PERGAMON

Journal of Structural Geology 22 (2000) 383–390

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.nl/locate/jstrugeo

Bi-axial quartz as a stress indicator

John Starkey

Department of Earth Sciences, University of Western Ontario, London, Ontario N6A 5N7, Canada

Received 6 July 1998; accepted 28 August 1999

Abstract

Experiments confirm that stress causes quartz to become biaxial with the optical axial plane parallel to the direction of maximum applied stress. Five tectonites were studied for which published data indicate strong patterns of preferred orientation of quartz. Conoscopic investigation, using an optical universal stage, reveals that the quartz in these rocks is biaxial with the 2V as large as 22°. The optic axial planes display strong patterns of preferred orientation.

In the natural tectonites the maximum stress directions deduced from the orientations of the optical axial planes cannot be correlated with the supposed tectonic framework responsible for the quartz orientation fabric. The ease with which quartz can be made biaxial experimentally suggests that the orientation of the optic axial planes may be sensitive to tectonic events which affected the rocks subsequent to the development of the quartz orientation fabrics. The analysis of the orientation of optic axial planes in biaxial quartz may provide a tool for the investigation of neotectonics. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

It is a common petrological observation that many nominally optically uniaxial minerals are sometimes seen to be biaxial. This is usually attributed to strain produced by stresses induced either by internal crystal imperfections or by external forces, or both. Experiments on the influence of pressure on the optical properties of birefringent minerals were first conducted by Pfaff (1859). By applying pressure to basal plates of quartz, Pfaff observed that the optic axis separated into two, with the optical axial plane parallel to the direction of applied pressure. Pfaff also observed that the magnitude of the optic axial angle, 2V, and of the rotary polarization increased with increasing pressure. Similar experiments were repeated by Merten and Mach (1875) who reported the same development of an optic axial plane parallel to the applied pressure but did not confirm the changes with increasing pressure noted by Pfaff.

In this study, experiments similar to Pfaff's are repeated using apparatus designed to facilitate the observation of the behaviour of the optic axes using interference figures. The apparatus is not conducive to the measurement of rotary polarization. The experimental observations are supplemented by an investigation of the optics of quartz in five naturally occurring tectonites using the optical universal stage and both orthoscopic and conoscopic illumination. An attempt is made to correlate the deduced maximum stress direction with the tectonic framework of the quartz orientation fabric.

2. Experimentation

Fig. 1 illustrates a simple apparatus which allows stress to be applied to square plates of quartz. The quartz plate, A in Fig. 1, is supported on a glass microscope slide, B, which is placed on a metal base plate C, in which there is a hole, 13 mm. in diameter, to allow for the passage of light when the apparatus is placed on a petrographic microscope such that the base plate lies on the microscope stage. The base plate also supports the fixed arm of the apparatus. The quartz plate is located between two anvils. One is attached to the fixed arm, D, and the other, E, is

---

E-mail address: jstarkey@julian.uwo.ca (J. Starkey).

0191-8141/00/$ - see front matter
PII: S0191-8141(99)00148-0

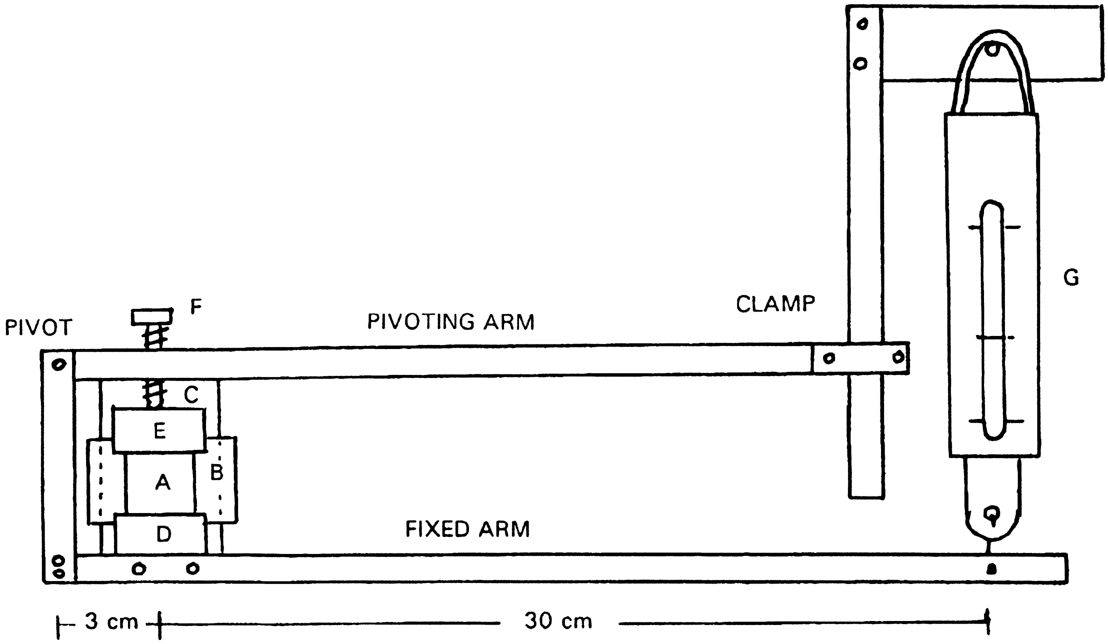


Fig. 1. Apparatus to apply stress to crystal plates. (A) Specimen, (B) Glass microscope slide, (C) Base plate, (D) Fixed anvil, (E) Floating anvil, (F) Adjusting screw, (G) Spring balance.

loosely placed between the quartz plate and a screw, F, which is located in the pivoting arm of the apparatus. A support for a spring balance, G, is clamped to the end of the pivoting arm. A force is applied by stretching the spring balance between the support attached to the pivoting arm and the fixed arm. The force applied by the spring balance is adjusted approximately by sliding the support until the required level is reached. The support is clamped and the final adjustment of the force is made using the screw, F.

During an experiment, glass hemispheres, 6 mm in diameter, are placed beneath the glass microscope slide and on top of the quartz plate. The hemispheres are centred on the microscope axis and provide a conoscopic interference figure when the quartz is viewed with a polarizing microscope using a low power objective and crossed polars. Films of glycerine at the glass-to-glass and glass-to-quartz contacts reduce light loss by reflection.

A plate was cut perpendicular to the crystallographic *c*-axis of a left handed quartz crystal. The plate was 2 mm thick and trimmed to a 10 mm square to produce four faces 10 mm × 2 mm. One pair of these faces was oriented parallel to a crystallographic *a*-axis, the other pair was therefore perpendicular to an *a*-axis. Experiments were conducted with stress applied normal to both of these pairs of parallel faces. Both orientations gave the same results. Under applied stress the optic axis separated into two, the separation of the optic axes increased as the stress increased, and the optic axial plane was parallel to the direction of applied stress and therefore independent of crystallographic orientation. Thus the observations reported by Pfaff (1859) were confirmed. The strain was elastic and the uniaxial interference figure was restored when the stress was removed.

The force was applied incrementally and photomicrographs of the conoscopic interference figure were obtained from which the 2V was calculated from the measured separation between the two isogyres. The geometry was calibrated using photomicrographs of a phlogopite with a known 2V of 8°. The 2V increased linearly to approximately $2\frac{1}{2}^\circ$ as the force was increased to 1500 gms.

3. Observations in natural tectonites

In order to investigate the orientation of the optic axial plane in quartz in naturally occurring rocks, specimens were sought with a strong parallel orientation of quartz *c*-axes. This allowed thin sections to be prepared in which most of the quartz grains were oriented with their optic axes approximately perpendicular to the plane of the section and therefore close enough to the microscope axis to provide more or less centred optic axis interference figures.

Five rock specimens were selected. Two, JSB1 and JSB2, are from the Poughquag Quartzite near Ten Mile River in Dutchess County, New York. They were collected from within 10 feet of a thrust plane. Quartz *c*-axis orientation patterns for these two specimens

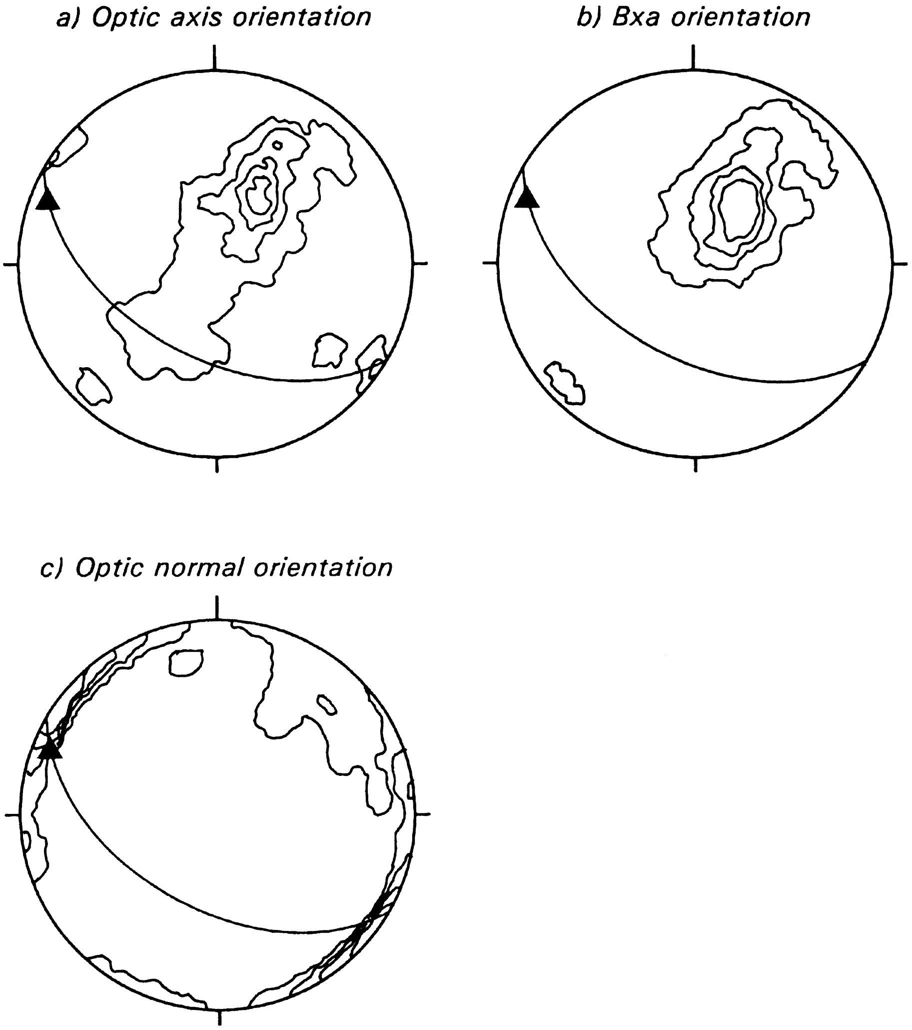


Fig. 2. The optical orientation of quartz in Poughquag Quartzite, specimen JSB1. (a) 99 optic axes. (b) 90 acute bisectrices. (c) 90 optic normals. Contours at 1, 5, 10 and 15 points per 100/n% of the projecting area. Lower hemisphere, Lambert Equal Area Projection. The great circle represents the schistosity, the triangle represents the stretching lineation.

were published by Balk (1952); his figs. 17, 18 and 19 are from JSB1 and figs. 15 and 16 are from JSB2. The crystallographic orientation of quartz in specimen JSB2 was also studied by X-ray diffraction by Higgs et al. (1960). Specimen JSK1 is from a quartzite which occurs in the Bergsdalen Quadrangle of western Norway, described by Kvale (1945). A quartz *c*-axis orientation pattern for this specimen was published by Starkey (1993, fig. 2h), and the orientation of quartz was analyzed by X-ray diffraction by Starkey (1974). The remaining two specimens, JSL915 and JSL945, are of quartzite from the Connemara Schists of western Ireland. Quartz *c*-axis orientation patterns from these specimens were published by Leake (1970, figs. 7b and c, respectively).

The orientations of the quartz optic axes in the five thin sections were determined using an optical universal stage in the conventional configuration for orthoscopic observation. Approximately 100 grains within a randomly selected area were measured. From these data, *c*-axis orientation patterns were prepared (Figs. 2a, 3a, 4a, 5a and 6a). The same quartz grains were examined using an optical universal stage equipped for conoscopic observation. For most grains this permitted the complete orientation of the optical indicatrix to be determined. The orientation patterns of the acute bisectrices, Bxa, and the optic normals are presented in Figs. 2(b) and (c), 3(b) and (c), 4(b) and (c), 5(b) and (c) and 6(b) and (c). All orientation diagrams are represented on a lower hemisphere Lambert Equal Area Projection and contoured in multiples of 100/n% of the projected area (Starkey, 1977). The orientation diagrams were prepared using the computer program Fabric (Starkey, 1996).

All the quartz grains measured conoscopically are biaxial. The 2V ranges from 2° to 22°, most commonly being between 6° and 12°. There is no systematic variation in the magnitude of the 2V with the angle

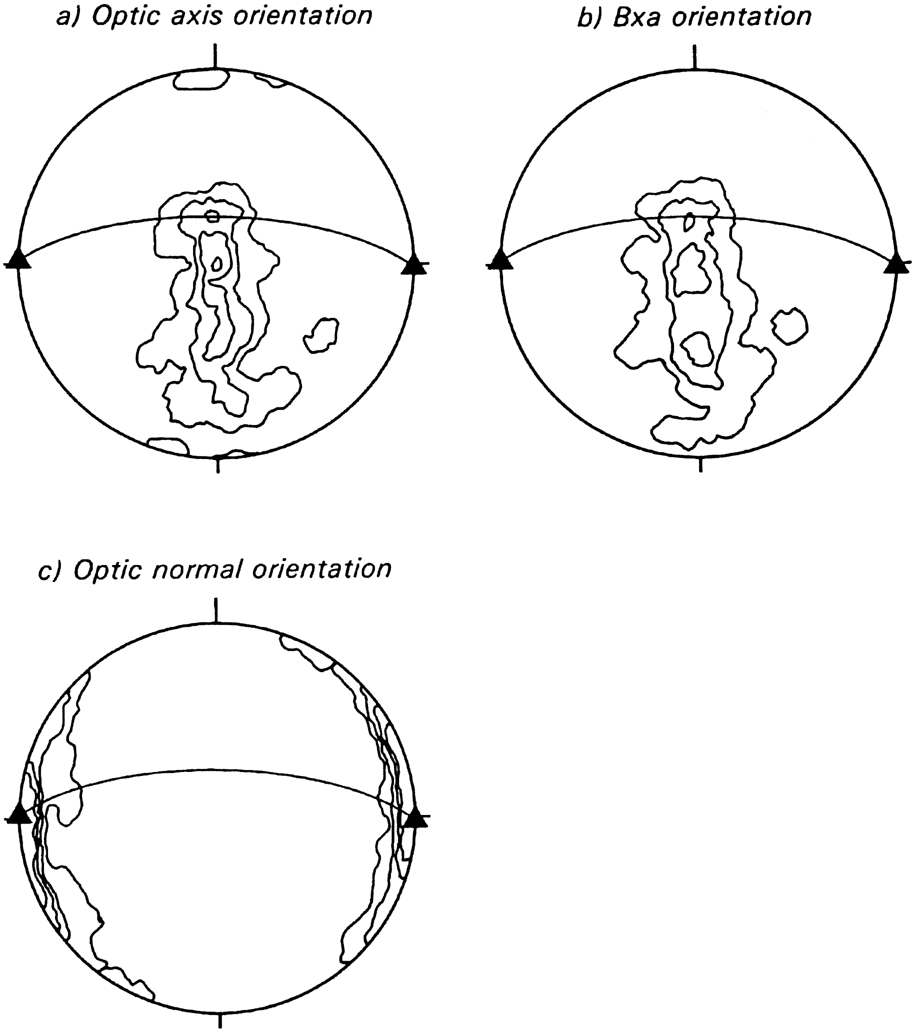


Fig. 3. The optical orientation of quartz in Poughquag Quartzite, specimen JSB2. (a) 99 optic axes. (b) 88 acute bisectrices. (c) 88 optic normals. Contours at 1, 5, 10, and 15 points per 100/n% of the projected area. Lower Hemisphere, Lambert Equal Area Projection. The great circle represents the schistosity, the triangle represents the stretching lineation.

between the Bxa and the schistosity, which was used as a plane of reference. The patterns of preferred orientation of the Bxa are very similar to the patterns of the optic axes determined orthoscopically. Thus it appears that optic axes measured orthoscopically tend to represent 'average' optic axes which lie somewhere between the locations of the two optic axes within an individual grain and thus tend to be close to the Bxa. In those orientation patterns, Figs. 2–5, where the concentrations of optic axes and Bxa occur as elongated maxima, the elongation tends to be perpendicular to the maximum concentration of the optic normals. Thus the spread of the optic axis and Bxa orientations appears to define the average orientation of the optic axial plane.

The quartz *c*-axis sub-fabric in the Poughquag Quartzite is attributed to thrusting which, close to the thrust plane, produced a strong, penetrative schistosity parallel to the thrust plane and a stretching lineation parallel to the direction of tectonic transport (Balk, 1952). Thus the lineation probably lies in the plane containing the minimum and maximum regional stresses, close to the direction of maximum stress. Hence, the lineation should be parallel to the optic axial planes in the quartz and perpendicular to the optic normals. However, Figs. 2(c) and 3(c) illustrate that the optic normals are concentrated approximately 15° away from the lineation. Based on the X-ray orientation data of Higgs et al. (1960) the optic normals in specimen JSB2 are concentrated close to the mean orientation of a crystallographic *a*-axis.

The tectonic setting of the Bergsdalen Quartzite is similar to that of the Poughquag Quartzite (Kvale, 1945). As shown in Fig. 4(c), the orientation pattern of optic normals is more asymmetric with respect to the stretching lineation than in Figs. 2(c) and 3(c); the

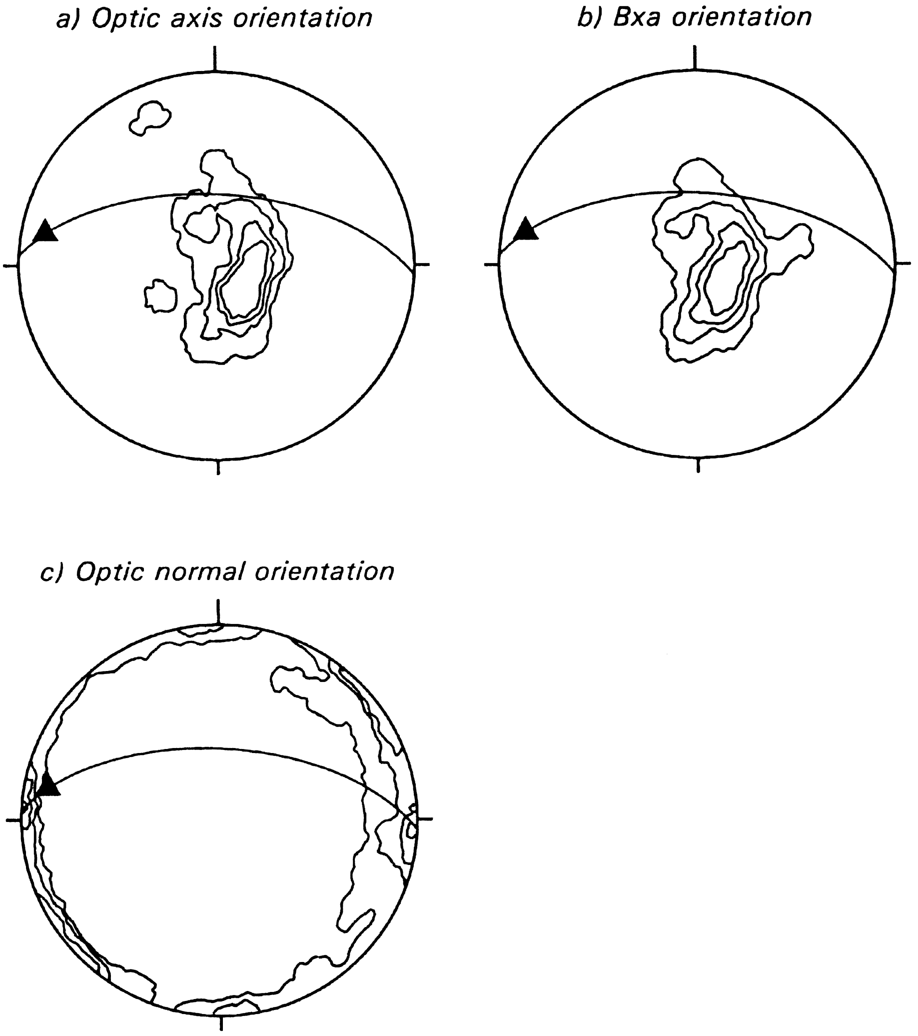
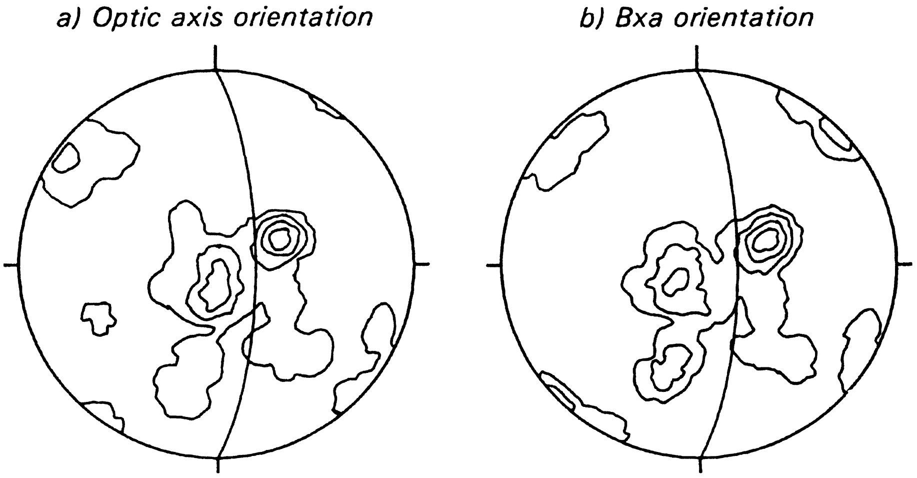


Fig. 4. The optical orientation of quartz in Bergsdalen Quartzite, specimen JSK 1. (a) 98 optic axes. (b) 94 acute bisectrices. (c) 94 optic normals. Contours at 1, 5, 10 and 15 points per 100/n% of the projected area. Lower hemisphere, Lambert Equal Area Projection. The great circle represents the schistosity, the triangle represents the stretching lineation.

maximum concentrations extend up to approximately 50° away. On the basis of the X-ray data published by Starkey (1993) the optic normals tend to occur more than 10° from a crystallographic *a*-axis.

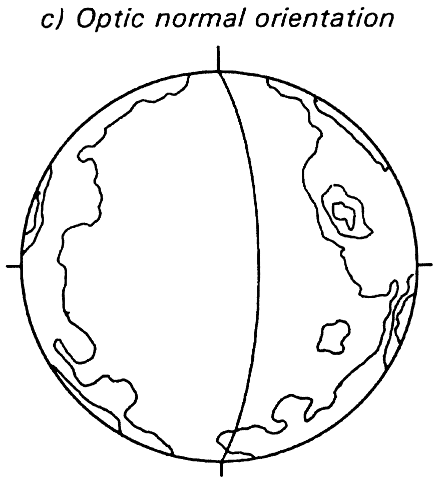
The tectonic setting of the Connemara Schists is more complex. Several phases of deformation are recognized, dominated by isoclinal folds with the schistosity parallel to their axial surfaces. In the area of the Connemara Schists mapped by Leake (1970) the structures can be interpreted as primarily due to flattening, suggesting that the schistosity is approximately perpendicular to the maximum regional stress. The optic normals in the quartz should therefore be parallel to the schistosity. Figs. 5(c) and 6(c) illustrate that the maximum concentrations of the optic normals tend to be approximately 30° and 60° from the normal to the schistosity.

These five tectonites are amongst those known to have the strongest recorded maximum concentration of quartz *c*-axis orientations. However, even though these rocks also possess strong preferred orientations of the optic normals of quartz, the orientation patterns cannot be reconciled with the suggested tectonic frameworks responsible for the development of the preferred crystallographic orientations of the quartz. Possibly, either the optic axial plane in quartz in naturally deformed rocks does not have the same significance with respect to applied stress as that observed in experiments, or the postulated orientations of the mean maximum stresses are wrong. However, a more likely explanation seems to be that the observed biaxial nature of the quartz was not produced by the deformation responsible for the development of the quartz orientation fabric. In view of the ease with which quartz can be rendered biaxial in laboratory experiments, it seems probable that quartz is quite sensitive to tectonic events. In this case, the biaxial character of the quartz observed in these tectonites may have been



a) Optic axis orientation

b) Bxa orientation



c) Optic normal orientation

Fig. 5. The optical orientation of quartz in a quartzite from the Connemara Schists, specimen JL915. (a) 101 optic axes. (b) 100 acute bisectrices. (c) 100 optic normals. Contours at 1, 5, 10 and 15 points per 100/n% of the projected area. Lower hemisphere, Lambert Equal Area Projection. The great circle represents the schistosity.

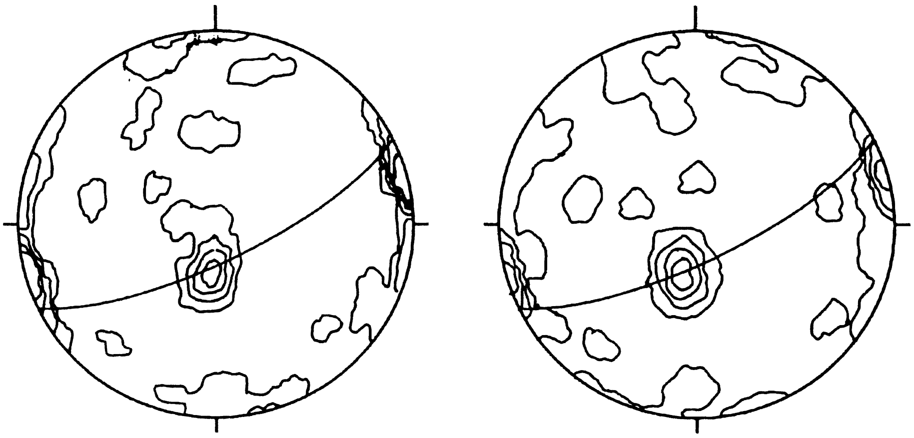
imposed on the quartz independently and subsequent to the development of the preferred crystallographic orientation.

4. Conclusion

The preservation of the biaxial character of quartz in naturally occurring rocks, while it is an elastic phenomenon in stress experiments, suggests that geological conditions can be such that crystal defects induced by stress attain a static configuration. In the experiments the structural distortions produced by stress spontaneously revert, when the stress is removed, to restore the pre-existing structural state. The similar behaviour of elastic versus permanent mechanical twins in plagioclase feldspars has been noted previously, although here subtle changes in crystal chemistry are involved (Starkey, 1963; Starkey and Brown, 1964).

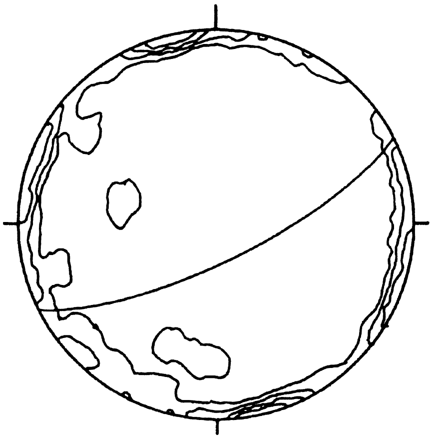
The conoscopic examination of quartz in five tectonites from three different geological environments confirms that the quartz is biaxial. X-ray diffraction data indicate that the orientation of the optic axial planes is not crystallographically controlled. Experimentally, it is easy to impart biaxial optical properties to quartz by the application of stress such that the optic axial plane contains the maximum stress direction. However, there is no apparent correlation between the suggested direction of maximum stress in the tectonites described here and the orientation patterns of the optic axial planes. The biaxial character of quartz observed in the rocks was probably imposed on an existing quartz fabric by subsequent tectonic events.

The strong preferred quartz orientations present in these specimens, which were selected to simplify optical



a) Optic axis orientation

b) Bxa orientation



c) Optic normal orientation

Fig. 6. The optical orientation of quartz in a quartzite from the Connemara Schists, specimen JSL945. (a) 129 optic axes. (b) 92 acute bisectrices. (c) 92 optic normals. Contours at 1, 5, 10 and 15 points per 100/n% of the projected area. Lower hemisphere, Lambert Equal Area Projection. The great circle represents the schistosity.

measurements, unfortunately mitigate against using the orientation patterns of the optic axial planes for a three dimensional analysis of late or neotectonics. Such an analysis requires rocks in which the quartz is randomly oriented so that an applied stress would generate optic axial planes which would have the unique direction of applied stress in common, resulting in a common direction of intersection of optic axial planes. In the rocks of this study, it is the strong *c*-axis preferred orientation that provides a common direction so that the intersections of optic axial planes are close to the maximum concentrations of *c*-axes.

A test of the usefulness of the orientation of the optical axial planes in quartz as an indicator of directions of applied stresses must await further evaluation as part of a systematic analysis of neotectonics in rocks with a weaker preferred orientation of quartz. A similar application to calcite might also prove useful, since it is known that calcite also becomes biaxial in response to stress, although in this case the optic axial plane is perpendicular to the direction of applied stress (Pfaff, 1859).

Acknowledgements

The assistance of Sandee Taylor with the optical measurements and the support of an operating grant, OGP0003555, from the Natural Sciences and Engineering Research Council of Canada are gratefully acknowledged.

References

Balk, R., 1952. Fabric of quartzites near thrust faults. Journal of Geology 60, 415–435.

Higgs, D.V., Friedman, M., Gebhart, J.E., 1960. Petrofabric analysis by means of the X-ray diffractometer. In: Griggs, D., Handin, J. (Eds.), Rock Deformation, Geological Society of America, Memoir 79, pp. 275–292.

Kvale, A., 1945. Petrofabric analysis of a quartzite from the Bergsdalen Quadrangle, western Norway. Norsk Geologisk Tidsskrift 25, 193–215.

Leake, B.E., 1970. The origin of the Connemara migmatites of the Cashel district, Connemara, Ireland. Quarterly Journal of the Geological Society of London 125, 219–276.

Merten, J., Mach, E., 1875. Bemerkungen über die Aenderung der Lichtgeschwindigkeit im Quarz durch Druck. Annalen der Physic 156, 639–654.

Pfaff, F., 1859. Vesuche über den Einfluss des Drucks auf die optischen Eigenschaften doppelbrechender Krystalle. Annalen der Physik 117, 333–338.

Starkey, J., 1963. Glide twinning in the plagioclase feldspars. A.I.M.E. Metallurgical Conferences 25, 177–191.

Starkey, J., 1974. The quantitative analysis of orientation data obtained by the Starkey method of X-ray fabric analysis. Canadian Journal of Earth Sciences 11, 1507–1516.

Starkey, J., 1977. The contouring of orientation data represented in spherical projection. Canadian Journal of Earth Sciences 14, 268–277.

Starkey, J., 1993. The analysis of three-dimensional orientation data. Canadian Journal of Earth Sciences 30, 1355–1362.

Starkey, J., 1996. Presentation of orientation data in spherical projection. In: de Paor, D.G. (Ed.), Structural Geology and Personal Computers, Computer Methods in the Geosciences 15, pp. 203–215.

Starkey, J., Brown, W.L., 1964. Kunstliche Erzeugung mechanischer Zwillinge in Anorthit, $CaAl_2Si_2O_8$. Zeitschfrift für Kristallographie 120, 388–392.