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An optical method for the determination of ⟨a⟩ axis orientations in deformed aggregates of quartz

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Abstract

Knowledge of ⟨a⟩ axis orientation is of paramount importance to the understanding of deformation mechanisms in quartz and by extension, quartz rich rocks. The positions of the ⟨a⟩-axis cannot be measured by standard optical (U-stage) techniques since quartz is optically uniaxial. Many quartz grains, however, contain abundant fluid inclusions and in many instances, these fluid inclusions occupy negative crystal-shaped cavities for which the ⟨a⟩-axis can be optically determined. This study has utilized these negative crystals to locate ⟨a⟩-axis positions using a U-stage. In order to test the validity of this approach a blind comparison was performed on a deformed quartz aggregate from the Simplon Fault Zone (Central Alps: Switzerland). Both ⟨a⟩ and ⟨c⟩ axis positions for this sample were measured using the proposed optical technique and via an X-ray texture goniometer. The locations for ⟨a⟩ axis maxima contoured on a Schmidt net using the two techniques agree closely, demonstrating that the optical technique was successful. Advantages of the optical technique are (1) that it is simple and requires inexpensive equipment and (2) that ⟨a⟩ axis positions can be determined on a grain-by-grain basis allowing for the detailed study of crystallographic orientation differences across grain boundaries in deformed aggregates of quartz.

Keywords: Quartz microstructures; a-Axis; Fluid inclusions; Simplon Fault Zone

1. Introduction

Our understanding of the development and significance of preferred orientations in mineral aggregates has increased dramatically in recent years. Studies of experimentally and naturally deformed quartz-rich rocks have demonstrated the usefulness of quartz fabric analyses in unraveling the deformational history of a sample and a region (e.g. Law, 1986; Schmid and Casey, 1986; Mancktelow, 1987a,b; Hirth and Tullis, 1992). Measurements of c-axis orientations in quartz-rich rocks can be made microscopically with the use of a universal stage and c-axis preferred orientation data are therefore the most widely reported.

However, knowledge of the full crystallographic preferred orientation is clearly critical to any thorough understanding of the crystal–plastic deformation of quartz. The preferred orientation (if any) of the ⟨a⟩ axis, which represent the closest packed direction and therefore the most common slip direction in quartz, is often of particular interest (e.g. Lister and Williams, 1979; Schmid et al., 1981; Law, 1986; Law et al., 1986, 1990; Schmid and Casey, 1986; Etchecopar and Vasseur, 1987; Mancktelow, 1987a,b, 1990). In particular, Lister and Williams (1979) pointed out that ⟨a⟩-axis fabrics generally display an asymmetry that can be consistently related to the sense of shear. McLaren (1986) noted that detecting high angle boundaries in quartz-rich rocks is especially difficult due to the impossibility of determining ⟨a⟩-axis orientations from standard thin sections using the polarizing microscope. This technique provides a method for collecting these data. The development of a method for obtaining ⟨a⟩-axis orientations from spatially related quartz grains in thin section is also essential to the study of variations in quartz grain orientations across grain boundaries. Currently, the only available method is the electron backscatter diffraction technique (EBSD, e.g. van Daalen et al., 1999; Prior et al., 1999; Trimby and Prior, 1999). This paper presents an optical method for the

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determination of ⟨a⟩ axis orientations from deformed aggregates of quartz that utilizes the morphology of negative-shaped fluid inclusion cavities in the host grain. This method can be used to determine the preferred orientation of ⟨a⟩ axis for a sample and to directly compare ⟨a⟩ axis orientations from individual grains across grain boundaries.

2. Method

Fluid inclusions are minute volumes of fluid trapped with a mineral during or subsequent to the host mineral's growth. Many fluid inclusions are introduced into grains during formation and subsequent healing of microfractures or during grain boundary migration recrystallization. The role that fluid inclusions play in inhibiting and/or promoting deformation of the host have long been debated (Johnson and Hollister, 1995; Hollister, 1990; Vityk et al., 2000). Urai et al. (1986) and Karato (1988) envisioned fluid inclusions as impurities located within the material, which can pin migrating grain boundaries. During grain boundary migration (GBM) recrystallization these impurities provide a barrier to a migrating grain boundary. Fluids, which have developed along migrating grain boundaries, can undergo 'break away' and be incorporated within the recrystallized grain as fluid inclusions. Once trapped in the grain, the shape of the fluid inclusion can be modified so as to decrease the energy of this large defect. The most efficient energetic response is the formation of low energy faces on the inclusion walls. The end result of this is that the fluid inclusion cavity takes on a negative crystal morphology. Anderson and Bodnar (1993) show that these negative-shaped crystal voids directly reflect the crystallographic orientation of the host mineral. Based on these observations, we propose that fluid inclusion morphology could be used to determine the ⟨a⟩ axis orientation of the host grain and that these data could easily be obtained from standard thin-sections using a polarizing microscope equipped with a universal stage.

To test the proposed method, ⟨a⟩ axis orientations from a single sample were determined using an X-ray texture goniometer and compared with ⟨a⟩-axis measurements obtained from fluid inclusion morphologies using a universal stage. The sample used is a quartz mylonite from the Simplon Fault Zone (SFZ) in Central Switzerland (Mancktelow, 1990).

2.1. Sample location and characterization

The SFZ is located in the Central Alps of Switzerland and northern Italy. It is a major transverse structure reflecting Neogene orogen-parallel extension during continued convergence (Mancktelow, 1985, 1990). The oriented mylonite sample used for this study was obtained in the footwall of the southeast section of the SFZ (Fig. 1A), which is a foliated zone of generally ductile mylonites. The quartz microstructure in this sample is characterized by GBM and exaggerated grain growth, resulting in a coarser average grain size (Mancktelow, 1990). Photomicrograph and measured CPO are shown in Fig. 1B (Mancktelow, 1990).

2.2. Sample preparation

The sample was cut perpendicular to the mylonitic foliation and parallel to the stretching lineation Orientation of the sample is referenced to the down lineation and structurally up (perpendicular) directions (see Fig. 2A). Samples used for the comparison between X-ray texture goniometry and U-stage measurements were cut from the same billet. The equipment used for this study was a standard optical petrographic microscope (Jenapol) equipped with a 4 spindle Universal Rotary Stage.

Texture goniometer measurements for sample SP 136 were conducted at the ETH Zürich. The sample was scanned perpendicular to the foliation to give a better statistical representation of the overall crystallographic preferred orientation and the scan distance was approximately 14 mm.

2.3. Alignment of the thin section on the U-stage

Correct alignment of the thin section on the U-stage is important in order to ensure correspondence of the reference directions on the thin section (*l* and *up*) with the measured and plotted orientations of the ⟨a⟩ axis data. Initial settings on the U-stage for both horizontal and vertical planes were set to 0°. The thin section was then aligned on the microscope U-stage relative to the marked directions inscribed on the thin-section.

Large (mm scale) quartz grains containing abundant fluid inclusions were identified and used for analysis. Once a grain was chosen, the U-stage was adjusted until a centered optic axis (COA) interference figure was obtained for the grain. Once a COA figure was obtained for a grain, the vertical and horizontal readings of the U-stage were recorded so that all subsequent measurements could be restored to their original orientation. Regions within the grain containing hexagonal-shaped inclusions were photographed (see Fig. 3).

Inclusions on the printed photograph were outlined to best show the hexagonal morphology and facilitate measurement of the ⟨a⟩-axis positions. A line extending beyond one outer edge of the photograph was drawn to define the positions of the ⟨a⟩-axis. The angular orientation of the ⟨a⟩-axis was determined relative to a reference line drawn parallel to one edge of the photograph, using a protractor. These data were plotted on a Wulff net together with the c-axis orientation (vertical) and the now rotated orientation markers. The positions of the ⟨a⟩ axis were rotated back to their initial positions using the recorded U-stage measurements. Compilations of the measured ⟨a⟩-axis

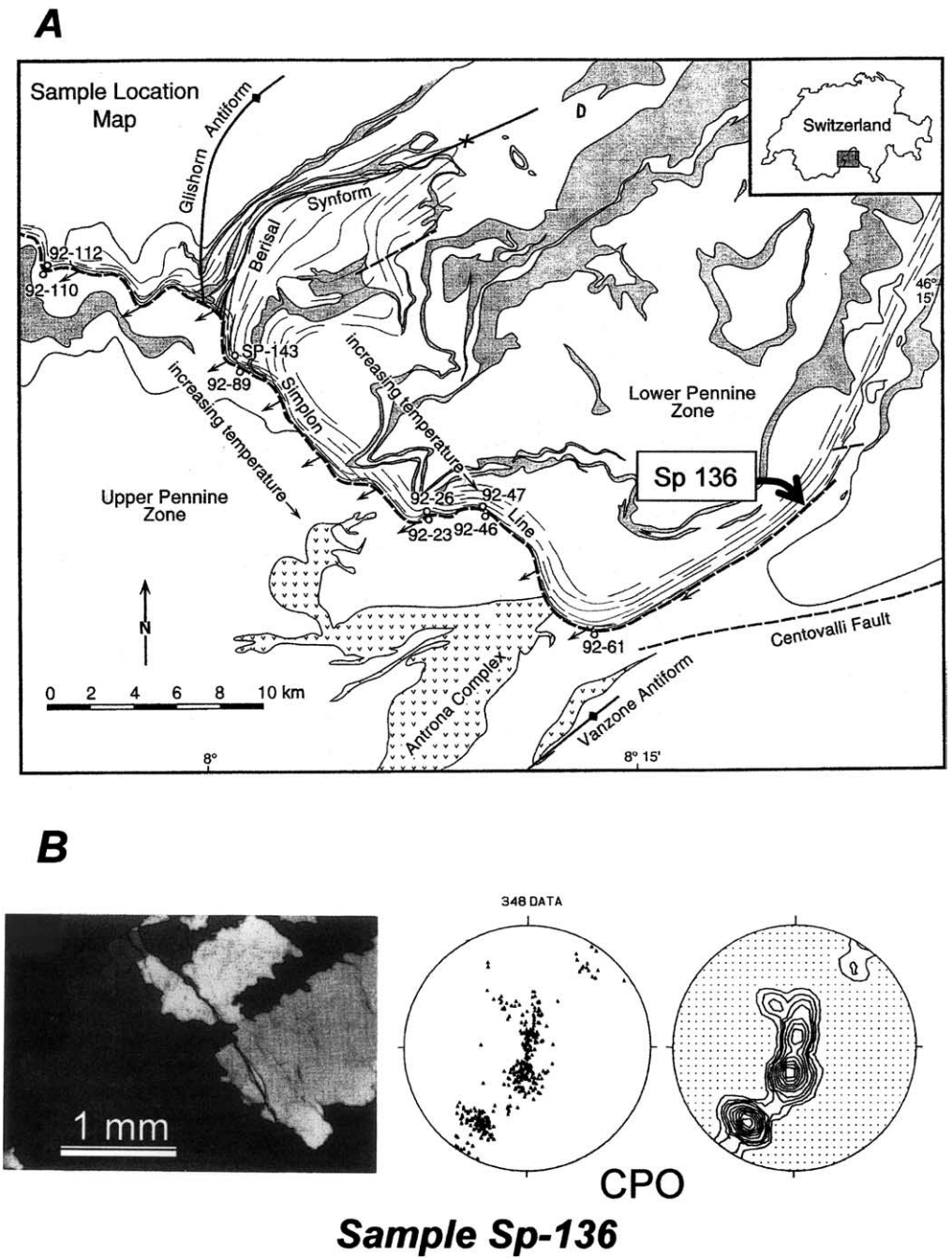

Fig. 1. (A) Map of the Simplon Fault Zone showing sample location for Sp-136. Inset map shows the location of the study area. (B) Photomicrograph of sample SP-136 and contoured c-axis plot for this sample (after Mancktelow, 1990).

orientations were transferred to a Schmidt net and contoured using the program Stereoplot (Mancktelow 1993).

3. Results

Two sets of 10 quartz grains with inclusions were chosen, photographed and scanned into the computer. Of the scanned photographs, 88 hexagonal-shaped inclusions ranging in size from 8 to 20 μm (diameter) were deemed suitable for measurement. Axial measurements from these inclusions were plotted and the contoured stereographic projection is shown in Fig. 4A. Contoured ⟨a⟩-axis data obtained from the X-ray texture goniometer is shown in Fig. 4B and Fig. 4C provides a direct comparison of the ⟨a⟩ axis maxima orientations determined using both methods. Resolving the axial position in terms of azimuth and plunge, the optically determined maxima for axial azimuth are within 2–8° of those determined using the X-ray goniometer. Lesser agreement is shown in the measured plunge angle where deviations between the two methods range to 18°. This disparity is not surprising since the

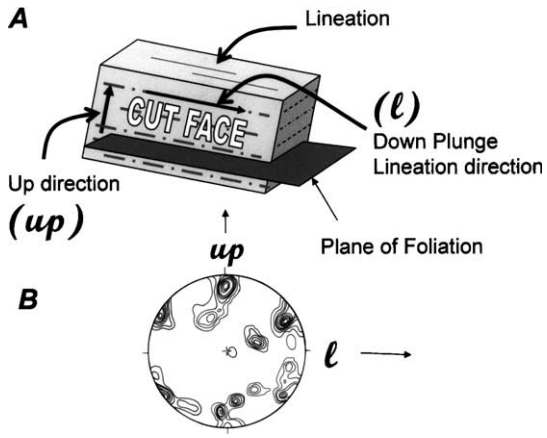

Fig. 2. (A) Diagram showing relationship between structural data and orientation directions as marked on the billet and thin sections. (B) Equal area plot of a-axis data for sample Sp-136 showing how the reference orientations relate to Schmidt net plots.

U-stage used precluded measurement of inclusion morphologies for vertical adjustments of the stage exceeding 15° (due to loss of optical resolution). Despite this limitation the results of the ⟨a⟩-axis optical map, compiled from the morphology of the fluid inclusions found within sample SP-136, demonstrate that the location of ⟨a⟩ axis maxima do coincide with contoured points measured with the X-ray goniometer from the same sample.

Optical measurement errors are directly related to the size of the inclusion cavity. For small inclusions (2–5 μm diameter), uncertainties can exceed 10° in measured axis position. This error stems from the rounded appearance (low optical resolution) of the inclusion cavity. These errors can be reduced by directly measuring the axial positions via stage rotation rather than utilizing photomicrographs. In addition, by measuring the axis positions directly on the stage, greater vertical stage rotations may be possible, further improving the results. For best results, fluid inclusion cavities of 5 μm or larger should be used.

4. Conclusions

The results of the fluid inclusion morphology method for the determination of ⟨a⟩ axis orientations in quartz-rich rocks adequately reproduced the maxima patterns determined using the X-ray texture goniometer. Since negative-crystal shaped inclusions are most common in

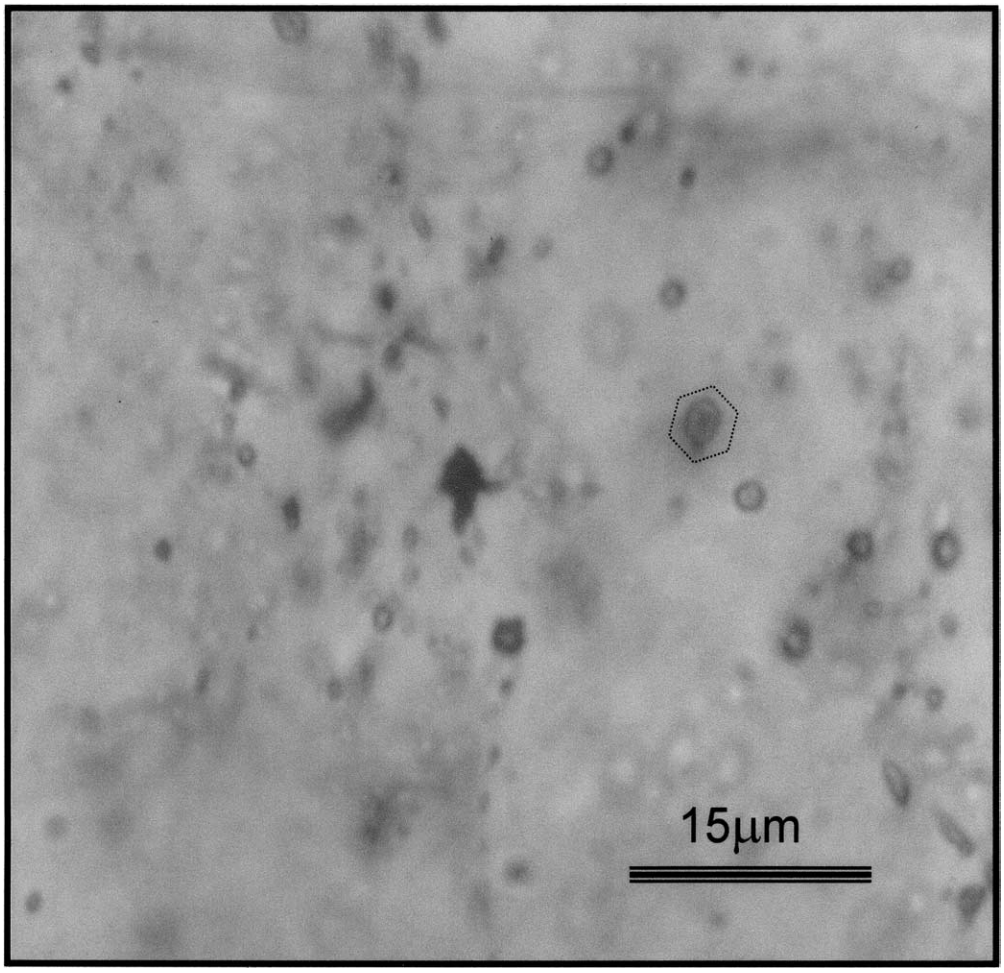

Fig. 3. Photomicrograph of small hexagonal shaped fluid inclusion in sample Sp-136.

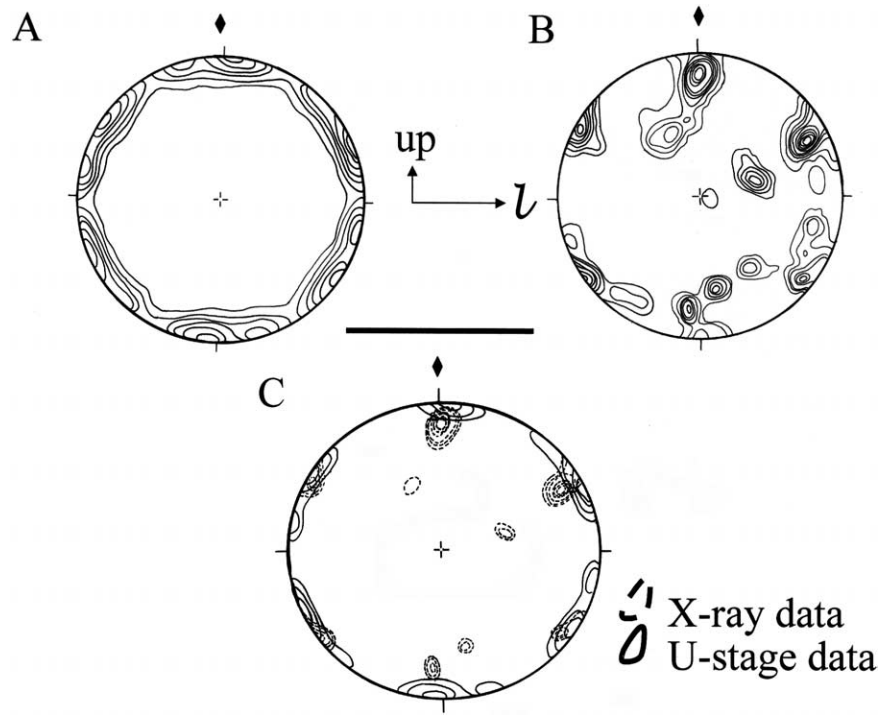

Fig. 4. ⟨a⟩ axis data contoured on the Schmidt net. Sections were cut perpendicular to the plane of foliation (shown as a line) and parallel to lineation. Arrows labeled (*l*) and (*up*) show down plunge lineation direction and outcrop up direction, respectively. (A) Contoured upper hemisphere ⟨a⟩ axis orientations determined using the negative crystal inclusion morphology method (88 inclusions). Contours are a 1–6 times uniform. (B) Contoured upper hemisphere projection of ⟨a⟩ axis orientations for the same sample using the texture goniometer. Contours are at 0.5, 1.0, 1.5, 2.0… times uniform. (C) Overlay of the results of the two methods. The maxima are defined by the 4–6 times uniform contours for the negative crystal morphology method and 2.0–4.5 times uniform levels for the texture goniometer method.

amphibolite–granulite facies rocks, this technique will be most applicable to quartz rich rocks recrystallized under these conditions.

While this method suffers some limitations, it can be used to obtain ⟨a⟩ axis orientations from quartz grains with abundant fluid inclusions with inclusion cavity diameters of 5 μm or greater and has the advantage that ⟨a⟩ axis data from individual quartz grains can be determined and compared with neighboring grains in a quartz mosaic. Knowledge of ⟨a⟩ axis orientations for quartz grains involved in grain boundary migration or progressive subgrain rotation recrystallization could be used to study the relative stability of grain orientations in deforming aggregates of quartz, without the need for sophisticated measurement techniques.

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References

Anderson, A.J., Bodnar, R.J., 1993. An adaptation of the spindle stage for geometric analysis of fluid inclusions. American Mineralogist 78, 657–664.

Etchecopar, A., Vasseur, G., 1987. A 3-D kinematic model of fabric development in polycrystalline aggregates: comparisons with experimental and natural samples. Journal of Structural Geology 9, 705–717.

Hirth, G., Tullis, J., 1992. Dislocation creep regimes in quartz aggregates. Journal of Structural Geology 14, 145–159.

Hollister, L.S., 1990. Enrichment of CO_2 in fluid inclusions in quartz by removal of H_2O during crystal plastic deformation. Journal of Structural Geology 12, 895–901.

Johnson, E.L., Hollister, L.S., 1995. Syndeformational fluid trapping in quartz: determining the pressure–temperature conditions of deformation from fluid inclusions and the formation of pure CO_2 fluid inclusions during grain boundary migration. Journal of Metamorphic Geology 13, 239–249.

Karato, S., 1988. The role of recrystallization in the preferred orientation of olivine. Physics of Earth and Planetary Interiors 51, 107–122.

Law, R.D., 1986. Relationships between strain and quartz crystallographic fabrics in the Roche Maurice quartzites of Plougastel, western Brittany. Journal of Structural Geology 8, 493–515.

Law, R.D., Casey, M., Knipe, R.J., 1986. Kinematic and tectonic significance of microstructures and crystallographic fabrics within quartz mylonites from the Assynt and Erribol regions of the Moine thrust zone, NW Scotland. Transactions of the Royal Society of Edinburgh 77, 99–125.

Law, R.D., Schmid, S.M., Wheeler, J., 1990. Simple shear deformation and quartz crystallographic fabrics: a possible natural example from the

Torridon area of NW Scotland. Journal of Structural Geology 12, 29–45.

Lister, G.S., Williams, P.F., 1979. Fabric development in shear zones: theoretical controls and observed phenomena. Journal of Structural Geology 1, 283–297.

Mancktelow, N.S., 1985. The Simplon Line: a major displacement zone in the western Lepontine Alps. Ecologae Geologicae Helvetiae 78, 73–96.

Mancktelow, N.S., 1987a. Quartz textures from the Simplon Fault Zone, southwest Switzerland and north Italy. Tectonophysics 135, 133–153.

Mancktelow, N.S., 1987b. Atypical textures in quartz veins from the Simplon Fault Zone. Journal of Structural Geology 9, 995–1005.

Mancktelow, N.S., 1990. The Simplon Fault Zone. Materiaux pour la Carte. Geologique de la Suisse, Lieferung 163, 1–74.

Mancktelow, N.S., 1993. Stereoplot, Geologisches Institut, Zurich, Switzerland.

McLaren, A.C., 1986. Some speculations on the nature of high-angle grain boundaries in quartz rocks. Mineral and Rock Deformations: Laboratory Studies, Geological Monograph 36, 263–286.

Prior, D.J., Boyle, A.P., Brenker, F., Cheadle, M.C., Day, A., Lopez, G., Peruzzo, L., Potts, G.J., Reddy, S., Spiess, R., Timms, N.E., Trimby, P., Wheeler, J., Zetterstrom, L., 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. American Mineralogist 84, 1741–1759.

Schmid, S., Casey, M., 1986. Complete fabric analyses of some commonly observed quartz c-axis patterns. In: Hobbs, B.E., Heard, H.C. (Eds.), Mineral and Rock Deformation: Laboratory Studies. The Paterson Volume, Geophysical Monograph, 36. American Geophysical Union, pp. 263–286.

Schmid, S.M., Casey, M., Starkey, J., 1981. An illustration of the advantages of a complete texture analysis described by the orientation distribution function (odf) using quartz pole figure data. Tectonophysics 78, 101–117.

Trimby, P.W., Prior, D.J., 1999. Microstructural imaging techniques: a comparison between light and scanning electron microscopy. Tectonophysics 303, 71–81.

Urai, J.L., Means, W.D., Lister, G.S., 1986. Dynamic recrystallization of minerals. Mineral and Rock Deformation: Laboratory Studies, Geophysical Monographs 36, 161–195.

van Daalen, M., Heilbronner, R., Kunze, K., 1999. Orientation analysis of localized shear deformation in quartz fibres at the brittle–ductile transition. Tectonophysics 303, 83–107.

Vityk, M.O., Bodnar, R.J., Doukhan, J.-C., 2000. Synthetic fluid inclusions. XV. TEM investigation of plastic flow associated with reequilibration of fluid inclusions in natural quartz. Contributions to Mineralogy and Petrology 139, 285–297.