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An unusual 'crack–seal' vein geometry

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Abstract—Inclusion bands in quartz that fills extensional veins are considered to be the result of a mechanism named 'crack–seal' by Ramsay. A microstructure is decribed here in which chlorite grains, occurring as inclusions arranged in inclusion bands, are oriented with their long axes oblique to both the quartz high-angle grain boundaries and inclusion-band traces. Syntaxial growth of chlorite on wall-rock phyllosilicates may have caused this microstructure. Consequences of this process in the determination of the strain history of extensional veins are discussed.

INTRODUCTION

KINEMATIC interpretations of small-scale extensional structures indicate that several formation mechanisms can be active. Durney & Ramsay (1973) described syntectonic crystal growth in veins and pressure shadows from the Swiss Helvetic nappes and concluded that the present morphology of fibrous minerals provides information about the processes of development and strain history of these extensional structures. More recently, special attention has been given to specific microstructures within vein fibres, where, for example, inclusion bands and inclusion trails indicate vein extension by repeated cycles of fracturing and healing, a mechanism known as 'crack–seal' (Ramsay 1980). In the examples discussed by Ramsay (1980), the growth of the fibrous vein material is considered to be *antitaxial*—the fibres grow from a median surface and get progressively younger towards the vein wall. The inclusions, on the other hand, are the result of *syntaxial* growth—a mineral grain in the wall rock develops an overgrowth of the same species at the vein-wall boundary. Successive stages of cracking and sealing passively transport the inclusions in the vein fibres.

In this paper a quartz vein in a low-grade metamorphic mafic greywacke from Newfoundland, Canada, is described. It shows a different morphology from crack–seal veins described by Ramsay (1980). The long axes of the inclusions (chlorite) in the inclusion bands are not perpendicular to the band, nor are they parallel to the long axes of the vein-quartz grains. High-angle grain-boundaries (h.a.g.b.) in the quartz, on the other hand, are approximately perpendicular to the inclusion bands. Furthermore, the vein-quartz is not fibrous, although a long axis can generally be recognized. This geometry warrants a discussion on the kinematics of formation of extensional veins and their relation with the deformation history.

DESCRIPTION OF THE VEIN

The vein described (Fig. 1) is one in a series of similar vein structures from a 400 m wide movement zone on the Milleners Peninsula of New World Island, Newfoundland (Karlstrom *et al.* 1982). The rocks in this zone show a complex deformation history, resulting from thrusting and subsequent folding and faulting. As a consquence, the contacts between the veins and the host rock are mostly deformational (sheared margins). Internally, however, the veins show little effect of deformation. The section studied is oriented approximately parallel to the extension direction and perpendicular to the trend of the zone. The vein described here is approximately 1 mm long (Fig. 1).

Quartz grains (up to 175 μm in length) are crosscut by many inclusion bands. The bands are regularly spaced at 7–40 μm intervals with an average spacing of 20 μm. They have a well defined orientation (Fig. 1b, rose diagram A). Some inclusion bands are curved, e.g. grain (1) in Fig. 1(b).

The inclusions in the inclusion bands are all chlorite, and display a very strong shape preferred orientation. The inclusion grain size varies from a few microns to 13 μm in length and a maximum width of 4 μm. Commonly, the chlorite inclusions are too small and too closely spaced to be imaged separately, resulting in an inclusion band of nearly continuous chlorite (anomalous brown under cross-polarized light) in the quartz grains.

The (001)-planes of the phyllosilicates are parallel to the long axes of the grains. The orientations of the basal planes, as seen in the section plane, are shown in Fig. 1(b), rose diagram C. A well defined orientation exists, which does not vary with the curvature of an inclusion band, but remains approximately the same throughout the band (Fig. 1b, grain (1)).

Two sets of h.a.g.b. in quartz are present. One set runs from upper left to lower right, the other set from lower left to upper right in Fig. 1. The statistical orientation of the set representing the long dimension of the grains (Fig. 1b, rose diagram B) is at an angle of approximately 20° to the basal plane orientation of the chlorite (Fig. 1b, rose diagram C) and approximately perpendicular to the inclusion bands (Fig. 1b, rose diagram A). The other set runs at approximately 65° to the first set

(Fig. 1b, rose diagram B). Commonly, the h.a.g.b. running from lower left to upper right of Fig. 1 are, at least in part, parallel to an inclusion band (e.g. grain (2) in Fig. 1b). The h.a.g.b. orientations were measured by assuming a straight line as average grain-boundary direction. They commonly show discrete steps where they intersect an inclusion band. This results in 'saw-tooth' shaped grains (Ramsay 1980), illustrated in Fig. 2. The stepping is not systematic: both sinistral and dextral offsets occur. In some cases opposite offsets occur in the same quartz 'layer' in between two inclusion bands, giving rise to wedge-shaped grains (e.g. Fig. 1b, grain 4, Fig. 2). Generally the h.a.g.b. in between two inclusion bands are approximately perpendicular to the bands (e.g. grain (4) in Fig. 1b). In the inclusion band, however, the h.a.g.b. are parallel to the chlorite long axis and consequently not perpendicular to the inclusion band. Chlorite grains physically define the quartz h.a.g.b. in the inclusion bands (Fig. 2).

Locally, plastic deformation has occurred, demonstrated by undulatory extinction in some grains (e.g. grain 3 in Fig. 1b). Subsequent recrystallization processes formed new, small grains in parts of the vein. Therefore, only large quartz grains showing little intracrystalline deformation were studied.

To study the relationship between the vein and quartz crystallographic orientation, quartz *c*-axes have been measured. Figure 1(b) shows the *c*-axis direction and amount of plunge for individual grains. These orientations indicate a correlation between the long axes and the *c*-axes of the quartz.

DISCUSSION

Earlier workers (Ramsay 1980, Cox & Etheridge 1983) showed inclusions in inclusion bands, oriented length-parallel to the h.a.g.b. of the vein fibres. In this example an oblique relationship exists. Other veins in the rock section show similar features. On the other hand, the quartz h.a.g.b. are approximately orthogonal to the inclusion bands. These two relationships cannot be explained by overall oblique extension, because they conflict. Superimposed deformation after vein formation, accommodated by slip on the inclusion bands, is also rejected because of (1) the optical continuity of quartz in inclusion bands and outside these bands and (2) the absence of systematic quartz h.a.g.b. stepping on the bands.

A possible mechanism for these relationships is syntaxial growth of chlorite grains on wall-rock phyllosilicates. The orientation of phyllosilicates in the host rock (e.g. a foliation) governs the nucleation and growth of phyllosilicates in the fluid filled crack. In this particular example, the foliation was originally oblique to the vein-wall, reflected in the angle of inclusions with inclusion bands (originally parallel to the vein-wall). Subsequent growth of phyllosilicates and vein-quartz closes the crack and the process is repeated when built up elastic strain is released by cracking at the vein-wall (Ramsay 1980). As a result of the repeated crack–seal process, the phyllosilicate orientation is the same throughout the vein, since the relationship between crack and wall-rock is the same for each crack–seal increment.

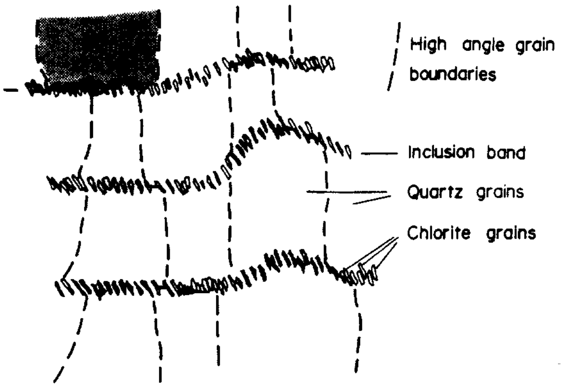

Fig. 2. Composite sketch of observed relationships between quartz h.a.g.b., inclusion bands and chlorite inclusions. Tones represent different quartz grains.

This microstructure shows that the orientation of inclusions in inclusion bands is not necessarily indicative of the incremental strain history during vein formation. Similarly, the significance of straight vein fibres needs consideration. The formation of crystals in veins is probably the result of precipitation from oversaturated fluids, occupying an open crack in the vein. If the crack is sufficiently wide, the fluid will be under hydrostatic stress conditions, irrespective of the external differential stress-field (cf. Cox & Etheridge 1983). Oblique extension under these conditions is therefore indistinguishable from orthogonal extension. Alternatively, in some cases, straight fibres can reflect the strain history (cf. Ramsay & Huber 1984, p. 258).

The significance of curved fibres for the strain history also needs consideration. In many cases superimposed deformation is an equally adequate explanation of these microstructures. Thus, the geometry of extensional structures will not always provide information about the (incremental) strain history.

Finally, it is noteworthy that the inclusion band spacing in this vein is of the same order of magnitude (7–40 μm) as those reported by Dietrich & Ramsay (1980), Ramsay (1980) and Cox & Etheridge (1983). This possibly reflects similar strain-rates under approximately the same metamorphic conditions (low-grade rocks).

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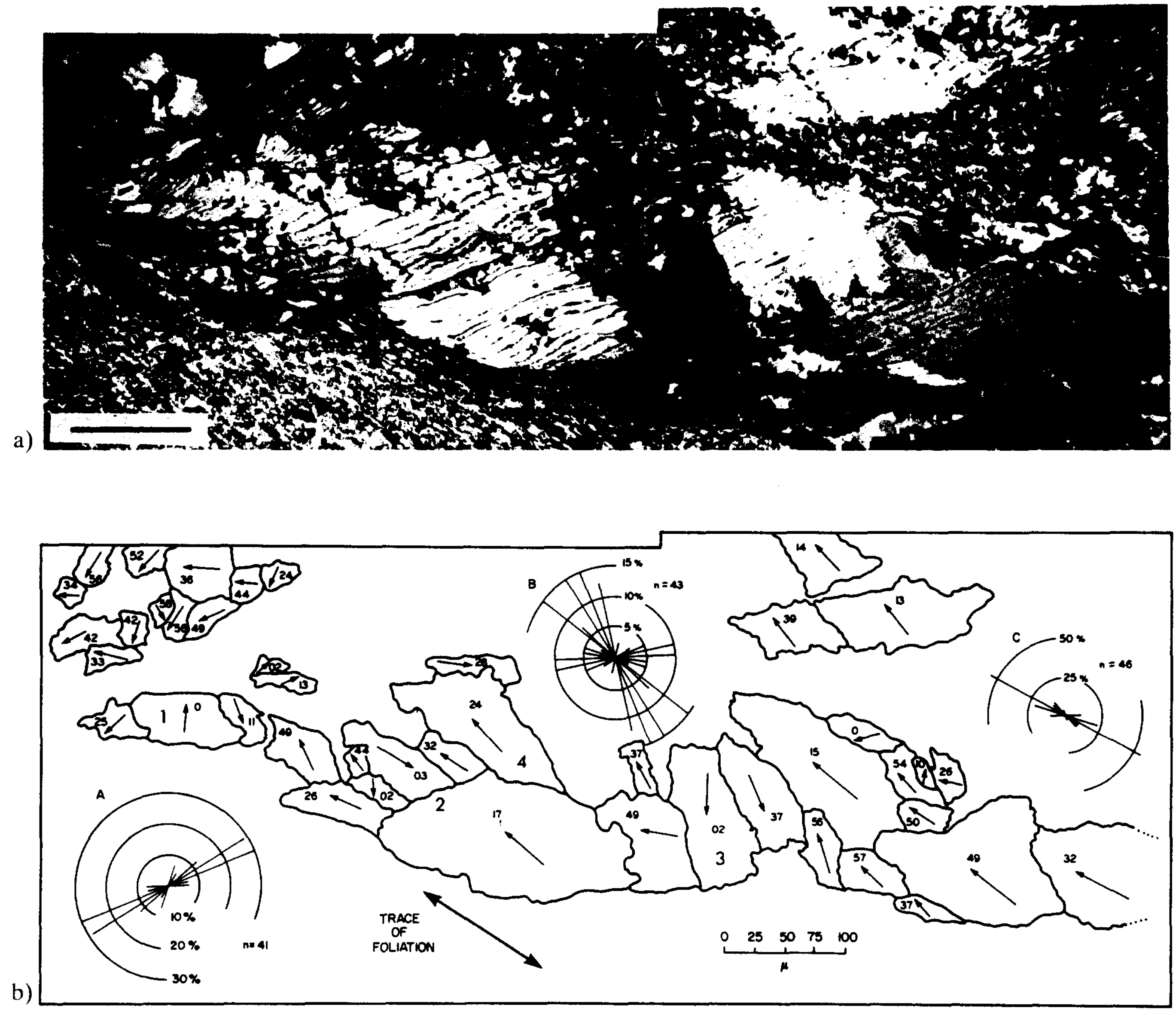

Fig. 1. Extensional quartz vein with inclusion bands. (a) Image in cross polarized light; scale bar is 100 μm. (b) Line drawing of (a) showing high-angle grain-boundaries of quartz grains, with *c*-axis direction and amount of plunge. Numbers are referred to in the text. Rose diagram A represents inclusion band orientations, rose diagram B represents h.a.g.b. of quartz grains and rose diagram C shows the distribution of the long axes of inclusions. Percentages at 10° intervals and number of measurements (*n*) are given.

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