On the arrangement of solid inclusions in fibrous veins and the role of the crack-seal mechanism

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Abstract

The arrangement of solid inclusions in veins was examined in three different rock types and tectonic settings. Common to all samples is a new type of sinusoidal inclusions, associated with inclusion bands oriented parallel to the vein wall and inclusion trails at high angle to the vein wall.

Crosscutting relationships of inclusion bands and the sinusoidal inclusions imply that inclusion bands do not reflect individual crack-seal increments. In our veins, inclusion bands are not a sufficient criterion to infer the crack-seal mechanism. Further evidence for solid inclusions not formed by the classic crack-seal mechanism is given by inclusion bands in gypsum crystals grown in soft clay.

During incorporation, solid inclusions can become folded or boudinaged, depending on their orientation with respect to the opening direction. The complex displacement field within the vein is recorded by curved crystal fibres, which track the opening direction.

Based on the arrangement of solid inclusions within the vein we suggest that our veins grew continuously during syntectonic vein formation. Solid inclusions formed by a fluctuation of adhesion at the vein wall interface rather than by crack-sealing, and vein growth was at least partly driven by the force of crystallisation.
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1. Introduction

The growth mechanisms of fibrous veins have been much discussed because of the special mineral habit and their potential to contain information on kinematics of deformation in rocks (Grigor'ev, 1965, p. 200; Durney and Ramsay, 1973; Cox, 1987; Urai et al., 1991; Means and Li, 2001). It has been shown that fibrous crystals grow in a curved shape, and that the fibre curvature is not caused by deformation (Durney and Ramsay, 1973; Spencer, 1991). These curved fibre grain boundaries are often used to infer the opening trajectory of the fracture during growth. On the other hand, many studies have shown that the curvature itself is not a sufficient tool to reliably reconstruct the opening kinematics of veins (Cox, 1987; Urai et al., 1991; Hilgers et al., 2001).

Important information about the vein opening process or opening direction is provided by solid inclusions within veins. These inclusions may be particles detached from the vein wall, or different phases grown contemporaneously during vein growth (Ramsay, 1980; Cox and Etheridge, 1983; Hilgers and Urai, 2002).

Based on linear bands of solid inclusions parallel to the vein wall, Ramsay (1980) proposed a process of repeated fracturing and sealing—the so-called crack-seal mechanism. These crack-seal veins display saw-tooth shaped grain boundaries between adjacent elongated grains and overgrowth of favourably oriented crystals. The texture does not show a constant aspect ratio of grains and is thus not fibrous sensu stricto, but columnar. Fisher and Byrne (1990) and Fisher et al. (1995) correlated the length of mica inclusions bands with crack seal increments and inferred that

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discontinuous inclusion bands are caused by partial sealing of the vein before cracking. They noted that inclusion bands are restricted to columnar grains that outgrowth their neighbour grains.

A second type of solid inclusions forms trails at high angle to the vein wall, which are interpreted to originate from a point source in the wall (Dunne and Hancock, 1994). Such inclusion trails are also proposed to be associated with the crack-seal process (e.g. Cox, 1987; Heaney and Fisher, 2003). Heaney and Fisher (2003) showed evidence for fracture events in the vein based on inclusions hosted in columnar quartz crystals, which contain a jagged/fractured end pointing towards the vein wall and the site of crack sealing.

Cox (1987) noted the importance of solid inclusion trails to establish the opening direction of veins. The alignment of inclusion trails originating from a single source in the wall points to the opening direction regardless of the fibre grain boundary orientation. Thus, the arrangement of solid inclusions within veins is used as an important tool to deduce the vein opening direction, as well as the opening mechanism. The vein opening mechanism is generally described as mode I extension failure, initiated by an increase in fluid pressure and low differential stresses (Etheridge et al., 1984; Price and Cosgrove, 1990; Boullier and Robert, 1992; Sibson, 2003). Following classical fracture mechanics, the vein continues to grow as long as the fracture propagates by dynamic growth, i.e. if the critical fracture toughness K_{IC} is exceeded (Ingraffa, 1987; Wiltschko and Morse, 2001). Solid inclusions will be incorporated when a fracture reopens after crack collapse and re-sealing, i.e. if the fluid pressure increases to values larger than the minimum principal stress normal to the fracture wall and the tensile strength of the rock. Another model favours subcritical crack growth rather than dynamic growth. It is based on the observation that the topography of the vein wall interface (interpreted to be rhythmically repeated as inclusion bands within the vein) is too high on a micrometer scale to be opened by dynamic growth (Boullier and Robert, 1992; Cox, 1995). A third model explains fibrous veins as continuous growth phenomena, the vein being opened either actively by the force of crystallisation (Fletcher and Merino, 2001; Means and Li, 2001; Wiltschko and Morse, 2001) or passively with space provided during ongoing deformation (e.g. around pressure shadows). All three mechanisms require the opening of a gap, and thus cover a continuum dependent on the gap's size and the timing of opening increments (Hilgers et al., 2001). Although the incorporation of host rock fragments seems unlikely during continuous growth, repeated inclusion bands plugged off from the wall and arranged parallel to the vein wall have been observed in fibrous veins grown by the force of crystallisation (Means and Li, 2001).

In this paper we present the result of a study of solid inclusions found in syntectonic fibrous veins from three different settings, and discuss the evolution of the microstructure in terms of opening mechanisms. A new type of sinusoidal solid inclusion arrangement is described, which allows interpretation of the vein opening mechanism.

2. Sample description

2.1. Calcite veins

The first set of samples comes from the Upper Silurian Wills Creek formation, which was deformed during the Alleghian orogeny. The samples (taken from an outcrop on route 147 east of Milton, Pennsylvania) consist of thin-bedded, folded shale and siltstone with pressure solution cleavage, containing many bedding parallel fibrous calcite veins (Pringle, 1980; Gray, pers. commun.). In our samples calcite is absent in the host rock. Siltstone layers consist of quartz with grain sizes of about 20 µm and white mica and are arranged as continuous and lenticular beds in shale.

The bedding parallel veins have a lensoid shape (Fig. 1), terminating between bedding planes (Figs. 1 and 2). They contain abundant inclusions of host rock fragments of shale and siltstone, and some chlorites grown from the wall into the vein. Host rock fragments are layers, which can be traced laterally into zones without veins. These are locally folded inside the vein (Fig. 2B). At the other extreme, these layers are arranged in regularly spaced series of inclusions, indicating stretching sub-parallel to bedding (Fig. 2B). Other series of inclusions are sinusoidal with amplitudes corresponding up to the vein's thickness (Fig. 2A).

The solid inclusion arrays themselves are sometimes connected by fibrous overgrowth between the fragments. The orientation of these fibre grain boundaries is not parallel to the fibres immediately outside the inclusions (insert in Fig. 3f).

The calcite fibres are commonly curved and without undulose extinction, and contain minor mechanical twins (Fig. 3). Fibre curvature and the type of host rock vs. vein composition are consistent with antitaxial growth at the vein-wall interface (Durney and Ramsay, 1973; Ramsay and Huber, 1983). The fibres are commonly, but not always, oblique to the wall rock, suggesting oblique opening during late stages of vein growth.

2.2. Tiger's eye (quartz veins)

The second set of samples contain Tiger's eye hosted in banded ironstone from a mine in the Hamersley Range in Western Australia (Powell et al., 1999; Taylor et al., 2001; Webb et al., 2003). Layers show approximately the same thickness as in our first set of samples, and are deformed into open to close folds (Fig. 4). The tiger's eye forms bedding-parallel veins between the iron rich layers.

The Tiger's eye consists of fibrous, bedding-parallel quartz veins and inclusions of iron oxide/hydroxides (see also Heaney and Fisher, 2003). The fibres are oriented at
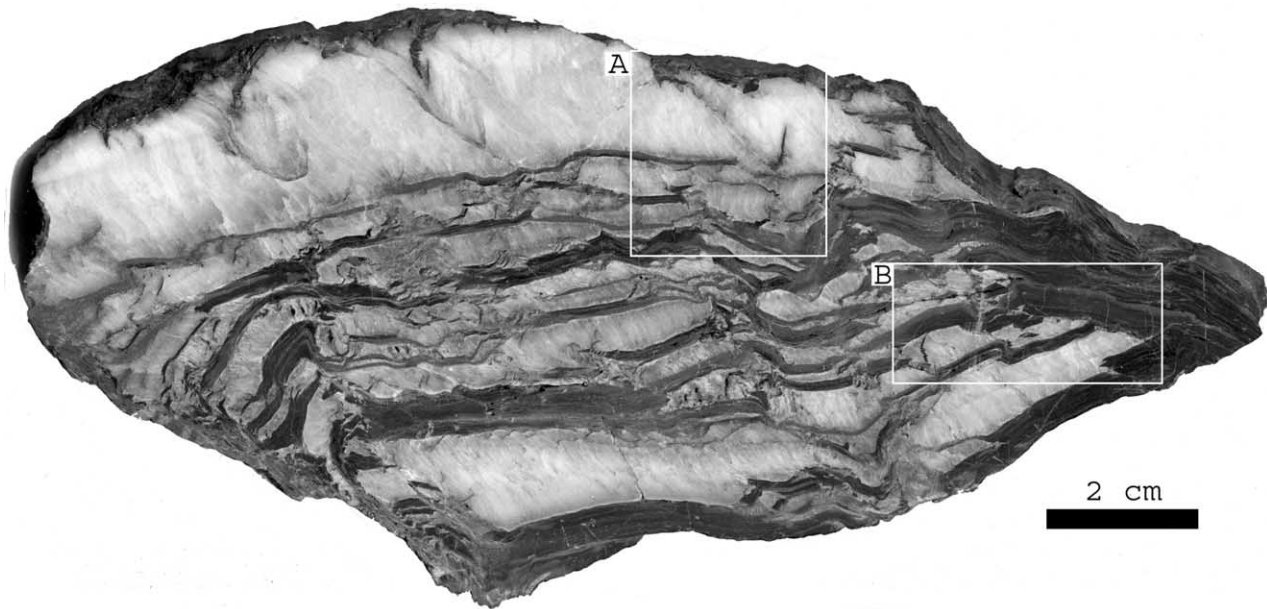
Fig. 1. Syntectonic calcite veins emplaced parallel to bedding and displaced fragments of host rock. Different arrangements of solid inclusions can be observed within the vein, which point to a complicated opening process. Details of two areas are highlighted and are described in Fig. 2.

high angle to the vein wall. The vein's thickness often increases within the fold hinge, suggesting syntectonic vein formation (Fig. 4). Both the composition of vein and host rock as well as fibre curvature points to antitaxial growth (Ramsay and Huber, 1983, p. 241; Heaney and Fisher, 2003).

Solid inclusions of host rock material of coherent layers made of iron hydroxide are included in the vein. The vein and solid inclusions are surrounded by a selvage about 20 µm wide, which consist of iron oxide. Host rock fragments are much larger than the fibre diameter (Fig. 6) and are arranged as inclusion bands and sinusoidal inclusions, the amplitudes of which are up to the vein's thickness (Fig. 5). The wall rock fragments can often be made to fit together following the fibre boundaries. In some cases, the wall rock fragments form spectacular triangular structures such as shown in Fig. 6.

2.3. Gypsum veins

Gypsum veins were sampled in deformed Eocene carbonates and shales on the coastline near Ras al Hamra, Muscat, Oman. Up to several centimetres thick gypsum veins are embedded in shales, while few millimetre-sized gypsum veins were found in adjacent carbonates layers. The frequency of veins increases towards a faulted anticline nearby. Veins are oriented sub-parallel to bedding and are located in rotated tension gashes (Fig. 7a) (Wilson, 1961, p. 453; Price and Cosgrove, 1990, p. 250).
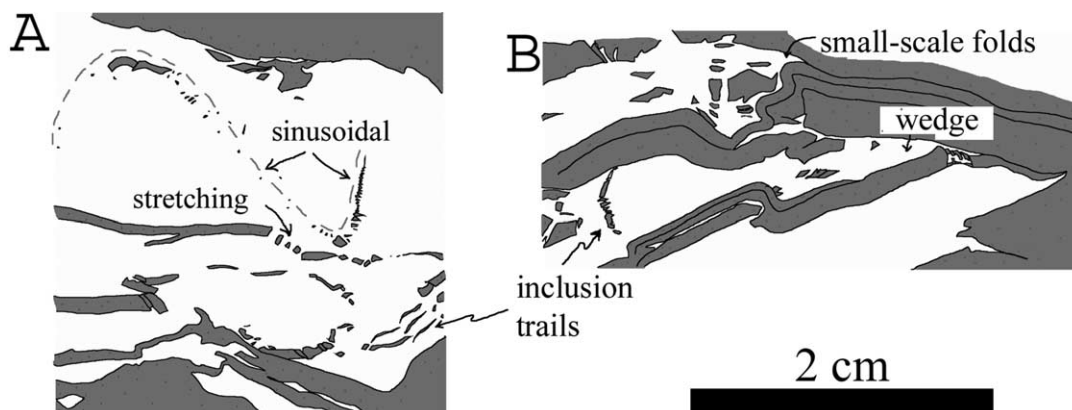
The overall vein microstructure is similar to the ones

Fig. 2. (A) Host rock fragments (grey) show different types of arrangements within the calcite vein. Linearly oriented host rock fragments suggest bedding parallel stretching. Other fragments are arranged in a sinusoidal manner (outlined by dashed line). (B) In other areas, solid inclusion can be found as typical inclusion trails, originating from a point source in the host rock. The host rock is folded and fractured, with pieces partly sliced off from the host rock (wedge-like). Scale bar refers to both images.
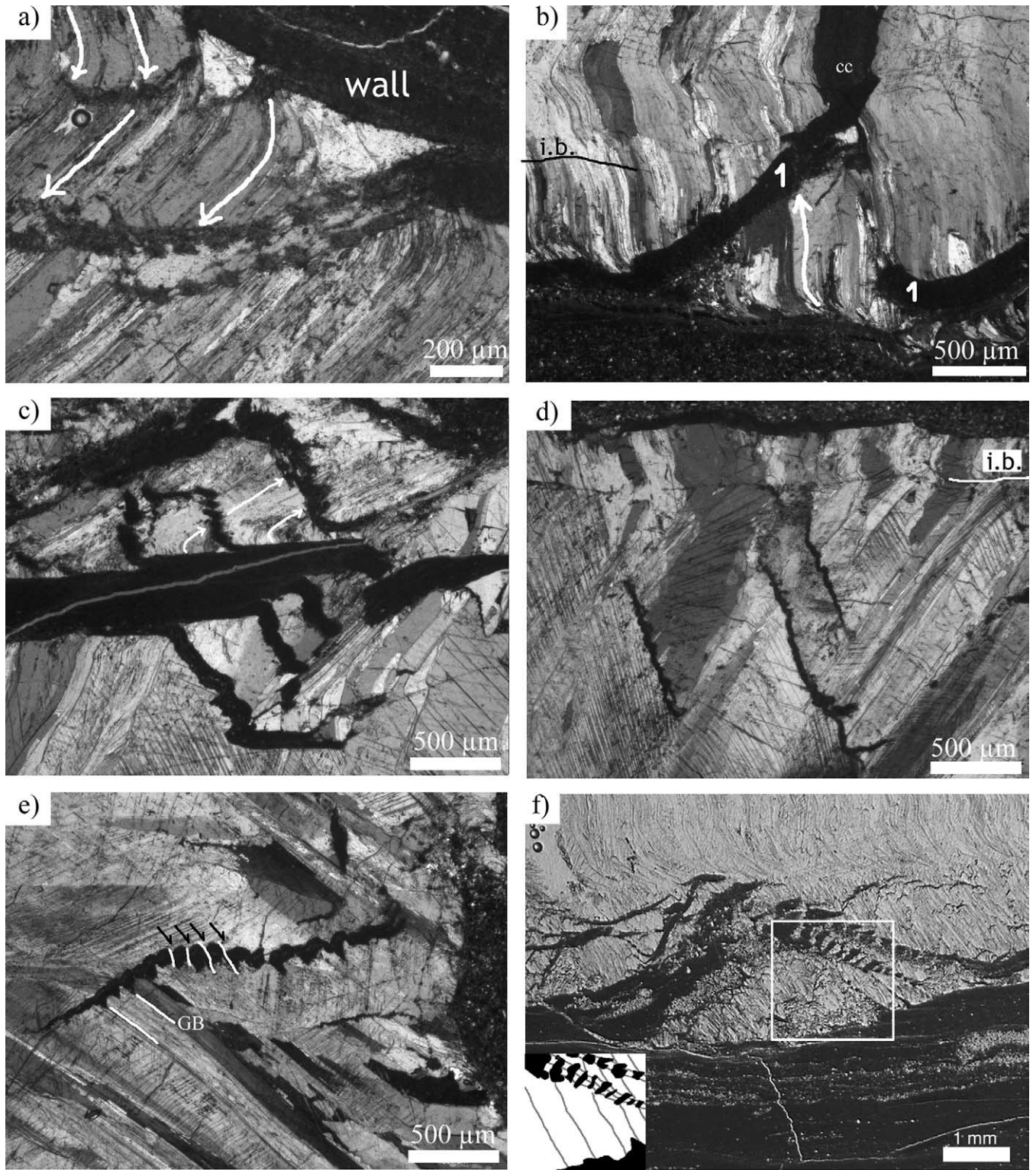
Fig. 3. (a) Host rock fragments (black) have been displaced along fibrous calcite grain boundaries. White arrows show the fibre grain boundaries, which are assumed to track the opening direction of the vein. Note that the arrowhead points to the direction of solid inclusion movement, opposite to vein younging. The inclusion progressively wedges off from the host rock (top of image), and becomes fragmented within the vein. (b) A small thin layer (marked as 1) curves into the vein in a wedge-like manner. Note that the black grain in the top is not bedding but a calcite fibre (cc). (c) Small layers of shale become successively displaced from their country rock. Close to the host rock bedding is curved, while it forms solid inclusions displaced along fibre grain boundaries within the vein. The white arrows trace the fibre grain boundary and point to the direction of solid inclusion movement during vein growth, opposite to the fibre growth direction. (d) Within the calcite vein, three lines of solid inclusion bands are arranged at high angle to the wall rock, easily misinterpreted as inclusion trails (see text for discussion). Next to the host rock (at top of image) a thin solid inclusion band (marked as i.b.) is arranged parallel to the vein–wall interface and

described above, i.e. gypsum is fibrous and fibres continue from one side of the wall to the other (Fig. 7c and d). Within these antitaxial veins, solid host rock inclusions are arranged as inclusion bands parallel to the vein–wall interface. Other inclusions are aligned in straight lines highly oblique to the vein wall, or show a sinusoidal shape (Fig. 7c and d). Inclusion bands continue across sinusoidal inclusions, without any change in inclusion band spacing (Fig. 7d).

3. Discussion

The three sets of samples come from different deformed sedimentary environments but show very similar structures of the solid inclusions in fibrous calcite, quartz and gypsum veins, respectively. Following the arguments given in Heaney and Fisher (2003), that tiger's eye is a result of vein growth and not a pseudomorphic substitution of quartz after pre-existing crocidolite asbestos, suggests that all settings described here expose primary vein microstructures.

Bedding-parallel veins are located on both fold limbs and around the fold hinge in our quartz and calcite veins. Their thickness has the tendency to increase in the fold hinge (saddle reefs), pointing to vein growth during folding (Fig. 4). In our gypsum veins, saddle reefs have not been observed in the outcrop and in our samples, but the association of veins with faults and folds nearby suggests syntectonic emplacement. These veins emplaced in tension gashes oriented at various angles to bedding (Fig. 7a and b).

3.1. Vein opening mechanism

Two models have been proposed for the formation of bedding parallel veins:

(i) Fractures may have opened at depth during horizontal compression when fluid pressure overcomes the minimum principal stress and the tensile strength across the bedding plane (Cosgrove, 1993, 1995; Jessell et al., 1994; Mandl, 2000, p. 194–205). Under such conditions, crystals will grow until fluid pressure drops due to fracturing and the void collapses (crack-seal mechanism with incremental growth). This may result in a feedback system, where the discharge seals off the fluid pathways and fluid pressure repeatedly increases until the rock fails (Sibson, 1992; Ortoleva, 1994, chapter 16). Collapse structures have been described as

dark insoluble residues tracing euhedral terminations being aligned sub-parallel to the vein wall interface (Fisher and Byrne, 1990). They may be either fragments of the wall or residue of minerals not found precipitated in the vein. Such microstructures have not been observed in our veins.

(ii) Alternatively, veins may grow continuously, opened actively by the force of crystallisation (Bunsen, 1847; Taber, 1916; Correns, 1949; Means and Li, 2001; Wiltschko and Morse, 2001) or passively during ongoing deformation. This mechanism implies that the vein–wall interface does not heal but is a zone of low adhesion and continuous accretion of new material. La Iglesia et al. (1997) measured crystallisation pressures in aqueous sulphate solutions of higher than 40 MPa in fluid saturated dolostone at room temperature. Winkler (1973) calculated pressures for anhydrite as 40 and 230 MPa, and for halite as 66 and 380 MPa at 50 °C and supersaturations 2 and 50 (supersaturation is expressed as concentration divided by the equilibrium concentration), respectively. High supersaturation is not uncommon in rocks. Silica supersaturation reaching values of three have been reported in reservoir brines in Cretaceous sandstones (Ross, 1994). Putnis et al. (1995) describe much higher supersaturation above 10 in finely porous media without onset of crystallisation. They present an alternative model for precipitates such as veins based on transport of fluid from very small fractures or grain boundaries into an open fracture. The force of crystallisation has not yet been experimentally measured for common vein minerals like quartz and calcite under hydrothermal conditions, but calculations suggest pressures of 80 MPa (calcite) and 300 MPa (quartz) for low supersaturations of two (Wiltschko and Morse, 2001). Dewers and Ortoleva (1990) noted that such calculations based on equilibrium thermodynamics are valid under equilibrium conditions only, and thus represent an upper bound. Their non-equilibrium model calculates pressures being about a factor of three smaller.

Estimating the vertical stress, we can determine whether the force of crystallisation may have caused vein opening in our samples. Tiger's eye grew at a depth of about 5 km at about 180 °C (Smith et al., 1982; Oliver, pers. commun.; based on thickness of younger stratigraphic units and mineral assemblages). Calcite veins are assumed to have formed with an overburden of about 6.75 km at 150–300 °C (Gray pers. commun.; based on thickness of younger

corresponds with the morphology of the host rock. (e) Solid inclusion band arranged at high angle to bedding (right hand side). The inclusions are homogeneously displaced parallel to fibre grain boundaries (GB). (f) Inclusion bands heterogeneously displaced from the host rock (lower part of image). The inclusion band is slightly buckled on the left hand side and fragmented/boudinaged on the right hand side. This matched with the local displacement field within the vein, indicated by the orientation of the fibre grain boundaries. (g) Thin section showing the bending of bedding (lower part of image) into the vein. Solid host rock inclusions become fragmented and are aligned highly oblique to the vein–wall interface. In the upper left of the image, their orientation changes and is aligned in the opposite direction.
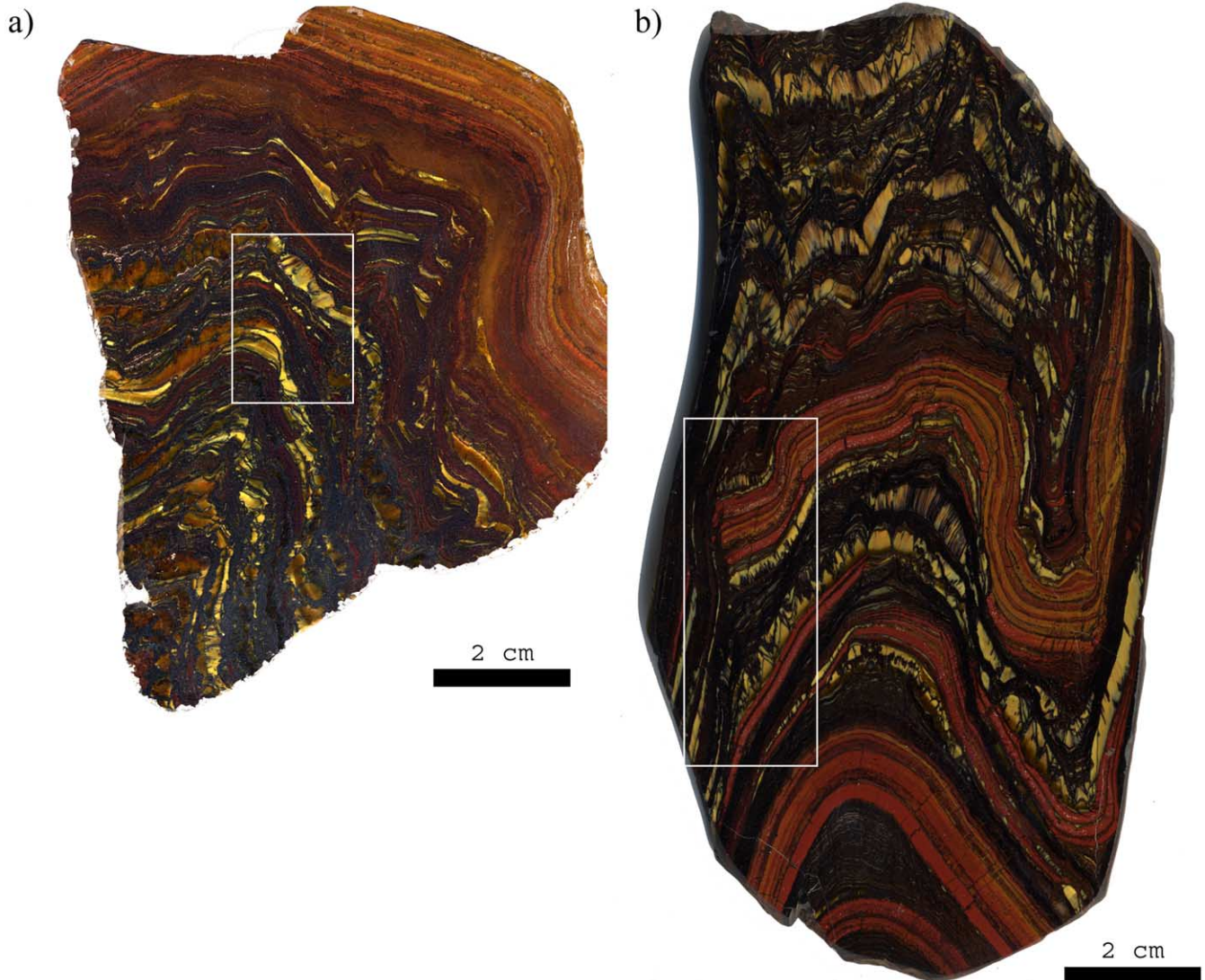
Fig. 4. Two rock samples of folded, banded ironstone containing bedding-parallel quartz veins (tiger's eye, bright colours). The zones A and B are described in detail in Fig. 5.

stratigraphic units and conodont colour alteration index of 3.5–4), corresponding to a maximum overburden stress of 175 MPa. Gypsum fibres hosted in Eocene carbonates were overlain by less than 1 km overburden, corresponding to approximately 25 MPa. The force of crystallisation stresses described above are higher than the stresses required to open the vein, even though our conservative calculations do not take into account elevated fluid pressure. If one assumes that the fluid pressure in the porous host rock is close to lithostatic, the stresses required to open a vein by the force of crystallisation will be close to zero. Thus, the force of crystallisation may explain vein opening in all three settings.

The fundamental difference of the fracture vs. force of crystallisation model is the vein orientation. While regular vein patterns are formed by far field stresses, the orientation of pure force of crystallisation veins only depends on local stresses governed by the strength of the surrounding matrix (e.g. low strength across bedding planes) and the location of other growing veins. Our gypsum veins are emplaced in tension gashes that require tectonic stresses as the kick-off process for vein formation (Wiltschko and Morse, 1998). Our calcite and quartz veins formed bedding parallel, so no firm conclusion can be drawn on the opening mechanism from their orientation. However, their syntectonic nature suggests the same interpretation. Better insight on the opening mechanism may be derived from the arrangement of solid host rock inclusions.

3.2. Inclusion arrangement

The presence of inclusion bands and inclusion trails aligned parallel to the vein wall interface has been frequently used to infer the crack-seal mechanism (Ramsay, 1980; Cox and Etheridge, 1983; Cox, 1987; Fisher and Byrne, 1990; Fisher and Brantley, 1992). Others argued for
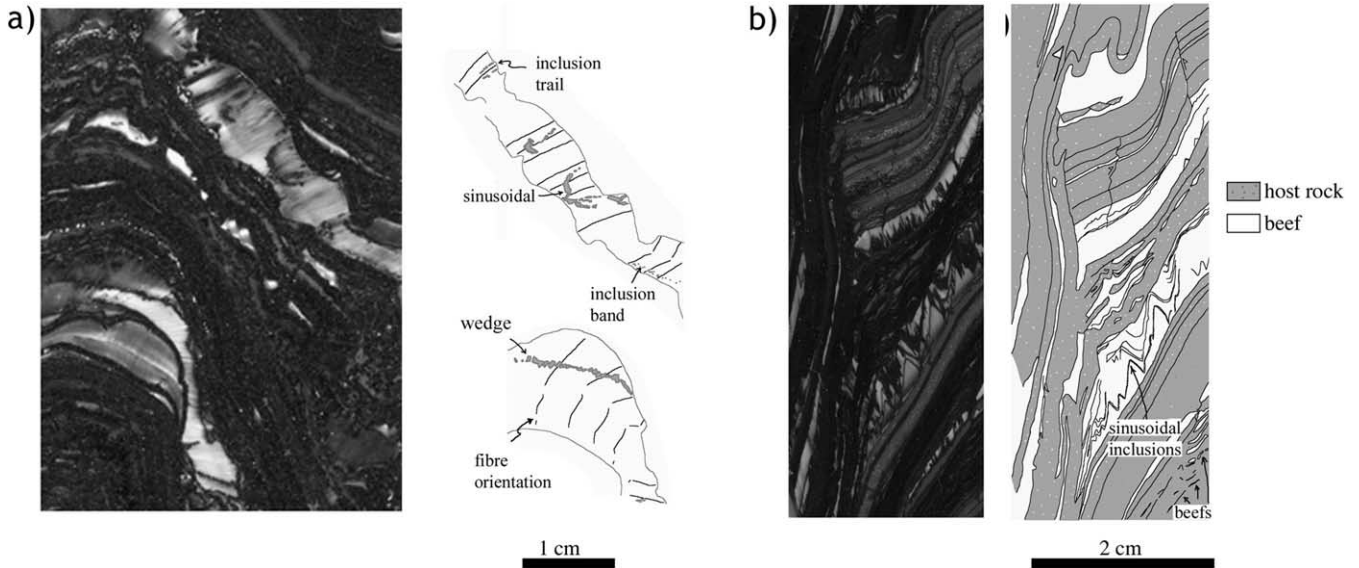
Fig. 5. (a) Details of zone A in Fig. 4. Three different types of inclusions appear within a single vein. Solid inclusions are arranged in a sinusoidal manner, and as inclusion trails and inclusion bands. (b) The microstructure of zone B includes a zone of faulting trending N–S (left side of image), causing an off-set of the veins. Veins are arranged as beefs parallel to bedding, containing sinusoidal inclusions with amplitudes close to the vein's thickness. Note that the asymmetry of sinusoidal inclusions corresponds to the mesoscale folds (compare with Fig. 4).
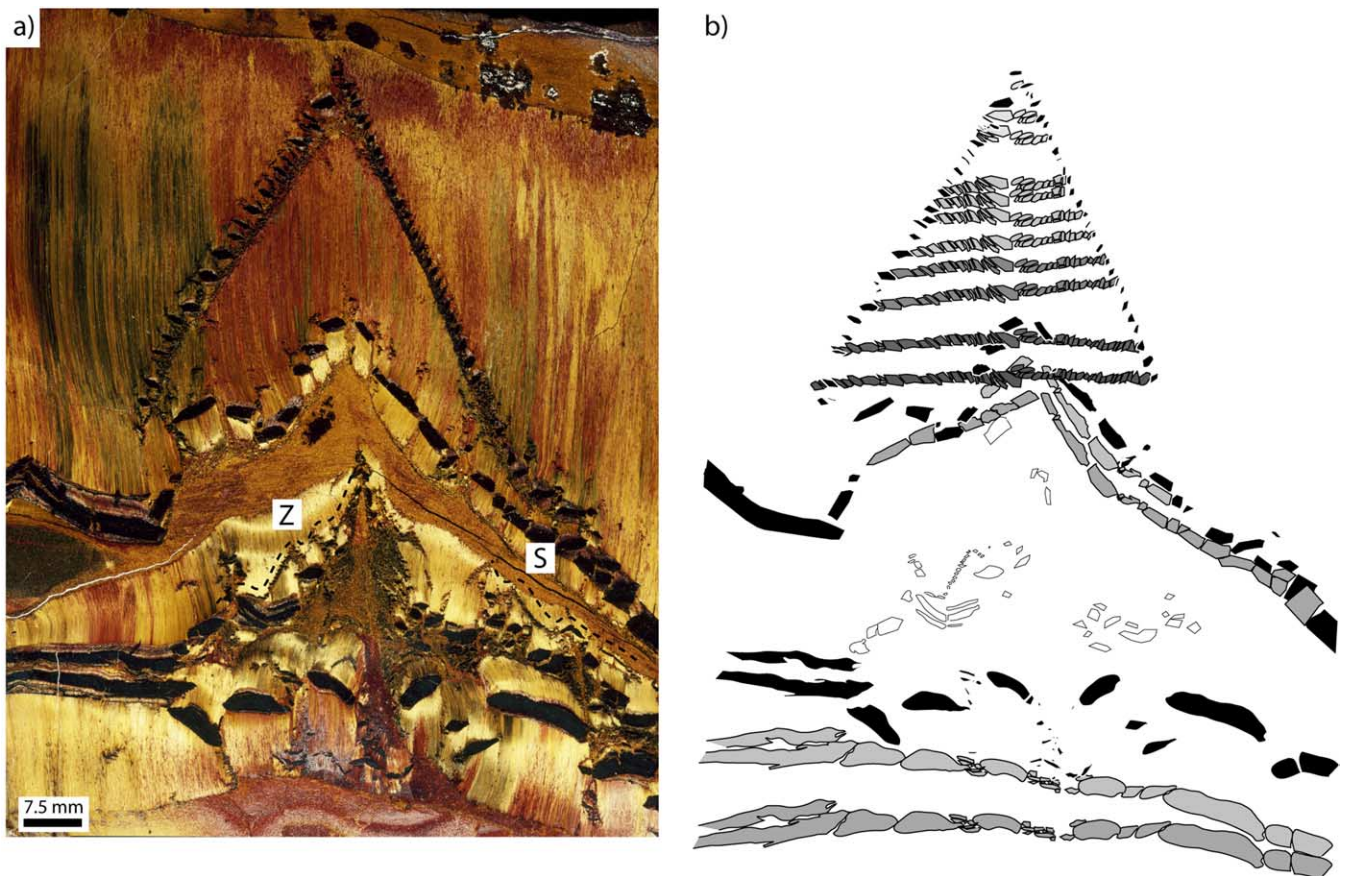
Fig. 6. (a) Detail of solid inclusion arrangements within a single beef. Four layers of bedding have been displaced along the fibre grain boundaries, forming sinusoidal solid inclusion fragments. Note that small inclusions in the lower part of the image form Z-, S- and M-parasitic folds (dashed line, image taken from Wiersma (2002)). (b) Reconstruction of solid host rock inclusions by movement along fibre grain boundaries. The original position of host rock fragments and their shape is coloured in black, the different stages during movement are shown in grey (white inclusions have not been restored). Note that the movement along fibre grain boundaries results in perfect alignment as straight beds of solid host rock inclusions.
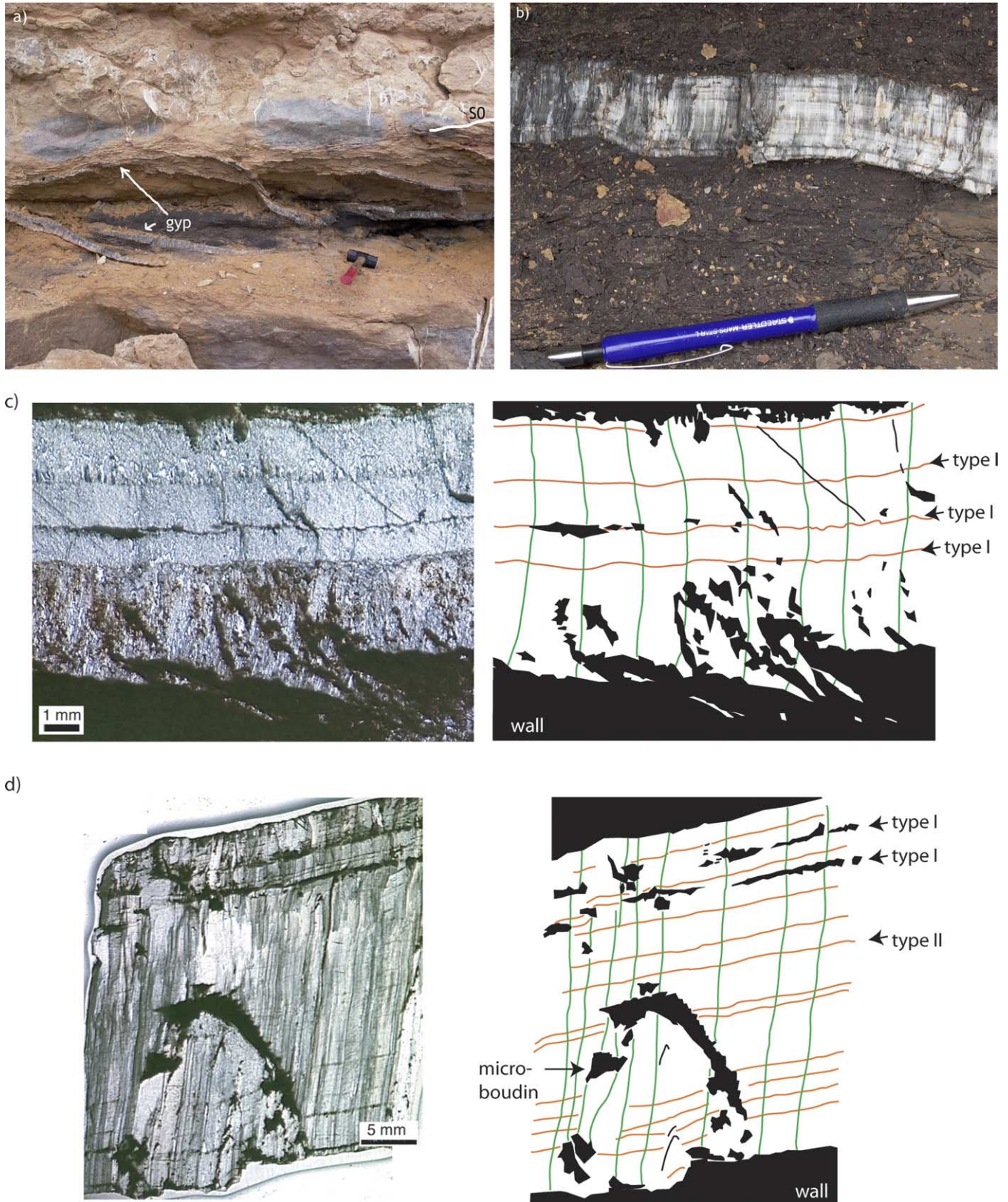
Fig. 7. (a) Outcrop showing a shale layer between two limestone beds (S0—bedding). Gypsum (gyp) tension gashes become sub-parallel to S0 at the shale–limestone interface and indicate top to the right shearing (hammer for scale). (b) The vein contains numerous inclusion bands aligned parallel to the vein–wall interface. On the right hand side and in the central part the vein shows minor inclusions arranged oblique to the vein wall interface. (c) Solid inclusions in gypsum veins are arranged as bands parallel to the vein wall, and highly oblique to the wall. Échelon veins wedge into the host rock causing inclusions oriented

a continuous diffusional process for fibrous vein micro-structures (Durney, 1972; Durney and Ramsay, 1973; Bons and Jessell, 1997; Wiltschko and Morse, 2001).

The detachment of solid inclusions is caused by changes in the adhesion between the host rock, vein and inclusion. Adhesion may be changed by processes such as a variation in fluid geochemistry resulting in a different wetting angle of the fluid film between vein and wall rock, vein growth rate keeping pace with the opening rate of the vein, fluid pressure causing the dilation of pore space which provides better access of growing grains into the wall rock, or fracturing. Fracturing of an interface may trigger the detachment of wall rock fragments, but is one of several processes possible.

In our samples, all three types of inclusion arrangements (inclusion bands, inclusion trails, sinusoidal inclusions) were observed within a single antitaxial vein, in samples from all three settings. We thus conclude that all different types of solid inclusions were formed simultaneously by the detachment of fragments from the wall rock. These inclusions can be incorporated in veins by the crack-seal mechanism *and* continuous growth such as the force of crystallisation mechanism, as long as there are changes in adhesion between the wall and the growing crystals.

In many cases, regular banding is a result of oscillating growth phenomena, as has been shown for banded agates, Liesegang rings, banding in MVT ores, stylolites, and solution growth (Allègre et al., 1981; Ortoleva et al., 1987; Reeder et al., 1990; Wang and Merino, 1990; Ortoleva, 1994; L'Heureux and Jamtveit, 2002). Microstructural criteria for authigenic minerals grown by the force of crystallisation have been described by Maliva and Siever (1988). They noted that $\leq$ µm-sized host rock inclusions within the grown microstructure point to force of crystal-lisation growth. Li (2000) and Means and Li (2001) grew fibrous veins using highly soluble material and also observed a banding parallel to the vein wall during ongoing vein growth. They distinguished two different types of wall-parallel inclusions; type I opaque layers caused by fluctuation in the growth conditions, and type II disconti-nuities with much smaller spacing of some 10 µm apart. These fibrous microstructures grow at a cohesive interface during continuous dilatant growth (Li, 2000), the inclusion bands probably caused by an oscillation process.

Fig. 8 is a natural example of non-crack-seal solid inclusion bands hosted in a large single crystal of gypsum, which has grown in soft clay at less than 1 m depth in a salt lake in Utah, USA. Because the crystallographic orientation of this gypsum crystal does not change across the inclusion

band, it must have grown into the porous wall rock before inclusion bands were dragged off. A change in boundary conditions then caused further growth at the new vein wall interface rather than growth into the wall, which formed zones without inclusion bands. In summary, the occurrence of inclusion bands is not sufficient to demonstrate crack-seal. Additional criteria to prove crack-seal are required e.g. a columnar rather than fibrous texture and serrated grain boundaries.

In all samples solid inclusions form a *wedge* with the country rock curved into the vein (esp. Figs. 3a–c and 7c and d). Depending on the local displacement field, these inclusions may become folded, sheared or extended into a series of micro-boudins (Figs. 3c and e and 7d). With extreme stretching, these series of micro-boudins may become oriented at very high angle to the vein wall. This raises an interesting question in nomenclature because fragmented inclusion bands highly oblique to the vein–wall interface can be easily misinterpreted as inclusion trails (especially Fig. 3d).

These wedge-like solid inclusions aligned oblique to the vein wall may be interpreted as being incorporated during bedding-parallel, distributed, échelon crack growth with bent bridges of wall rock between overlapping fractures (Nicholson and Pollard, 1985; Nicholson, 1991; Hilgers and Urai, 2002). However, the small size of the wedges, their strong curvature into the vein and high topography as well as their repeated occurrence within close distance (e.g. Fig. 3a and c) are unlikely to be formed by dynamic fracturing (see also Boullier and Robert, 1992). We suggest that these irregular morphologies are more likely caused by continuous growth e.g. variations in force of crystallisation.

In our samples the reconstruction of *sinusoidal solid inclusions* along fibre grain boundaries results in a perfect alignment at the vein wall (Figs. 3f, 6 and 7c,d). Thus, host rock fragments have been displaced at various distances, starting from an inclusion band (e.g. Fig. 6b). Such displacement is either a result of (i) internal deformation of the vein which contains an originally planar solid inclusion band by heterogeneous simple shear, (ii) a variation of vein growth rate along-vein, (iii) a change of the location of vein growth and total constant growth rate (defined as the summed growth rate along one vein–wall interface at different locations), or (iv) a combination of these processes.

Because fibre-parallel displacements cannot be traced into the host rock, we conclude that solid sinusoidal inclusions have not been formed by heterogeneous simple shear and reject (i). If simple shear and growth take place

at high angle to the vein–wall interface. Widely spaced solid inclusion bands may be correlated with Means and Li (2001) type I pattern. A separate sketch outlines the overall vein microstructure. (d) Sinusoidal inclusion hosted in shale with crosscutting inclusion bands parallel to the vein–wall interface. Note that the inclusion bands are not displaced on top of the sinusoidal inclusion. The inclusion band spacing does not change significantly across the sinusoidal inclusion. The limb on the left hand side of the sinusoidal inclusion is boudinaged, with a fibre connecting the fragments. This fibre grain boundary connects the displaced fragments, and is slightly oblique to the general fibre orientation. On the right hand side, sinusoidal inclusions form a continuous line without gaps. Some inclusion bands and the overall vein microstructure are highlighted in a separate sketch.
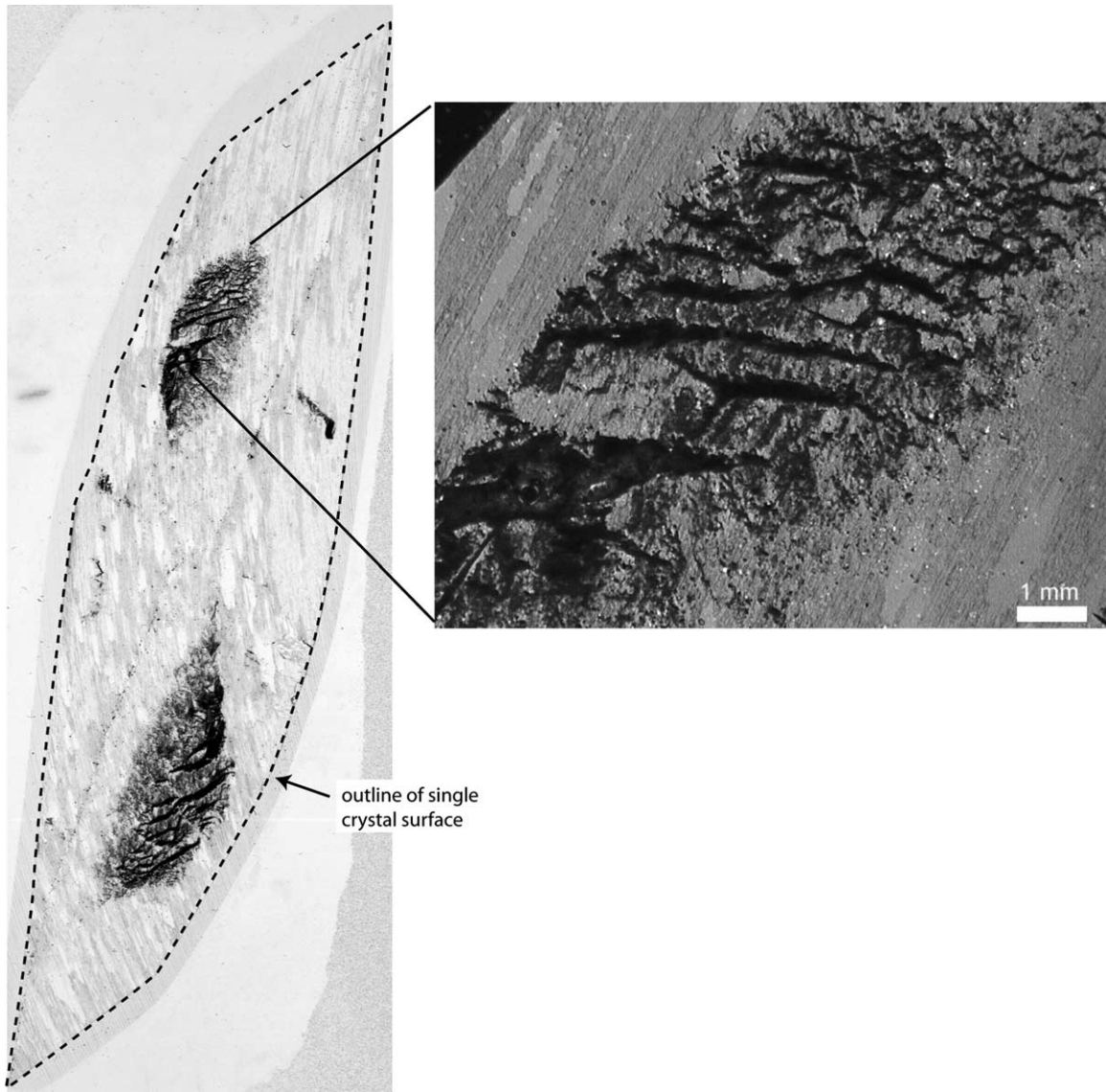
Fig. 8. Solid clay inclusions in a large gypsum single crystal from a salt lake in Utah, USA. The crystal is undeformed and has grown approximately 1 m below the surface without being exposed to tectonic stresses. Clay beds are arranged as opaque inclusion bands.

simultaneously, we would still expect a curvature of the vein–wall interface similar to the shape of the sinusoidal inclusion (Fig. 9a). A similar microstructure may result from a change in vein growth rate below a sinusoidal inclusion (Fig. 9b). In both cases, inclusion bands will be offset within the vein. This leaves (iii) as the most likely kinematics.

Crosscutting relationships of inclusion bands and sinusoidal inclusions are best displayed in the gypsum veins (Fig. 7d). Parallel bands of solid inclusions continue above and below sinusoidal inclusions, without a change in band spacing. Inclusion bands crosscutting the sinusoidal inclusion are located at higher elevation outside the arc, but continue as straight line above the arc (Fig. 7d).
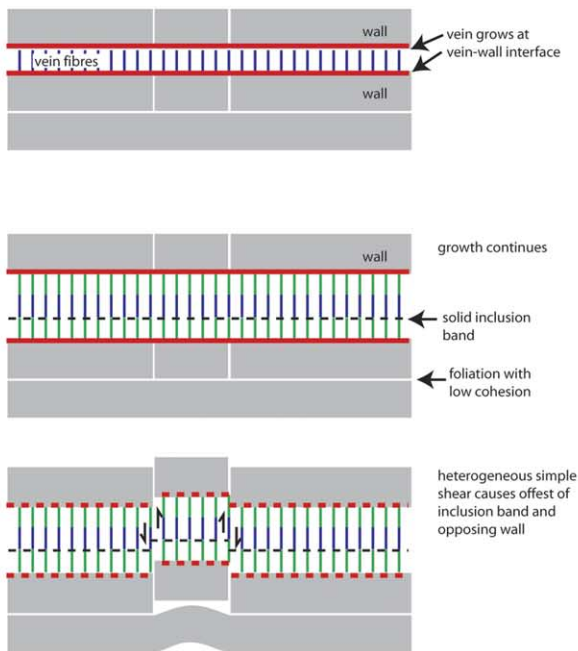
This can be explained by a model in which the total growth rate along-vein is continuous, but distributed at different growing interfaces (Fig. 9c). This model explains the continuity of solid inclusion bands above sinusoidal inclusions, and the constant inclusion band spacing within the vein.
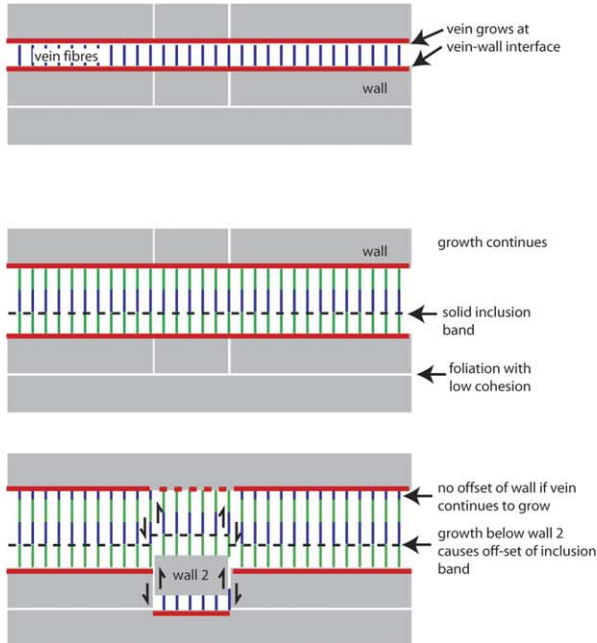
Crack seal opening increments are generally interpreted to represent the distance between inclusion bands, this distance sealed by growth of vein material. This mechanism would cause fragmentation on both limbs of sinusoidal inclusions, its spacing correlating with the distance between inclusion bands. Such regular fragmentation has not been observed in our veins. Therefore, solid inclusion bands cannot be used as crack-seal indicators in our veins. Rather, a continuous growth process is required to explain the arrangement of solid inclusions.

However, a displacement of inclusions driven actively by a continuous growth process only is unlikely, because one
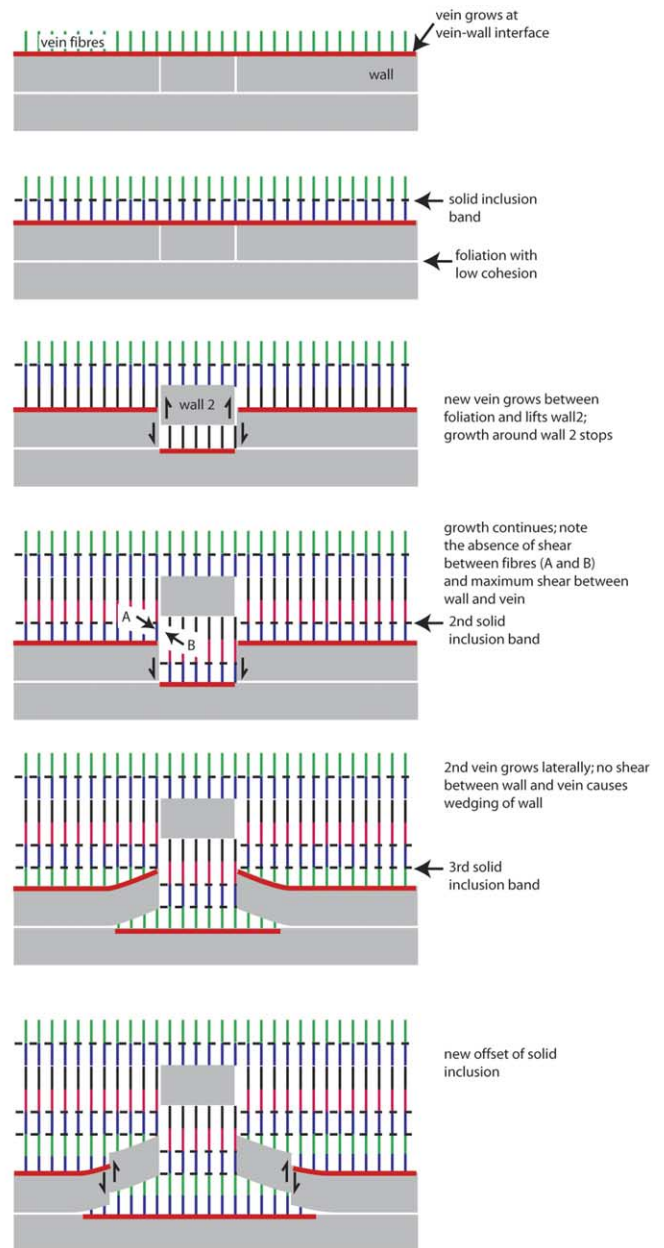
Fig. 9. Sketch illustrating the incorporation of solid inclusions using three different models. In all models, veins grow antitaxial (at the vein–wall interface, towards the host rock). Sites of growth are marked with a dark line. (a) Heterogeneous simple shear will cause slip parallel to the fibre grain boundaries, causing displacement at the vein–wall interface. This interface will be bent or sheared with the same amplitude as the sinusoidal inclusion. Inclusion bands within the vein will be offset during slip. In this model, the vein emplaced before displacement took place, e.g. by heterogeneous simple shear folding. The vein might continue to grow during shear, displayed by a dashed line. (b) Assuming variable growth rates below sinusoidal solid inclusions, the resulting microstructure is similar to the model described in (a), i.e. solid inclusion bands above wall2 will be displaced. (c) If the growth rate remains constant along-vein, inclusion bands and vein–wall interface will not be displaced. Note that there is no growth once the inclusion is surrounded by vein material. Slip only occurs parallel to the fibre axis along the wall-inclusion (marked as wall2) contact. Slip is absent between adjacent fibres as long as the growth rate along-vein is constant. This model best explains the formation of solid inclusion as observed in our rock samples. (d) Overview of the vein's evolution and formation of sinusoidal inclusions using the constant growth rate model shown in (c).
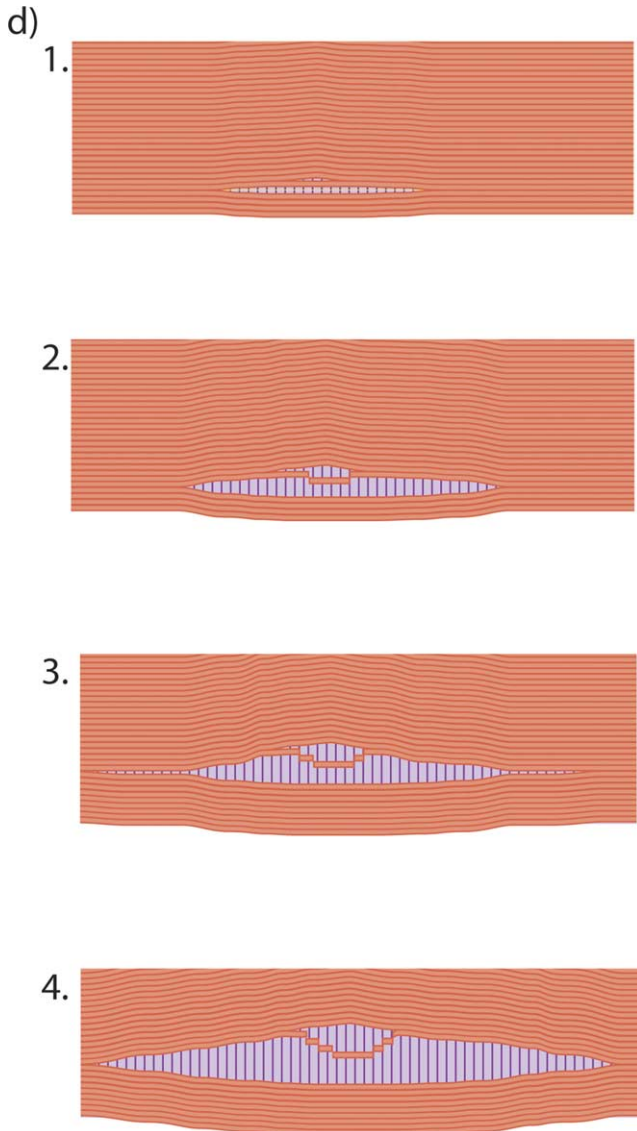
Fig. 9 (*continued*)

fracturing can (and are expected to) act simultaneously, a regular vein pattern does not indicate the absence of force of crystallisation during vein formation.

The following opening scenario is suggested for our veins (Fig. 9c and d): initially, small lensoid veins formed (i) parallel to bedding, probably initiated as bedding parallel tensile fractures (quartz and calcite veins) and (ii) as oblique tension gashes (gypsum veins), respectively. Antiaxial vein growth caused the wall rock to be wedged off, causing folding or boudinage depending on the orientation of solid inclusions relative to the local displacement field. Inclusion bands, inclusion trails and sinusoidal inclusions are formed by constant total growth rates at variable accretion sites, the displacement field being illustrated by the orientation of fibre grain boundaries.

4. Conclusions

Our samples from three different lithologies and tectonic settings display similar sinusoidal solid inclusion arrangements, originally formed as inclusion bands. Crosscutting relationships of sinusoidal inclusions and inclusion bands require a growth model with constant total growth rate along-vein (defined as constant growth rate at different locations on one side of the vein). Inclusion bands themselves are not a sufficient criterion to deduce the crack-seal mechanism, and do not reflect crack seal increments in our veins. Although clear evidence for crack-seal vs. force of crystallisation mechanisms are difficult to establish, microstructures suggest that a continuous growth mechanism contributed significantly to vein formation in our samples.

The local displacement field of growing veins can alter the position of solid inclusion bands caused by vein growth and slip parallel to fibre grain boundary. Due to a heterogeneous displacement of solid inclusions, fragments of inclusion bands can be easily misinterpreted as inclusion trails.

would not expect a regular arrangement of sinusoidal inclusions corresponding to the higher order fold structure, as displayed in our quartz and calcite samples (especially the Z-, S- and M-parasitic fold geometries in the tiger's eye) (Figs. 5b and 6). This awaits full explanation but suggests that the incorporation of solid inclusions during syntectonic vein emplacement is not a pure growth phenomenon.

As outlined above, vein-opening scenarios (fracture vs. force of crystallisation opening) have been much discussed because of the problematic interpretation of distinctive microstructures. The fundamental difference of both processes is the stress field in which the vein has been formed. Stress fields are variable on a local scale during force of crystallisation growth, and are much more regular over large scales for fracture opening. Consequently, force of crystallisation growth could be deduced from irregular vein arrays. However, as force of crystallisation and

and David Wiltschko led to considerable clarification of the manuscript.

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