochtonous Brunia basement (Dudek, 1980) and two basement derived nappes – Lower Moravian Nappe (LMN) and Upper Moravian Nappe (UMN; Fig. 1b) (Schulmann et al., 1995). The basement consists of the Cadomian Thaya granite/orthogneiss overlain by a Proterozoic metapelitic and metapsamitic sequence. The lower Moravian Nappe consists of the strongly sheared Weitersfeld orthogneiss at the base that is overlain by metapelites, marbles and calc-silicate rocks. The Upper Moravian Nappe is composed of the Bíteš orthogneiss body at the base and a metavolcano-sedimentary cover in the upper part of the section (Fig. 1b) (Schulmann, 1990; Schulmann et al., 1994).

The Thaya Dome reveals inverted Barrovian metamorphism interpreted as a result of continental underthrusting and later imbrications of crustal nappes (Štípská and Schulmann, 1995). The structurally highest unit in the western part (Upper Moravian Nappe) exhibits the highest grade of metamorphism (Suess, 1912). Peak metamorphic conditions for these three orthogneiss units were estimated from interlayered metapelites by average P–T method and standard Grt–Bt, St–Grt and Grt–Plg thermobarometry and are ranging from ~650 °C/10 kbar to ~500 °C/4 kbar (Štípská and Schulmann, 1995; Štípská et al., 2000). The kyanite-sillimanite bearing metapelites adjacent and interlayered with the Bíteš orthogneiss reveal metamorphic peak conditions of $\sim 670 \pm 20$ °C at 9 kbar. Staurolite bearing metapelites spatially connected with the Weitersfeld orthogneiss show peak metamorphic conditions $\sim 590 \pm 15$ °C at 6 kbar and the garnet bearing metasediments overlying the Thaya orthogneiss at the western border of the Brunia basement exhibit the lowest peak metamorphic conditions below 570 °C at 4–5 kbar (Štípská and Schulmann, 1995). Consequently, the peak metamorphic conditions of these three orthogneisses and associated metasediments match different crustal levels from where they were exhumed and therefore influence the mineral textures and microstructures of these rocks (Ulrich et al., 2002). In conclusion, the Upper Moravian Nappe was hotter than the Lower Moravian Nappe and the Brunia basement and these differences have led to temperature dependent variations in active slip systems of quartz and therefore also in analysed textures. The Bíteš, Weitersfeld and Thaya orthogneisses