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Antitaxial crack–seal vein microstructures and their relationship to displacement paths

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Abstract—The microstructures developed in an example of a syntectonic crack–seal vein indicate that antitaxial fibres do not necessarily track the incremental opening history during crack–seal vein growth. This observation serves as a caution against the uncritical use of fibrous microstructures to make inferences about displacement histories during fibre formation. It is demonstrated that crack–seal processes can lead to the development of both irregular and laminated vein microstructures, as well as fibrous microstructures. The types of microstructures which develop in crack–seal veins, and the extent to which they reflect the opening paths of veins depend on a range of factors. The most important of these include the nucleation and growth kinetics of phases precipitated from fluids in opening fractures, and the location of sites of material accretion during successive crack–seal increments.

INTRODUCTION

SYNTECTONIC FIBROUS microstructures formed both in extension veins and in fringe structures adjacent to rigid grains are being used increasingly to estimate incremental and finite strains during fibre growth, and thus to provide detailed information about strain histories during the development of both small- and large-scale structures (Ramsay & Huber 1983, Beutner & Diegel 1985, Ellis 1986). Implicit in the use of fibrous microstructures to evaluate displacement histories is the requirement that fibre long axes always track an incremental displacement path during fibre growth. Indeed, where fibres have not been deformed significantly after their growth, many observations do suggest that this may commonly be the case (Durney & Ramsay 1973). However, there are some types of fibrous microstructures which do not track an incremental displacement path. For example, individual fibres in fringe structures around rigid euhedra of pyrite or magnetite usually do not reflect the displacement history during fibre growth (Spry 1969, pp. 240–247, Durney & Ramsay 1973, Cox & Etheridge 1983, Ramsay & Huber 1983). Such fibres are said to be 'face-controlled' rather than 'displacement-controlled' (Ramsay & Huber 1983, p. 268).

Despite the recognition that many syntectonic fibrous microstructures develop by 'crack–seal' mechanisms (Ramsay 1980), it has not yet been demonstrated whether crack–seal fibres necessarily track a displacement path during their growth. This paper discusses a particular example of an antitaxial vein in which it is possible to demonstrate that the orientations of crack–seal fibres need not reflect a displacement path during their growth. This observation has significant implications for the use of fibrous antitaxial crack–seal microstructures to make inferences about displacement histories. The development of both irregular and laminated vein microstructures, as well as fibrous microstructures, during crack–seal vein growth will also be discussed. It will be shown that some laminated vein structures may be characteristic of crack–seal vein growth involving displacement parallel to the vein walls.

Terminology

The geometry and distribution of inclusions in some crack–seal veins provide a powerful means of evaluating the relationships between displacement paths and the development of microstructures such as fibres during vein growth. As discussed by Ramsay (1980), crack–seal veins develop by repeated increments of microcrack opening, followed by sealing due to precipitation of material from solution. During antitaxial crack–seal vein growth (i.e. vein accretion occurs at the vein margins) the development of *inclusion trails* provides particularly useful information about the vein growth history. Inclusion trails develop during successive accretion increments by syntaxial overgrowth of particular, and essentially isolated, host-rock grains present at the vein wall. All inclusions in the same trail thus have the same crystallographic orientation as the host grain. Most importantly, the trails record the opening directions and magnitudes of vein opening at successive crack–seal events.

The repeated syntaxial overgrowth of large numbers of closely adjacent host-rock grains during the crack–seal process results in the formation of more or less continuous layers of inclusions which have been termed *inclusion bands* (Ramsay 1980). Adjacent bands are essentially parallel to one another and the adjacent vein wall. The separation of adjacent inclusion bands records the amount of vein accretion during successive crack–seal events.

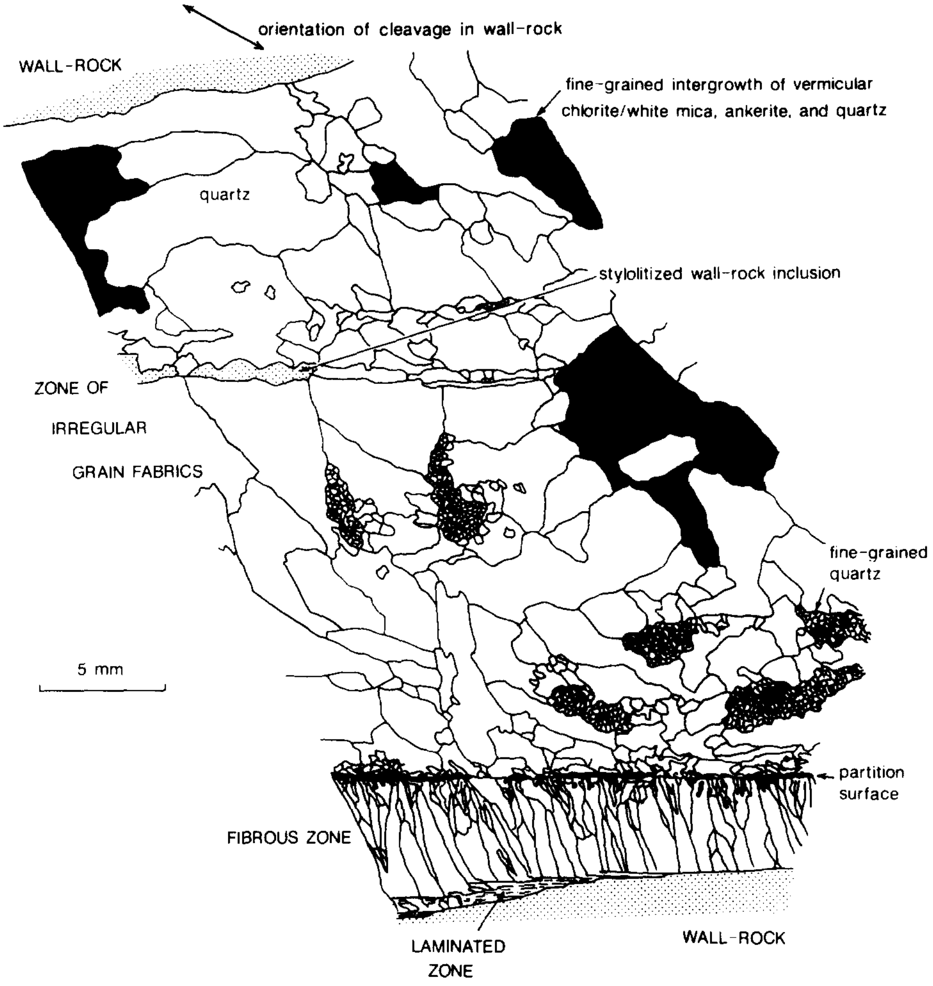


Fig. 1. Line drawing illustrating grain structure in a complete cross-section of the vein.

VEIN DESCRIPTION AND INTERPRETATION

General overview of vein structure

The vein microstructures to be described in this paper occur in a small quartz vein which developed during an episode of gold–quartz mineralization associated with regional deformation and low-grade metamorphism in the Ordovician quartzwacke–turbidite sequence of central Victoria in south-eastern Australia (Beavis 1976, Cox *et al.* 1983a). The particular example is from the Wattle Gully Gold Mine near Castlemaine (Thomas 1953, Cox *et al.* 1983b). In this area, the formation of major quartz vein systems occurred in response to the development of dilatancy within and adjacent to faults during movement in a high fluid pressure environment (Cox *et al.* 1985, 1987a,b).

The vein under consideration is subplanar, extends for several metres, and is up to 35 mm thick. It is composed dominantly of quartz, together with minor ankerite and fine vermicular to platy layer silicates. Several microstructurally distinct domains are present within the vein (Fig. 1). For most of its width the vein consists of coarse, irregularly shaped quartz grains having a grain size predominantly in the range 2–10 mm. There are localized patches of finer-grained quartz as well as intergrown ankerite and layer silicates in the zone of irregular grain fabrics. Lattice bending and the patchy development of subgrain boundaries indicate that the quartz in this part of the vein has been weakly deformed. Inclusions of fine quartz, ankerite and layer silicates are locally developed in the coarse-grained quartz. Several lines of quartz and ankerite inclusions are interpreted as crack–seal inclusion trails (Ramsay 1980), as all the inclusions within individual lines have the same crystallographic orientation: the orientation, however, differs from one line to the next. These indicate growth of this part of the vein by antitaxial crack–seal processes. The spacing of individual solid-phase inclusions within the inclusion trails ranges from about 4 μm to about 30 μm. The trails are subparallel to the vein margins, and indicate that vein growth involved a major component of displacement parallel to the vein margins.

A zone of dominantly fibrous quartz occurs adjacent to one side of the vein (Fig. 1). This zone ranges from 3.5 to 6 mm wide and consists largely of essentially unstrained quartz fibres which are up to 1 mm wide and inclined at a high angle to the vein margin. Separating the fibrous domain from the zone of irregular fabric is a generally subplanar partition surface containing fine

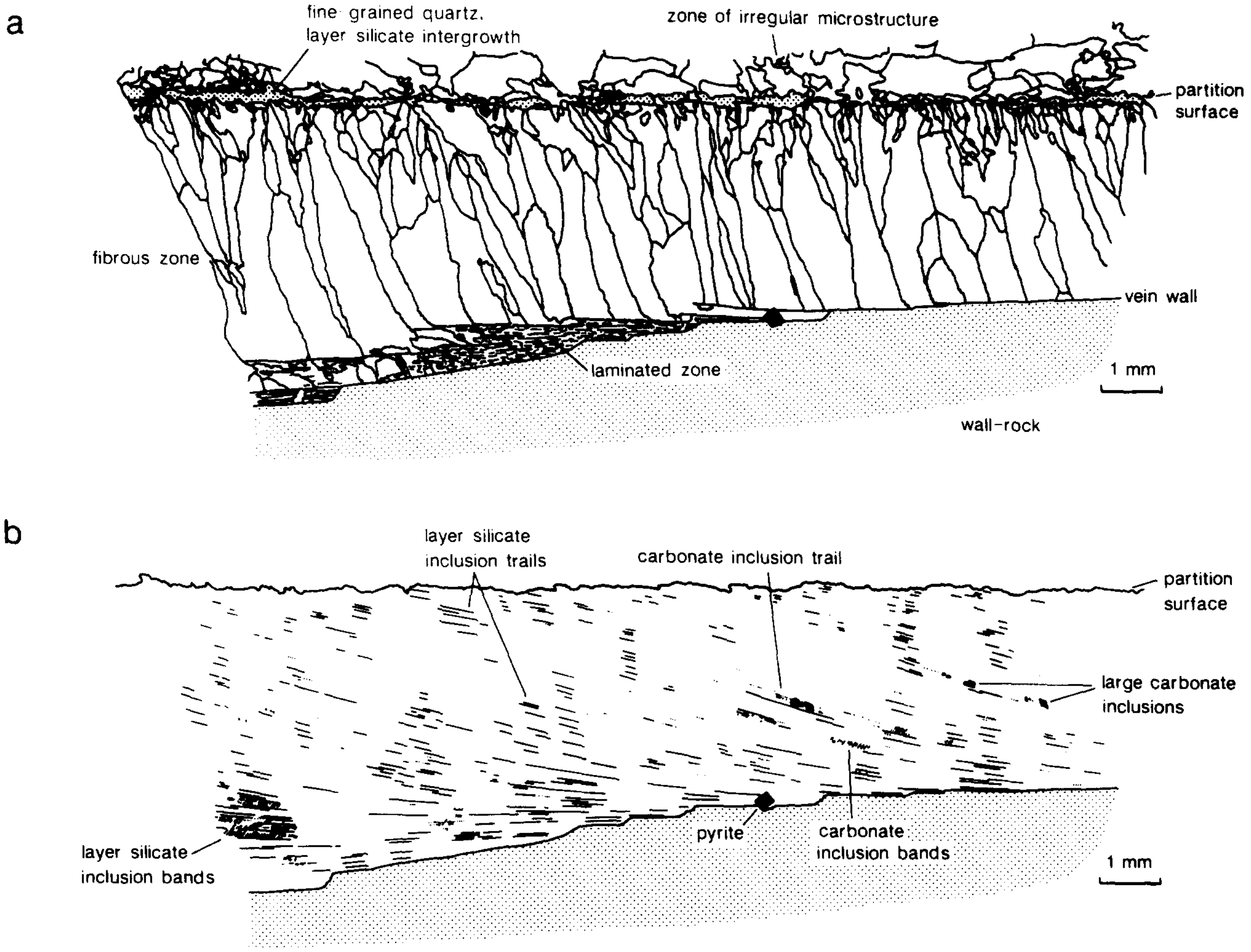


Fig. 2. (a) Line drawing illustrating details of grain structure of the fibrous and laminated parts of the vein. A small portion of the generally coarse-grained zone of the vein is also shown. (b) Distribution and orientation of inclusion trails and inclusion bands in the fibrous and laminated parts of the vein illustrated in (a).

layer silicates and carbonate, as well as fine-grained quartz. In detail, the partition surface is irregularly shaped (Fig. 2). The stylolitic morphology of segments of the partition surface suggests that some dissolution has occurred on this interface.

A narrow wedge-shaped domain of complex microstructure separates part of the fibrous zone from the vein wall (Fig. 2a). This area has a dominantly laminated structure defined by fine-grained equigranular to platy quartz fabrics and thin layer silicate sheets.

In detail, the vein boundary adjacent to the fibrous and laminated domains has an irregularly stepped configuration. Considerable intervals of the boundary are subparallel to the partition surface on the inner side of the fibrous zone. These planar segments are generally separated by short wall segments which are inclined at moderate to high angles to the gross orientation of the vein margin (Fig. 2).

The host-rock to the vein is a fine-grained slate having a well-developed domainal cleavage inclined at about 40° to the vein margin. Similar slates from the Wattle Gully Mine have been extensively described by Etheridge & Oertel (1979) and White & Johnston (1981). Selvages of cataclastically deformed wall-rock up to 1.5 mm thick, but usually less than 0.5 mm thick, occur on both sides of the vein. In this narrow crush zone the slaty cleavage locally becomes rotated towards parallelism with the vein margin and shear displacements on discrete anastomosing surfaces have produced lenticular, deformed slate fragments. There has been some modification of shear surfaces by stylolitization. The misoriented, lenticular slate fragments are intermixed with irregular masses and blebs of fine- to medium-grained polycrystalline quartz and ankerite having an irregular to fibrous grain fabric.

Growth of the fibrous zone of the vein probably post-dated the development of the cataclastic crush zone, as cataclastic microstructures are truncated by the vein wall in this part of the vein. A thin, discontinuous zone of carbonate alteration along parts of the vein walls, as well as overgrowth of the vein walls by some pyrite porphyroblasts, appears to be due to hydrothermal alteration which post-dates much of the vein growth history.

In the following sections, more detailed descriptions of the microstructures in both the fibrous and laminated zones of the vein are given, and their significance is discussed.

Fibrous microstructure zone

An overview of the microstructure in the fibrous part of the vein is given in Fig. 2. Fibre long axes are inclined at 70–80° to the general trend of the partition surface. Many of the quartz fibres extend from one side of the fibrous domain to the other. A general reduction in the number of fibres towards the vein wall (Fig. 3a) is interpreted to be due to occlusion during competitive fibre growth, and indicates that fibre growth commenced adjacent to the partition surface separating the equigranular and fibrous zones of the vein (Cox & Etheridge 1983, Ramsay & Huber 1983). Thus the fibres become younger towards the vein wall and have grown by an antitaxial mechanism.

Fibre–fibre boundaries range from being subplanar to irregular, or locally stepped. Systematic sinistral stepping of fibre–fibre boundaries is a prominent feature in many parts of the fibrous domain (Fig. 3b & c).

Curved lines of inclusions composed of very fine-grained layer silicates, quartz, or ankerite are developed throughout the fibrous zone of the vein (Fig. 2b) and are oblique to the long axes of the quartz fibres. In the earliest-formed parts of the fibrous domain, near the internal partition surface, the lines of inclusions are inclined to the vein walls at angles of around 5–10°. Towards the vein margins this inclination systematically increases, then decreases until adjacent to the vein walls the inclusion lines are locally parallel to segments of the vein wall (Fig. 2b). Individual quartz and ankerite inclusions within inclusion lines typically range up to about 30 μm in diameter and are spaced 5–30 μm apart. The ankerite inclusions vary from nearly euhedral rhombs to completely anhedral grains (Fig. 3d). Quartz inclusions tend to be subhedral to globular. Significantly, quartz and ankerite inclusions within individual lines have the same crystallographic orientation and similar shapes as those of other inclusions in the same line (Fig. 3d). In a few examples, inclusion lines can be traced to grains in the vein wall which have acted as hosts for syntaxial overgrowth. On this basis the lines of inclusions can be confidently interpreted as crack–seal inclusion trails. As such they must track the incremental opening path during growth of the fibrous zone. Most notably, this path is oblique to the quartz fibre long axes.

Locally, carbonate and layer silicate inclusions define inclusion bands having orientations which, although they are inclined to the gross configuration of the vein wall (Figs. 2b and 3e), are parallel to the small steps which are inclined obliquely to the overall orientation of the vein walls. Inclusion trails passing through the bands connect with these steps. As with individual inclusions in trails, the inclusion bands are spaced about 5–30 μm apart.

Trails of very fine-grained layer silicates are pervasively developed in the fibrous zone of the vein, and are parallel to adjacent quartz and ankerite inclusion trails (Fig. 3f). The long axes and (001) of layer silicate grains in these inclusion trails are typically inclined at low angles to the orientations of the trails, but are subparallel to the dominant layer silicate (001) orientation in the cleaved host-rock adjacent to the vein walls. The orientation of the layer silicates in the inclusion trails is thus interpreted to have been controlled by syntaxial overgrowth of oriented foliation-defining layer silicates in the vein wall. Such orientation relationships between layer silicates in the host-rock and crack–seal inclusions in adjacent veins have previously been described by Cox & Etheridge (1983) and van der Pluijm (1984).

Some of the layer silicate inclusion trails are associated with the well-defined steps which are present on some boundaries between quartz fibres (Fig. 3b). In a few cases, steps of a similar size occur on both sides of quartz fibres, as well as being coincident with the positions of inclusion trails passing through the fibres. In other cases, pairs of steps on the opposite sides of fibres are not equally developed. More generally, however, steps are developed on only one side of a fibre where a layer silicate inclusion trail intersects the fibre boundary. These points, together with the fact that many fibre boundary steps are not associated with layer silicate inclusion trails (Fig. 3c), indicate that the development of steps is not due to slip on layer silicate inclusion trails after fibre growth. Furthermore, it is not possible to explain the steps by local ductile strain after fibre growth as the fibres are essentially unstrained. Rather, it would appear that the steps are 'grown-in'. Some may have developed due to interference of densely populated inclusion trails with quartz fibre growth, whereas the development of others may have involved local displacement-control of fibre boundaries (see further discussion below). The consistent sinistral sense of stepping is presumably related to the sinistral displacement of quartz fibres relative to the vein wall at successive antitaxial crack–seal increments.

The most significant aspect about the microstructures in the fibrous zone of the vein is that the displacement path indicated by the syntaxial inclusion trails is very different from the orientation of the long axes of the associated antitaxial quartz fibres. The inclusion trails indicate that the displacement increments were inclined at low angles (up to 20°) to the vein wall. Despite this, the antitaxial fibres are inclined at high angles to the vein walls, and thus have not successfully tracked the separation path of the vein walls during vein growth.

Crack–seal fibre growth need not reflect a displacement path if growing fibres are not syntaxial overgrowths of grains present in the vein wall, and they become cleanly detached from the vein wall at each crack–seal increment (Fig. 5). Free growth of fibres into a fluid-filled microcrack is expected to result in fibres having long axes roughly perpendicular to the growth surface at each crack–seal increment, regardless of the sense of displacement across the microcrack (Cox & Etheridge 1983). In such a case, fibre shapes will be growth-surface-controlled rather than displacement-controlled. Significantly the fibres described here are not perpendicular to the vein wall or partition surface, but inclined slightly towards the direction of displacement indicated by the inclusion trails. As fibres have suffered negligible ductile

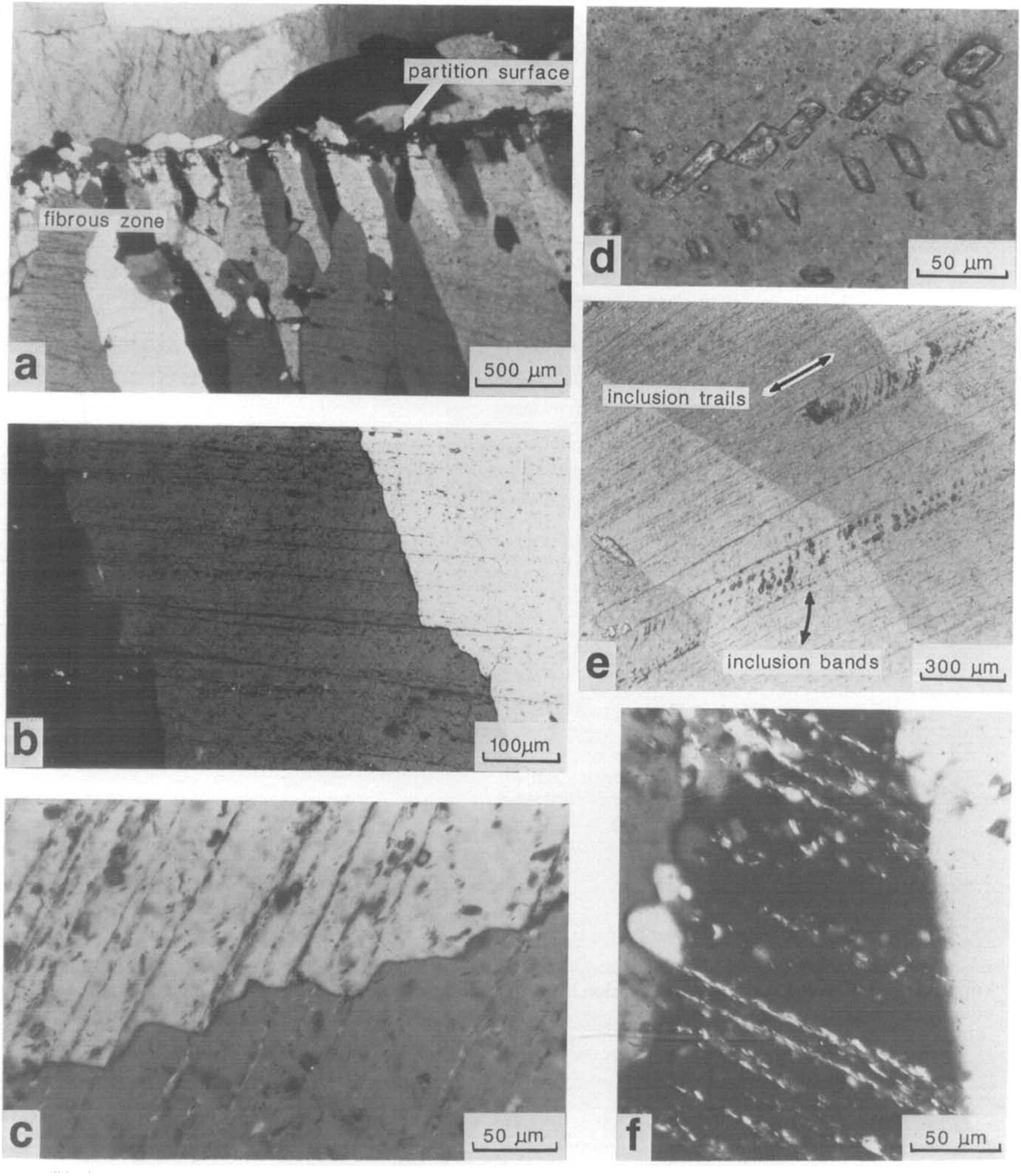


Fig. 3. (a) Boundary region between the fibrous and essentially equigranular parts of the vein. Note the rapid decrease in the number of fibres further away from the partition surface. (b) Growth steps on fibre–fibre boundaries. The position of major steps appears to be controlled by the presence of layer-silicate inclusion trails. (c) Detail of some small growth steps on a fibre–fibre boundary. In this case many steps have no spatial relationship to layer-silicate inclusion trails. (d) Two inclusion trails of ankerite grains in a quartz fibre. (e) Overview of the area surrounding (d). Carbonate inclusions define both trails and bands. The trails track an incremental displacement direction and are oblique to quartz fibre boundaries. The inclusion bands are developed parallel to small steps in the vein margin (see also Fig. 2b). (f) Detail of some layer silicate inclusion trails. The grain long axes of layer silicates in such trails are usually inclined at low to moderate angles to the trail orientation.

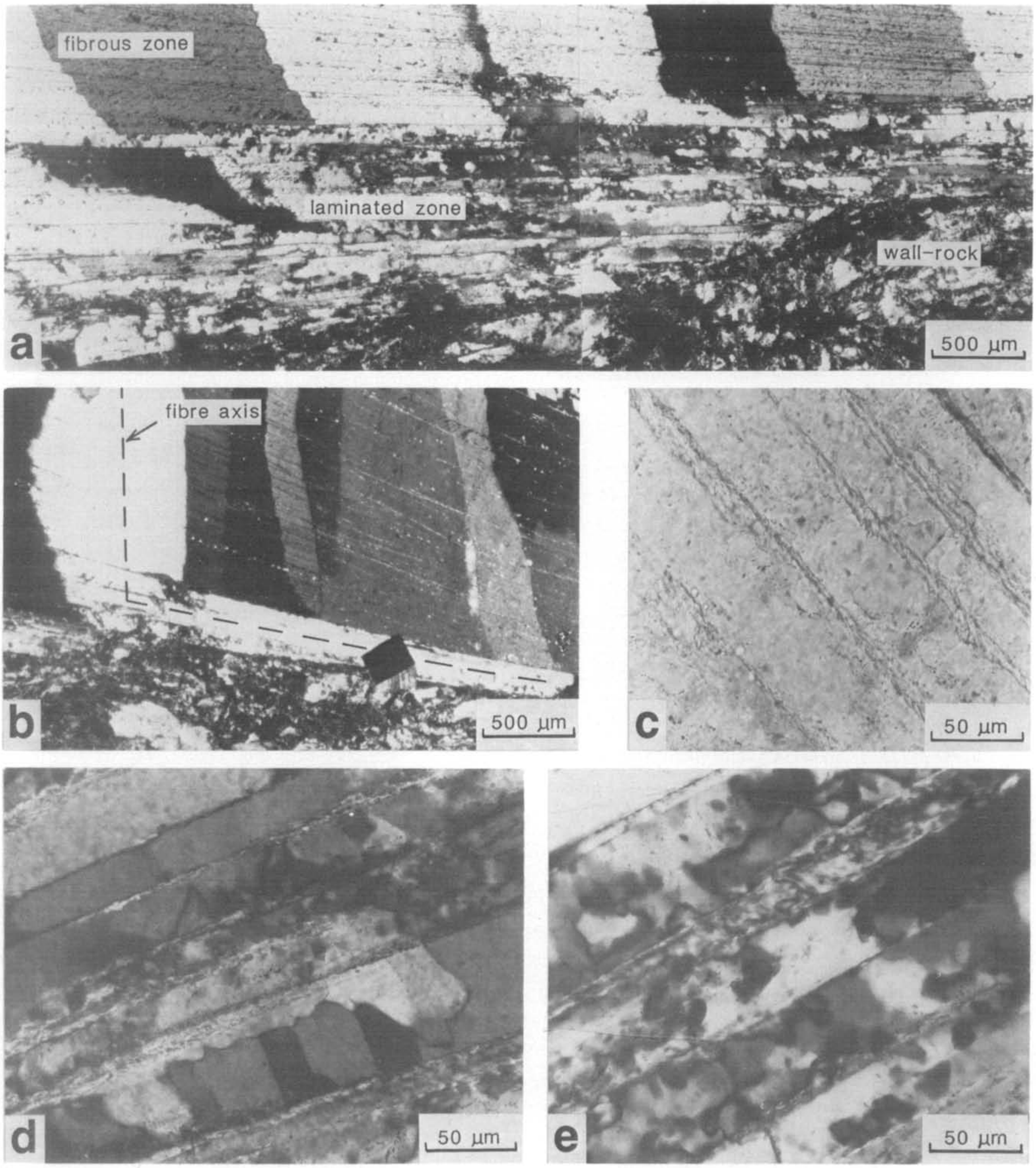
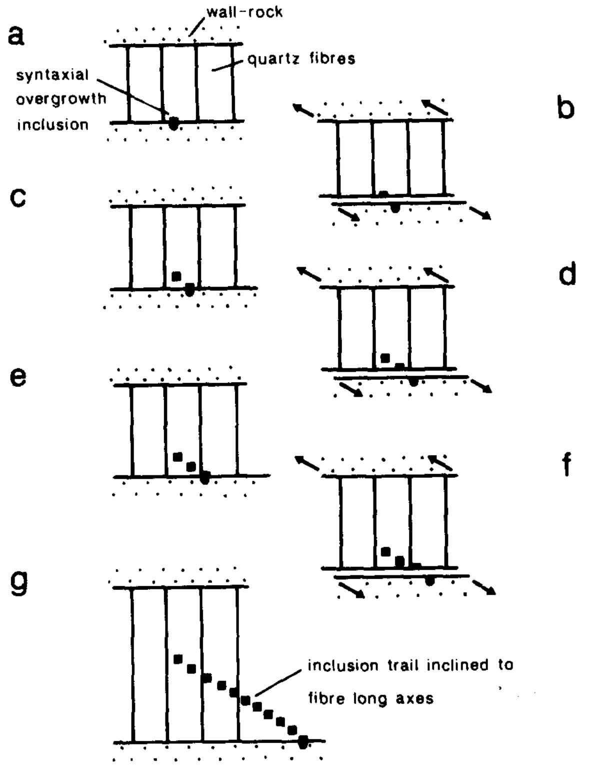


Fig. 4. (a) Typical microstructure in the laminated zone of the vein. (b) Development of an elbow in a quartz fibre adjacent to the vein margin and the edge of the laminated zone. Despite the marked change in fibre shape, the crystallographic orientation is the same on both sides of the elbow. (c) Densely populated layer-silicate inclusion sheets in the laminated zone. As in adjacent inclusion trails in this zone and the fibrous zone, grain long axes are inclined to the plane of the Fig. 5. Development of antitaxial crack–seal fibres having orientations which are growth-surface-controlled. (a)–(f) A sequence of three crack–seal increments involving antitaxial quartz accretion. Syntaxial overgrowth of wall-rock inclusions results in the development of inclusion trails which are inclined to quartz-fibre long axes. (g) Fibre and inclusion trail development following 10 crack–seal increments after stage (a).



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strain after their growth, their obliquity possibly indicates that even though the majority of crack–seal growth increments may have been growth-surface-controlled, during a small proportion of crack–seal increments antitaxial fibre growth may have been displacement-controlled. The fibre boundary steps which are subparallel to inclusion trails, but are not spatially associated with layer silicate trails, are recognizable examples of apparently successful tracking of a displacement path by a fibre boundary. It has been suggested previously that antitaxial crack–seal fibres may track a displacement path if, at successive cracking increments, clean detachment of fibres from vein walls does not occur, and the once-joined parts of fibres rejoin during the sealing events (Cox & Etheridge 1983).

Laminated microstructures

Adjacent to the vein margin, particularly where small steps oblique to its overall trend are well developed, the fibrous microstructure discussed above gives way to a generally much finer grained and microstructurally complex domain which is up to 0.7 mm wide and dominated by the development of laminated microstructures (Figs. 2a and 4).

At the internal margin of the laminated zone, most fibres present in the adjacent coarse-grained fibrous part of the vein abruptly terminate against densely populated sheets of layer silicate inclusions. These layer silicate sheets are subparallel to, or slightly inclined to, the long planar segments of the vein wall. They are also parallel to clear examples of quartz and ankerite inclusion trails within the laminated zone and the adjacent parts of the fibrous zone. In a few cases quartz fibres which are present in the fibrous domain do extend across the layer silicate inclusion sheets at the margin of the laminated zone. As they do so, they undergo an abrupt change in orientation and become confined between, and parallel to, the inclusion sheets (Fig. 4b). The crystallographic orientation of these quartz fibres is unchanged with respect to that of the host fibres in the fibrous domain, even though their long axes have changed orientation by 80° or so.

Layer silicate inclusion sheets occur throughout the laminated zone. They can be up to 8 μm thick and extend for distances of several hundred microns (Fig. 4c). Individual sheets are typically spaced at about 10–100 μm apart. As is the case for layer silicate inclusion trails in the fibrous zone, the layer silicate basal planes in the inclusion sheets and trails in the laminated zone are subparallel to the basal planes of cleavage-defining layer silicates in the host-rock.

Quartz in the laminated zone exhibits a variety of habits. It can occur as tabular grains, which are up to several hundred microns long and confined between adjacent pairs of densely populated inclusion trails (Fig. 4d). Very fine-grained crack–seal inclusion trails and inclusion bands composed of layer silicates, quartz and ankerite are well developed within some of these tabular grains, and clearly indicate that the displacement trajectory during growth has been parallel to the thick layer silicate inclusion sheets. In some cases several tabular quartz grains may be developed between pairs of densely populated layer silicate inclusion trails. The quartz–quartz grain boundaries separating such tabular grains are usually markedly serrate or dentate.

More typically, the quartz laminae between pairs of boundary-controlling layer silicate sheets consist of aggregates of grains having diameters in the range 10–20 μm (Fig. 4e). In a few laminae quartz grains have a columnar structure, with a high proportion of grain boundaries inclined at 70–80° to the laminae boundaries (Fig. 4d). The sense of the inclination of these columnar grains is usually the same as that of the coarse-grained quartz fibres in the nearby fibrous zone. In most cases, however, quartz–quartz grain boundaries within individual laminae are irregularly oriented and have planar, dentate or serrated morphologies.

Within the dominantly laminated zone of the vein there are also occasional coarse grained, equant to irregularly shaped quartz grains which cut across numerous layer silicate inclusion trails and sheets. Some of these also have long grain boundary segments inclined at 70–80° to the trails, as well as having major sinistral grain boundary steps where they intersect the more densely populated layer silicate inclusion sheets (Fig. 4a).

In one area adjacent to the vein wall a typical 'stretched-crystal' fibre fabric is also developed. Here,

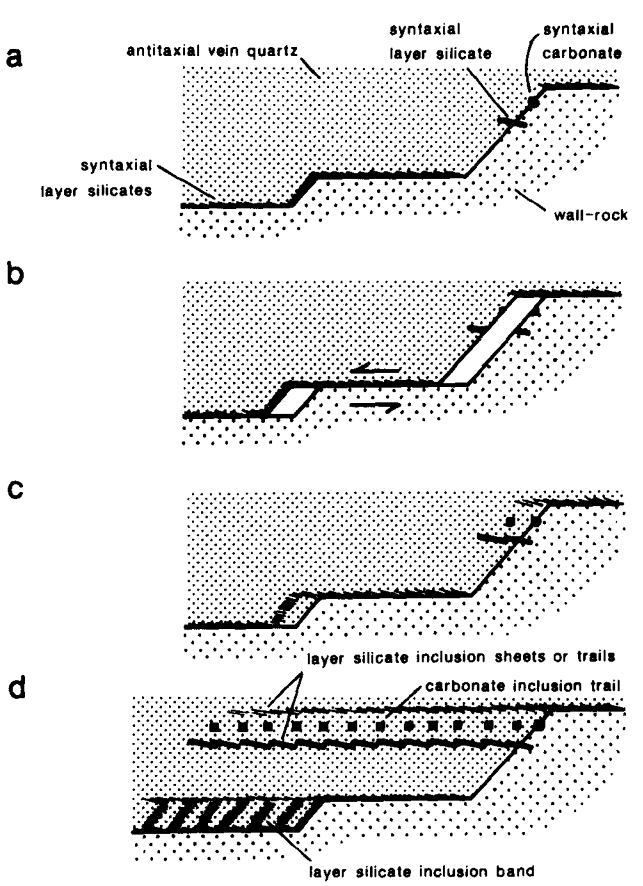

Fig. 6. Development of inclusion sheets, bands and trails as well as a laminated vein structure due to antitaxial quartz accretion and displacement essentially parallel to planar segments of stepped vein margins. (a)–(c) illustrate one complete crack–seal increment. (d) Relationship between crack–seal inclusion bands, trails and sheets after repeated increments of antitaxial crack–seal quartz accretion.

the fibre–fibre boundaries are highly serrated and fibre long axes are parallel to both the adjacent vein wall and nearby inclusion trails and sheets.

The occurrence of inclusion trails and bands throughout the laminated zone of the vein indicates that the laminated microstructure has developed by a crack–seal mechanism. The prominent layer silicate sheets differ from the usual layer silicate inclusion trails by being more densely populated with layer silicates and having a sheet-like rather than string-like form. Usually, crack–seal inclusion trails are string-like because they develop by repeated syntaxial overgrowth of individual grains at the vein wall. However, within the laminated zone, displacement increments have been essentially parallel to the long planar segments of vein wall between the smaller oblique steps. The development of the major inclusion sheets, which are connected to the planar vein wall segments, appears to have involved syntaxial overgrowth of numerous layer silicate grains in these wall segments. This process has also involved repeated detachment of the overgrowth layer and displacement essentially parallel to the vein wall orientation during successive crack–seal increments (Fig. 6). In this situation there can be no distinction between inclusion bands and inclusion trails. Only where bands, sheets or trails have developed by syntaxial overgrowth at the small oblique steps on the vein margin is the distinction meaningful in the laminated zone. The closely spaced inclusion sheets and trails which connect with these steps are likely to have developed by a process slightly different from that involved in the formation of the generally thicker inclusion sheets which connect with the long planar vein-wall segments. In this case, syntaxial overgrowth of spaced, cleavage-defining layer silicate films, or individual layer silicate grains which intersect the stepped vein margin, are interpreted to have controlled the inclusion sheet and trail morphology (Fig. 6).

The change from the essentially growth-surface-controlled fibrous microstructure to the laminated microstructure corresponds to a decreasing component of displacement normal to the vein walls and an increasing component of shear displacement parallel to the vein walls. The formation of the laminated structure also appears to be related to the development of the densely populated and closely spaced layer silicate inclusion sheets. Within the fibrous zone of the vein where the layer silicate inclusion trails are not usually so densely populated, the trails cut through the quartz fibres. Only locally have they interfered with quartz fibre growth by leading to the development of steps in fibre boundaries. However, in the laminated zone displacement parallel to the vein wall has produced densely populated and closely spaced layer silicate inclusion sheets which have severely inhibited quartz fibre growth.

McKinstry & Ohle (1949) and Chace (1949) have described laminated quartz veins from a number of localities. Some of their examples have microstructural similarities to the example described above. In other examples, quartz laminae are not separated by syntaxially developed inclusion sheets, but by rock selvages which may be analogous to the detached wall-rock inclusion bands which can be developed in antitaxial extension veins (Ramsay 1980).

DISCUSSION AND SUMMARY

This study has demonstrated that antitaxial crack–seal vein growth processes can lead to the development of a variety of vein microstructures including essentially equigranular to irregular grain fabrics and laminated microstructures, as well as fibrous microstructures. Most significantly, it has been demonstrated that the development of fibrous antitaxial crack–seal microstructures is not necessarily displacement-controlled. The latter result has important implications for our understanding of vein growth and the relationships of fibrous microstructures to the deformation history.

The development of vein microstructures clearly depends on a range of factors apart from the displacement history during the separation of the walls of dilating fractures. Probably the most important of these factors are the nucleation and growth kinetics of the phases being precipitated from fluids in the fractures, as well as the location of the sites of material accretion during successive crack–seal increments.

Fibrous vein microstructures are expected to develop only if a significant proportion of grains continues to grow during successive crack–seal increments without being occluded by more rapidly growing neighbours. Fibre growth will be displacement-controlled only if rejoining of the pulled-apart portions of originally joined grains is significant during the crack–seal process (Cox & Etheridge 1983). If fibre rejoining does not take place, and if grain shape is controlled largely by unidirectional competitive growth, with only limited grain occlusion at successive crack–seal increments, then the fibrous to columnar grain shapes that develop will not be displacement-controlled. Rather, these grains will tend to have long axes at high angles to the growth surface at each crack–seal increment, regardless of the relative displacements of vein walls and growing fibre ends.

Previous studies have successfully used displacement-controlled antitaxial fibres to evaluate progressive strain histories. On the basis of such studies there is a danger that fibrous microstructures will be used in strain analysis without critically examining whether the fibres do indeed track a displacement path during their growth. The observations reported in this paper serve to emphasize that the orientations of fibrous microstructures cannot be used to evaluate strain histories unless it has been demonstrated that fibre growth has been displacement-controlled. Clearly, microstructures such as crack–seal inclusion trails can be of considerable value in establishing this relationship.

The development of laminated crack–seal vein microstructures has been shown to correlate with displacement essentially parallel to vein walls and the attendant development of closely spaced layer silicate inclusion sheets. Such microstructures are expected to be indicative of crack–seal veins having a major component of displacement parallel to the vein walls.

The formation of irregular grain fabrics during crack–seal vein growth may simply be indicative of rapid growth occlusion by neighbouring grains dominating over successful growth of a large proportion of grains. If this is the case, the development of irregular grain fabrics is not expected to be influenced by the displacement path during vein growth, merely by growth kinetics. The demonstration that irregular grain fabrics can develop by a crack–seal mechanism is significant in that it clearly indicates that massive veins are not diagnostic of non-tectonic vein growth. Massive vein microstructures, as well as fibrous and laminated microstructures may develop during protracted syntectonic crack–seal vein growth histories.

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