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Shear sense indicators in striped bedding-veins

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Abstract

Striped bedding-veins are veins that lie subparallel to bedding and have an internal layering or lineation at a small angle to the veins' long axis. They form during bedding-parallel slip and can be used as shear sense indicators. Solid inclusion trails produce the visible internal layering or lineation and track the opening direction of the veins. Elongate quartz crystals however can be oriented at an angle of up to 80° to the opening direction, are non-tracking, and contain almost no information on the shear sense. The striped bedding-veins can be separated into three types according to the geometry of their internal segmentation. Veins of type B opened parallel to jogs oriented at a low angle to bedding, veins of type J opened parallel to jogs oriented at a high angle to bedding and veins of type O opened orthogonal to bedding and jogs. Striped bedding-veins of types B and J contain crack–seal inclusion bands and displacement parallel inclusion trails. Striped bedding-veins of type O feature only crack–seal inclusion bands. The example of striped bedding-veins presented in this paper from the Orobic Alps of Italy belongs to type B. The lineation in the veins and the orientation of the inclusion bands and inclusion trails, as well as the orientation of steps in the vein wall, can be used to determine the sense of shear and the direction and amount of vein opening or bedding-parallel slip. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

In tectonic analysis, it is useful to obtain information on the opening trajectory of veins during deformation, i.e. the path taken by two points in opposite wall-rocks that were originally in contact. Fibrous crystals in veins are commonly used to determine this opening trajectory (Ramsay and Huber, 1983; Urai et al., 1991). As such, they belong to the most important kinematic indicators in rocks. Of special interest are crack–seal veins, which form by a process of periodic fracturing and sealing (Ramsay, 1980), with inclusion bands thought to represent single cracking and sealing events. Studies on crack–seal veins have shown, however, that not all crystals in such veins track the opening trajectory (Ramsay, 1980; Van Der Pluijm, 1984; Cox, 1987; Urai et al., 1991; Fisher and Brantley, 1992). This has been attributed to the fact that growth of some crystals in crack–seal veins is crystal-face controlled, so that crystals growing at different speeds outpace each other (Fisher and Byrne, 1990). Such crystals develop an elongate or blocky form, with variable grain-size and aspect ratios of less than 20:1. In contrast to this anisotropic growth, crystals can also grow isotropically so that fibres develop that do not outgrow each other (Fisher and Brantley, 1992; Bons and Jessell, 1997; Koehn et al., 1998). Such fibres can have a very constant diameter and very high length to width ratio (up to 100:1). Elongate crystals have very poor or no tracking capability (Bons and Jessell, 1997; Koehn et al., 1998) in contrast to isotropically growing fibres.

In crack–seal veins containing elongate or blocky crystals, crack–seal inclusion bands and inclusion trails have been used to determine the opening history of the veins. Crack–seal inclusion bands are arrays of inclusions in a vein reflecting the wall-rock morphology. Inclusion trails are arrays of inclusions assumed to follow the opening trajectory of a vein (Ramsay and Huber, 1983). There are different ideas, however, on

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the interpretation of these inclusions, especially when the veins are striped and contain both inclusion bands and inclusion trails in different orientation (Nicholson, 1978; Ramsay and Huber, 1983; Cox and Etheridge, 1983; Gaviglio, 1986; Mawer, 1987; Cox, 1987; Labaume et al., 1991; Fisher and Brantley, 1992; de Roo and Weber, 1992; Cosgrove, 1993; Jessell et al., 1994). Of particular interest are striped bedding-veins that have been described from the Alps in Europe (Labaume et al., 1991) and from the Variscan (de Roo and Weber, 1992), the Caledonian (Nicholson, 1978; Cosgrove, 1993), the Appalachian (Stanley, 1990; Ohlmacher and Aydin, 1997) and the Lachlan fold belt (Jessell et al., 1994). These veins are usually found in basins with alternating sandstone and mudstone beds and formed during layer-parallel slip due to folding or thrusting (Jessell et al., 1994; Cooke and Pollard, 1997; Fowler and Winsor, 1997). Metamorphic conditions during growth are up to greenschist facies and fluid pressure was apparently high (Etheridge et al., 1984). This study describes striped bedding-veins from the Italian Alps and shows how different inclusion bands and inclusion trails can be interpreted, how striped bedding-veins can be classified, and expands on earlier work to show how these veins can be used to determine the direction and amount of bedding-parallel slip during folding or thrusting.

2. Regional geology

The study area lies south of the Insubric Line in the central Orbic Alps of northern Italy, which are part of the Southern Alps (Fig. 1). Alpine nappe transport is directed towards the south and Alpine metamorphism is low grade, in contrast to the Central Alps (Laubscher, 1985).

A basement consisting of orthogneiss and metasediments was deformed and metamorphosed up to amphibolite facies conditions during the Variscan orogeny. These basement-rocks are unconformably covered by a Permian to Triassic volcano-sedimentary sequence deposited in small fault-controlled basins (Cassinis et al., 1986). The sediments consist of coarse conglomerate at the base followed by the continental Collio Formation and the Verrucano Lombardo Formation. The Collio Formation is made up of an intercalated sequence of alluvial fan and lacustrine sediments, mainly sandstone and siltstone beds with minor conglomerate and felsic volcanics. The sequence varies laterally in thickness and composition. It is overlain unconformably by the Verrucano Lombardo Formation containing conglomerates and coarse grained sandstones. During the Alpine orogeny, normal faults were reactivated as thrusts or strike-slip faults. The whole sequence was folded and developed a strong S_1 cleavage (Cassinis et al., 1986; Blom and Passchier, 1997).

The study area is located to the west of Lake Diavolo (approximately at 9° 52′ E and 46° 03′ N) (Fig. 2). In this area bedding in the Collio Formation is deformed into an open anticline–syncline pair with gently east–west-plunging axes, bounded to the north and south by reactivated normal faults and south-directed thrusts (Fig. 2) (Blom and Passchier, 1997). The folds are upright with a wavelength of about 1 km and have a strong axial-planar S_1 slaty cleavage. A large number of striped bedding-veins is found in the Collio Formation where sharp contacts exist between mudstone and sandstone layers. They are absent in very fine-grained and very coarse-grained beds. The sample sites lie mostly along a small trail from the Rifugio Longo cabin along Lake Diavolo towards Passo di Venina. Numerous striped bedding-veins can also be found at the Passo di Cigola, which can be reached

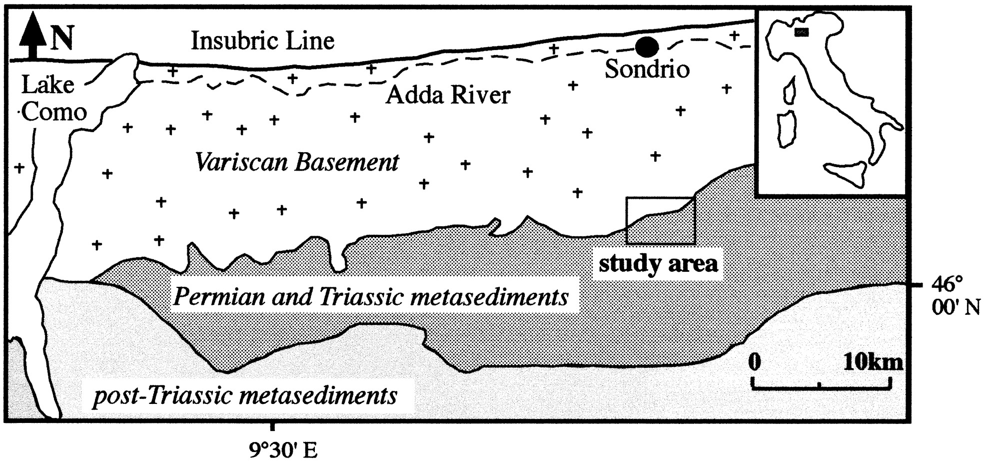

Fig. 1. Location of the study area south of the Insubric Line in the Orobic Alps of northern Italy (modified after Zhang et al., 1994).

from the Rifugio Longo along a trail passing Lake Diavolo.

3. Striped bedding-veins and their internal microstructure

3.1. Macroscopic appearance of the veins

Striped bedding-veins occur as sheets between sedimentary layers, are striped at a small angle to the vein and contain a lineation (Fig. 3). Most of the veins are made up of quartz with minor amounts of calcite, white mica and biotite. The lineation in the veins is parallel to displacement of the vein walls as can be determined by displacement of markers, but lies at a small angle to bedding (less than 10°).

Besides the dominant striped bedding-veins, two other systems of veins can be distinguished in the area, labelled V_1- and V_2-veins. Striped bedding-veins are connected with V_1-veins that are oriented perpendicular to the bedding and parallel to the S_1 cleavage. V_1-veins are widest close to the striped bedding-veins and die out in the wall-rock after 2–20 cm (Fig. 3). They appear on both sides of the striped bedding-veins. V_2-veins are late and cut all earlier veins. Striped bedding- and V_1-veins are mostly veins with inclusion bands and inclusion trails with elongate or blocky crystals, V_2-veins contain no solid inclusions.

V_1-veins are associated with, and apparently of the same age as, the striped bedding-veins, since each individual V_1-vein lies only on one side of a striped bedding-vein and does not cut it (Fig. 3; Ohlmacher and Aydin, 1997). A variable displacement rate along the striped bedding-veins is a possible explanation for the development of V_1-veins. When a striped bedding-vein is not detached completely from the wall-rock during an opening event, the wall-rock is locally in extension and creates V_1-veins that form along the S_1 pre-existing anisotropy. V_1-veins are filled with elongate crys-

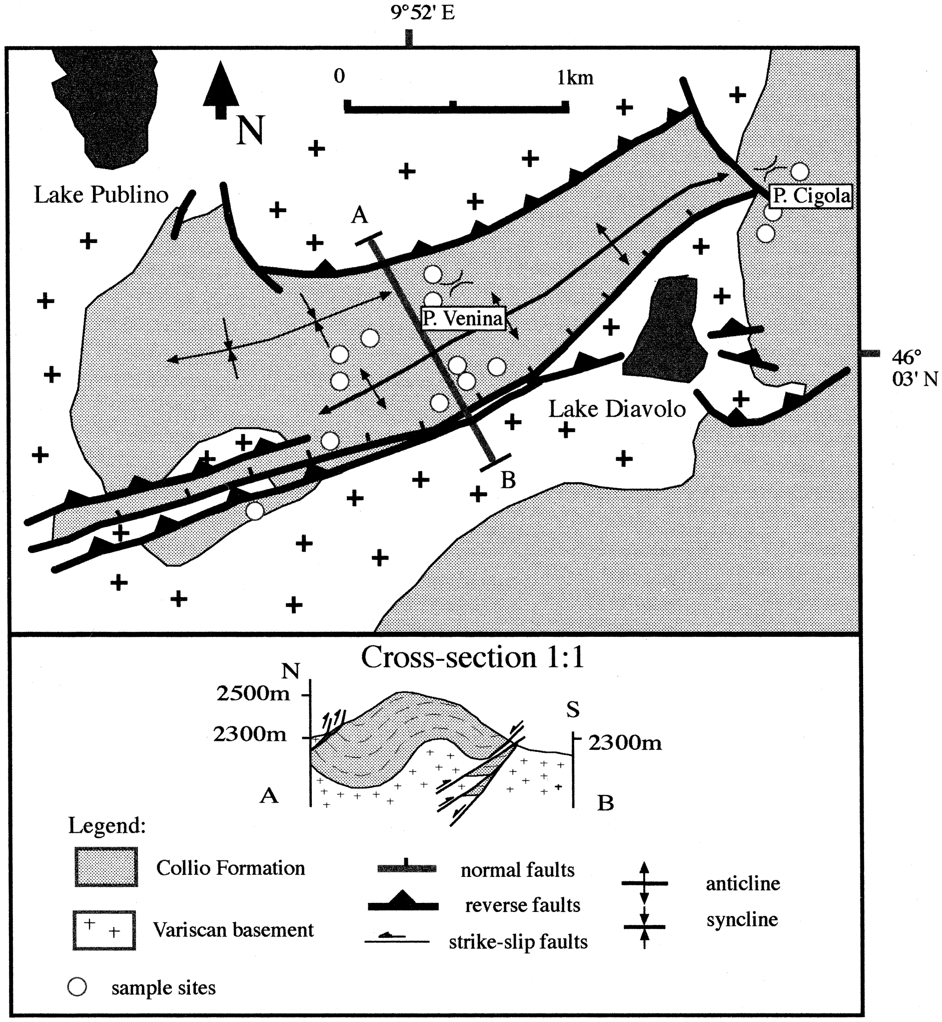

Fig. 2. Geological map and cross-section of the study area (modified after Zhang et al., 1994 and Blom and Passchier, 1997).

tals and crack–seal inclusion bands, suggesting periodic fracturing of the wall-rock.

Striped bedding-veins are commonly folded due to bedding-parallel shortening and are then cut by the S_1 cleavage. V_1-veins are normally not folded because they are oriented parallel to the S_1 cleavage planes and the S_1 cleavage is invariably associated with the folds. This shows that striped bedding- and V_1-veins formed early during S_1 development. For this study, only non- to weakly folded striped bedding-veins were used, since the internal structure of the veins is destroyed by the dynamic recrystallisation that accompanies folding. Most V_2-veins are later than the main folding event in the area or they developed very late during folding and do not have a consistent orientation with respect to the striped bedding-veins. The internal structure of V_2-veins is not discussed further as they are not associated with the striped bedding-veins that are the subject of this study.

3.2. Internal microstructure of the striped bedding-veins

Three different microstructures can be distinguished in the striped bedding-veins: (1) crack–seal inclusion bands (crack–seal bands); (2) inclusion trails; and (3) grain boundaries of crystals (Fig. 3). The inclusion trails and the crack–seal bands can be used to determine the opening direction and the amount of opening of the veins. Inclusion trails and crack–seal bands

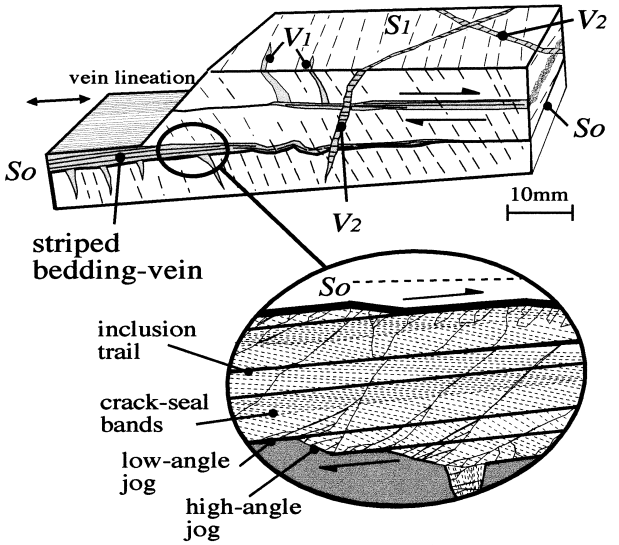

Fig. 3. Three different systems of veins can be distinguished in the field: striped bedding-veins; cleavage-parallel veins associated with the striped bedding-veins (V_1); and later vein systems (V_2). Arrows indicate the displacement direction. The inset shows the relative orientation of inclusion trails, crack–seal bands and elongate crystals. The S_1 cleavage is partly cut off by the striped bedding-veins but some of the cleavage seams cut the veins. V_1-veins are parallel to the S_1 cleavage.

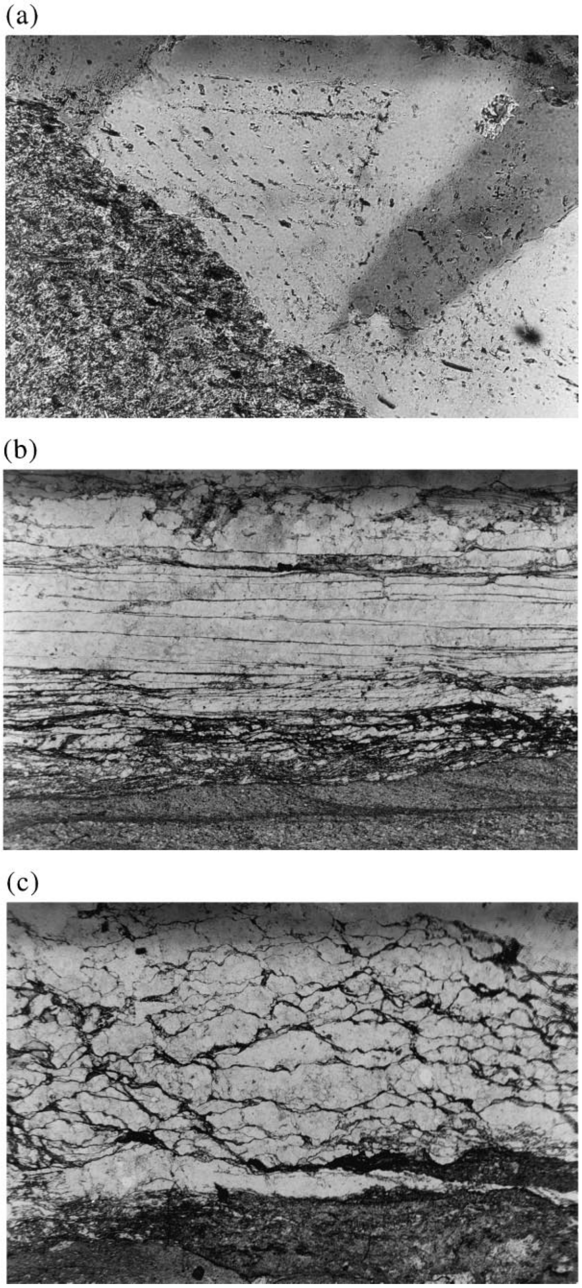

Fig. 4. (a) Crack–seal inclusion bands reflecting the morphology of the wall-rock. The vein is cut parallel to the vein lineation. The displacement is parallel to the lines connecting jogs in inclusion bands, i.e. parallel to the lower side of the image. Grain boundaries of crystals that can be seen at the upper right-hand side of the image do not track the opening of the vein. Width of view is 0.15 mm. Crossed polars. (b) Part of a striped bedding-vein cut parallel to the vein lineation. The wall-rock is located in the lower part of the image, the vein in the upper. Shear sense is sinistral. Bedding is horizontal. The inclusion trails are the dominant microstructure in the veins and form straight bands. Width of view is 20 mm. Plain polarized light. (c) Striped bedding-vein cut perpendicular to the vein lineation. The wall-rock is located in the lower part of the image, the vein in the upper. Bedding is horizontal. The inclusion trails are wavy and branching. Width of view is 3 mm. Plain polarized light.

form by different mechanisms and have different orientation with respect to the opening trajectory of veins, as outlined below.

Inclusion trails are always present whereas crack–seal bands, reflecting the wall-rock morphology, are not as common. The crack–seal bands and the inclusion trails are parallel to two different sets of jogs on the initial fracture surface, high-angle and low-angle jogs (Fig. 3). The distinction refers to the angle between jogs and the fracture surface. The angle of low-angle jogs is exaggerated in most drawings in this paper for clarity. The two differently oriented sets of jogs form a stair-stepping symmetry. If the initial fracture is not exactly bedding-parallel but one set of jogs is, then the displacement of the vein can be bedding-parallel but the vein itself will make an angle to bedding. If the vein is bedding-parallel then the displacement has to be at an angle to bedding and none of the jogs is bedding-parallel. The striped bedding-veins presented in this study are mostly parallel to bedding, inclusion trails and the displacement are parallel to low-angle jogs and crack–seal inclusion bands are parallel to high-angle jogs (Fig. 3).

3.2.1. *Crack–seal bands*

Crack–seal bands in the striped bedding-veins are arrays of inclusions of biotite and white mica with a grain-size of less than 5 μm that lie parallel to high-angle jogs in the vein wall-rock. They cannot be seen macroscopically and are never parallel to bedding or to the lineation in the veins. Single crack–seal bands have exactly the same morphology as the adjacent wall-rock, with small jogs in the wall-rock reflected by identical jogs in the crack–seal bands (Fig. 4a). Very pronounced jogs can form planes that are parallel to the inclusion trails (Fig. 4a). Crack–seal bands typically lie 6–50 μm apart and form sets of up to 200 parallel bands with a very constant spacing. Crack–seal bands are the most important microstructure in the veins since they can be used as shear sense indicators for an accurate reconstruction of vein wall movement.

3.2.2. *Inclusion trails*

Inclusion trails are the dominant structure in all veins in thin section. They lie at a low angle to the bedding (less than 10°), give the veins their striped appearance and separate sets of crack–seal bands. They consist mainly of white mica and biotite with a grain-size of 5–50 μm. They are about 10–100 μm thick and appear as straight bands in thin sections cut parallel to the vein lineation. The inclusion trails normally connect footwall and hanging wall of a vein (Figs. 3 and 4b) but some of the inclusion trails are discontinuous or cannot be followed across the whole vein. The distance between single straight inclusion trails is variable. In sections perpendicular to the vein

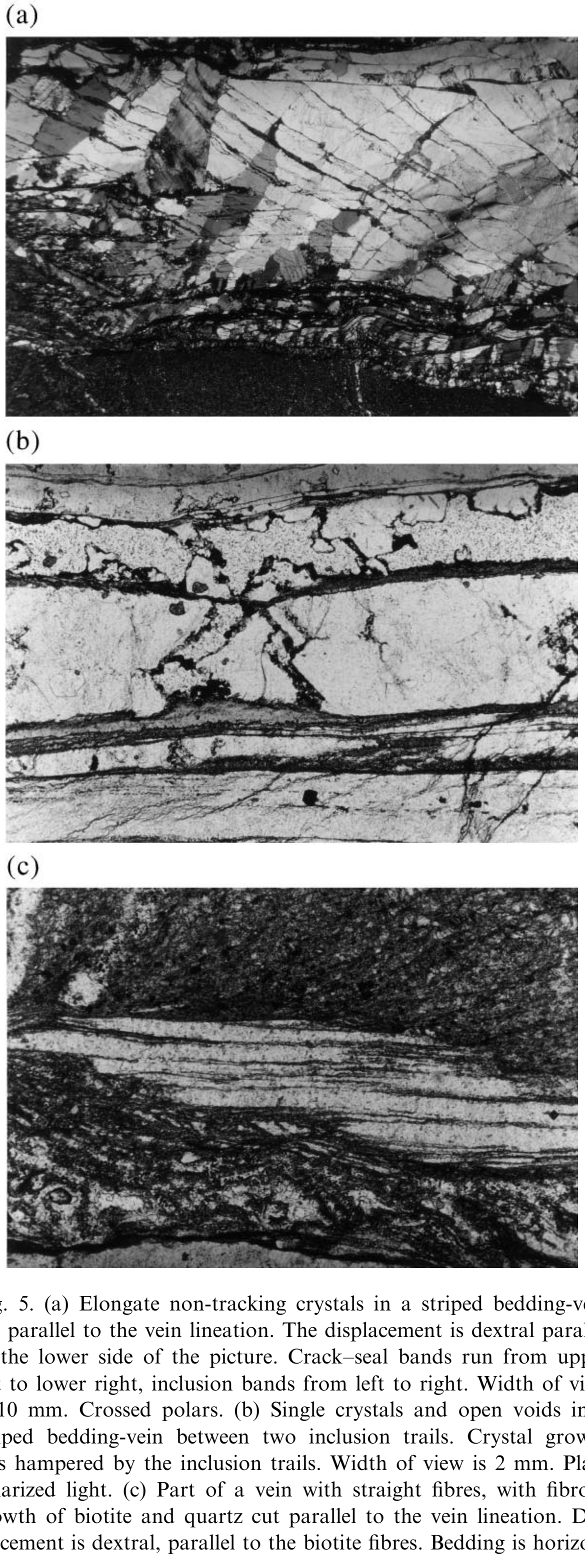

Fig. 5. (a) Elongate non-tracking crystals in a striped bedding-vein cut parallel to the vein lineation. The displacement is dextral parallel to the lower side of the picture. Crack–seal bands run from upper left to lower right, inclusion bands from left to right. Width of view is 10 mm. Crossed polars. (b) Single crystals and open voids in a striped bedding-vein between two inclusion trails. Crystal growth was hampered by the inclusion trails. Width of view is 2 mm. Plain polarized light. (c) Part of a vein with straight fibres, with fibrous growth of biotite and quartz cut parallel to the vein lineation. Displacement is dextral, parallel to the biotite fibres. Bedding is horizontal. These structures superficially resemble striped bedding-veins with inclusion trails, but here biotite grows with a straight fibrous habit next to straight fibrous quartz. No crack–seal inclusions or elongate crystals develop. Width of view is 0.1 mm. Plain polarized light.

lineation, the inclusion trails have a wavy and branching appearance and are discontinuous (Fig. 4c).

3.2.3. Grain boundaries of crystals

Most striped bedding-veins are deformed and crystals show strong undulose extinction, subgrains and evidence for dynamic recrystallisation. In weakly to undeformed veins, however, quartz grains without subgrains can be found. These quartz grains still preserve delicate patterns of solid inclusions and are therefore inferred to represent grains that formed when the veins developed.

The striped bedding-veins show two different kinds of undeformed crystals: elongate/blocky crystals and straight fibres, the former of which are dominant. The elongate crystals have the following appearance: close to the wall-rock, small grains with random crystallographic orientation can be found. Only a few of these grains extend further into the vein and form elongate crystals, mainly those that are oriented with the *c*-axis perpendicular to the wall-rock (Fig. 5a). Usually the grain boundaries extend across inclusion trails, but many crystals terminate on relatively thick trails (Fig. 5b). Isolated large blocky quartz crystals are present between some of the inclusion trails. These contain no crack–seal bands (Fig. 5b) and some show euhedral growth surfaces.

The second kind of crystals are straight quartz or mica fibres (Fig. 5c). They are not very common in the striped bedding-veins and are usually found close to the wall-rock. Adjacent fibrous crystals of mica and quartz are of the same length, about 100 μm. The quartz fibres are approximately 5 μm thick, the mica fibres about 1 μm, and both are oriented with their long axis parallel to the inclusion trails.

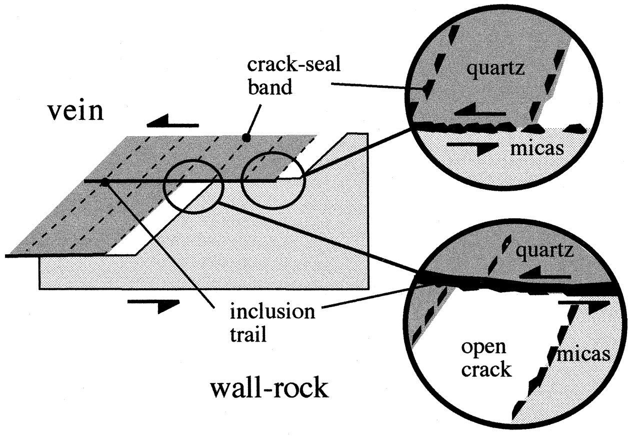

Fig. 6. Schematic illustration of the development of crack–seal bands and inclusion trails. After a cracking event, a fluid-filled space opens and micas grow on the wall-rock and on the inclusion trails while quartz grows on crystals in the vein. Quartz outgrows the micas and seals the void. Micas are detached from the wall-rock during subsequent cracking events and form the crack–seal bands. Detached micas and slivers of the wall-rock form the inclusion trails. Arrows show the displacement during vein opening.

3.3. Interpretation of the microstructures

3.3.1. Crack–seal bands

Crack–seal bands are interpreted to represent single cracking events during the formation of the crack–seal veins (Ramsay, 1980; Ramsay and Huber, 1983). This is envisaged as follows. When a vein cracks along the contact with the wall-rock, it provides space for the growth of new crystals. During the sealing period the crack is filled both from the wall-rock and vein sides, from the former dominantly by small micas, from the latter by quartz (Fig. 6). This may be due to the fact that the wall-rock is a slate and the vein consists mainly of quartz. When the space is filled, the vein opens again along the contact with the wall-rock, and the new grown micas and small parts of the wall-rock are detached from the wall-rock and become part of the vein forming the crack–seal bands (Cox, 1987).

3.3.2. Inclusion trails

Inclusion trails are interpreted to develop along low-angle jogs in the vein, parallel to the movement direction of the vein. Contrary to crack–seal bands, inclusion trails contain larger fragments of the wall-rock. Apparently, these fragments are sheared off the vein wall during an opening event parallel to the inclusion trails. The fracture that develops during an opening event parallel to the inclusion trails is a shear fracture whereas the fracture parallel to the crack–seal bands is mostly extensional. Along a shear fracture, pieces of wall-rock can be plucked off and included in the vein (Fig. 6). They then form part of the inclusion trails, so that inclusion trails are thicker and more pronounced than crack–seal bands. Because of this mechanism, the distance from one side of the vein to the other measured along one inclusion trail must equal the total amount of movement during layer-parallel slip.

3.3.3. Grain boundaries

The crystal microstructure in striped bedding-veins is interpreted as follows. The elongate crystals in the striped bedding-veins apparently nucleate in a part of the vein where single crystals are small and have a random crystallographic orientation. The site of nucleation is commonly close to the wall-rock but can be inside the vein as well. Away from the site of nucleation the crystals start to outgrow each other. Those crystals that are oriented with their fast growth direction perpendicular to the wall tend to become larger and outpace crystals that are less favourably oriented. The surviving larger crystals have an approximately similar lattice preferred orientation and form the elongate crystals that are typical of crack–seal veins.

The elongate crystals grow more or less perpendicular to the crack–seal bands, as these reflect the orientation of the growth surface after a cracking event. They are non-tracking, because the parameters controlling the direction of growth are the crystal habit and the angle between the crack–seal bands and the inclusion trails (Fig. 7). Thus, their direction of growth is not directly influenced by the direction of vein opening and they cannot be used to determine the opening direction of the vein.

Displacement parallel straight fibres of mica and quartz may form by a continuous growth mechanism without the formation of cracks or by a crack–seal mechanism with very small cracks. They do track the opening trajectory of the vein, as they are parallel to the inclusion trails (Fig. 7).

3.4. Model for the development of the striped bedding-veins

From the observed structures we infer that striped bedding-veins form as follows. A shear fracture develops approximately parallel to bedding with high-angle and low-angle jogs (Fig. 8a). Slip along the low-angle jogs at a small angle to bedding results in opening of high-angle jogs oblique to bedding along the fracture. The vein opens periodically by cracking and the resulting voids are mainly filled with elongate quartz crystals and minor mica along the vein wall (Fig. 8b). During each cracking event, small newly grown micas become detached from the wall-rock and form crack–seal bands (Fig. 8c, d). Once the opening vector of the striped bedding-vein exceeds the mean length of the low-angle jogs the vein sectors start to become interconnected (Fig. 8e). Detached fragments of the wall-rock and newly grown micas now lie inside the vein and form the inclusion trails (Fig. 8f, g).

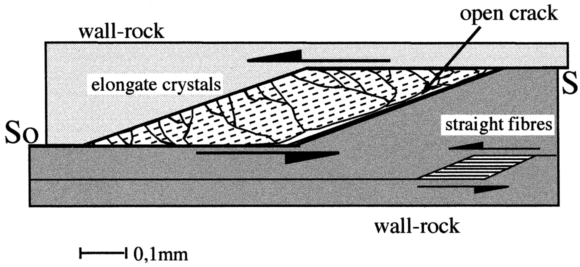

Fig. 7. Schematic illustration showing the difference between elongate crystals and straight fibres. Elongate crystals in the vein in the upper part of the wall-rock grow from upper left towards the lower right into an open crack. No straight fibres develop and elongate crystals outgrow each other. The direction of growth is perpendicular to the crack–seal bands (dashed lines) and is not tracking the opening of the vein which is horizontal (see arrows). Straight fibres in the vein at lower right grow parallel to the displacement direction.

3.5. Nature of the lineation in the striped bedding-veins

Hand specimens of the veins show a well-developed lineation, which in the field seems to be defined by straight (slicken-fibre type) quartz fibres. In fact, it is formed by the inclusion trails that define elongate ribbons, since these are anastomosing in sections cut normal to the vein lineation (Figs. 4c and 9). The anastomosing nature of the inclusion trails is partly due to the geometry of the initial fracture surface along the bedding plane and partly due to dissolution of parts of the vein during bedding-parallel slip (Stanley, 1990; de Roo and Weber, 1992). Although dissolution can explain part of the geometry in Fig. 4(c), they are not stylolites formed from planar surfaces, since individual segments can be traced to jog-segments in the wall-rock and branch lines of low-angle and high-angle jogs are not parallel, but anastomosing as well. The dissolution seams visible in the veins are

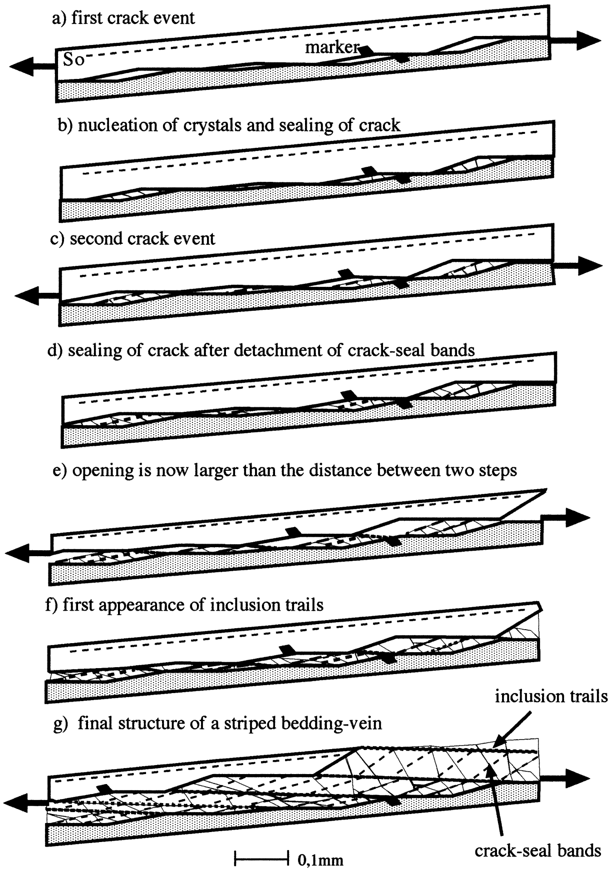

Fig. 8. Schematic diagram showing the development of a striped bedding-vein with crack–seal bands and inclusion trails. The vein forms along jogs on the bedding. There is an angle between the bedding and the opening direction, so that either the displacement or the vein are not exactly bedding parallel. This angle is very small in the field so that it cannot be seen macroscopically and sometimes not even with a microscope. The angle is exaggerated in this drawing for clarity.

not parallel to the opening trajectory of the veins and are associated with the folding of the veins. The inclusion trails in the veins cannot represent pressure solution seams that developed due to the shear movement because elongate crystals that grow across the inclusion trails are not offset. The jogs shown in Fig. 8 in two dimensions may be short segments in three dimensions (Fig. 9). Though the lineation looks similar to slicken-fibres, the elongate crystals in the vein are not growing parallel to the inclusion trails, although they are sometimes bounded by them. The rare slicken-fibres with displacement-parallel fibre growth in the striped bedding-veins mentioned above are too small and too short to be seen in hand specimen.

4. The role of striped bedding-veins in regional deformation

The striped bedding-veins and their complex internal structures allow reconstruction of the deformation sequence in the study area. The main deformation events are thrusting towards the south, folding of sediments, formation of a pressure-solution cleavage (Cassinis et al., 1986; Blom and Passchier, 1997) and bedding-parallel slip resulting in the formation of the striped bedding-veins. The following observations can be made in the field that constrain the timing of different events. Thrusting must start earlier than folding in the area, since the thrust planes are folded on a 100 m scale, where S_1 is the axial-planar cleavage of these folds. The striped bedding-veins cut S_1, and V_1-veins associated with the striped bedding-veins form along S_1, whereas some of the younger pressure solution cleavage seams cut the veins. The cleavage therefore developed over a longer period of time than the veins. The shear sense indicators in the striped bedding-veins, the crack–seal bands (see Section 5), show a consistent displacement of the vein hanging wall towards the south, independent of their location on the limbs of major and minor folds, and the veins tend to wrap over fold hinges in both limbs without a change in thickness. This suggests that the veins are not associated with large scale folding or layer-parallel slip during folding (Jessell et al., 1994; Fowler and Winsor, 1997; Cooke and Pollard, 1997) but rather with thrusting of sediments towards the south. The large-scale folds must have developed later, probably at the same time as cm-scale folds in the veins.

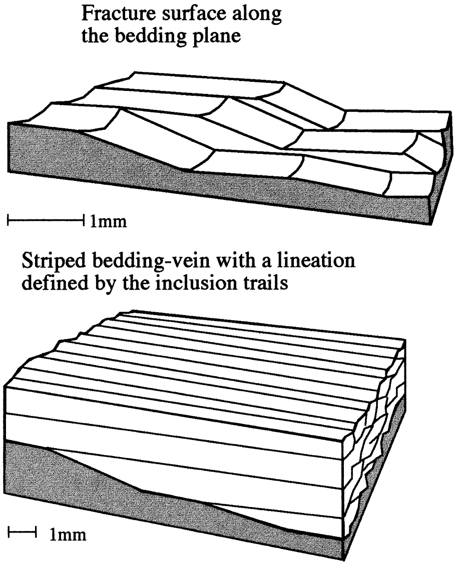

Fig. 9. Three-dimensional geometry of a striped bedding vein with lineations. The direction of movement is dextral, parallel to the vein lineation. The shape of the initial fracture surface determines the form of the inclusion trails and thus the formation of the vein lineation.

The sequence of deformation is reconstructed as follows. The first alpine event in the study area is the reactivation of normal faults as reverse and strike-slip faults accompanied by newly developed thrust faults. Early layer-parallel shortening resulted in the formation of an early S_1 cleavage. Further thrusting towards the south resulted in layer-parallel slip along bedding planes and the formation of the striped bedding-veins. The latest event in the study area is folding of bedding and veins accompanied by an intensification of the S_1 cleavage.

During large-scale folding, the striped bedding-veins developed parasitic folds with wavelengths of 2–5 cm. In the steep limbs of large-scale folds in the Collio Formation, boudinaged striped bedding-veins were observed, which were apparently first shortened, then folded. They rotated from the compressional into the extensional field during folding.

5. Discussion

Several different models have been proposed for the development and interpretation of striped bedding-veins and there has been some debate on how to interpret these veins and the inclusion bands within them. Striped bedding-veins are commonly attributed to flexural slip associated with folding, but in the Orobic Alps we found such veins to be associated with thrusting and to predate folding. Microstructures in striped bedding-veins have earlier been described by Jessell et al. (1994), Cox and Etheridge (1983), Gaviglio (1986), Cox (1987), Mawer (1987), Labaume et al. (1991) and de Roo and Weber (1992). Some of these contain both crack–seal bands and inclusion trails, some only contain crack–seal bands. Jessell et al. (1994) proposed four different models for the interpretation of striped veins containing crack–seal bands and inclusion trails.

Model (1) of Jessell et al. (1994) interprets part of the inclusions as pressure solution seams. Model (2) interprets the inclusion trails as shear bands similar to the models of de Roo and Weber (1992) and Labaume et al. (1991). Model (3) suggests opening of the vein parallel to inclusion trails and in model (4) crack–seal bands and inclusion trails are interpreted similarly and the opening of the veins is thought to be parallel to the crack–seal bands. We favour model (3) of Jessell et al. (1994) for striped bedding-veins from the Orobic Alps, since there is no slip along inclusion trails and displacement is not parallel to the crack–seal bands. The inclusion trails can sometimes be the site of pressure solution (Stanley, 1990; de Roo and Weber, 1992), but this effect is thought to be minor in the veins from the Orobic Alps, as explained in Section 3.5. Jessell et al. (1994) favour model (4), so their interpretation for striped bedding-veins differs from that of model (3) presented in this paper, with a more than 90° difference in the interpreted opening direction. As a consequence, the sense of shear is also different. The model of Cox and Etheridge (1983), Gaviglio (1986) and Cox (1987) for the development of striped bedding-veins is similar to the interpretation in this paper. These authors distinguish between crack–seal bands and inclusion trails and conclude that the opening direction is parallel to the inclusion trails, which is in agreement with our model. Mawer (1987) presented striped bedding-veins that contain two differently oriented inclusion bands that both reflect the morphology of the wall-rock. They are each interpreted as one set of crack–seal bands and these veins contain no inclusion trails.

Based on our observations, we suggest an alternative general classification for striped bedding-veins. Theoretically, the opening direction of striped bedding-veins is restricted by high- and low-angle jogs on the bedding that have a stair-stepping geometry with two end-member opening directions: parallel to low-angle jogs subparallel to bedding (striped bedding-veins of type B) and parallel to high-angle jogs oblique to bedding (striped bedding-veins of type J). All other opening directions are oblique to bedding and to jogs (striped bedding-veins of type O) (Fig. 10). Striped bedding-veins of types B and J have crack–seal bands and inclusion trails, whereas O type striped bedding-veins

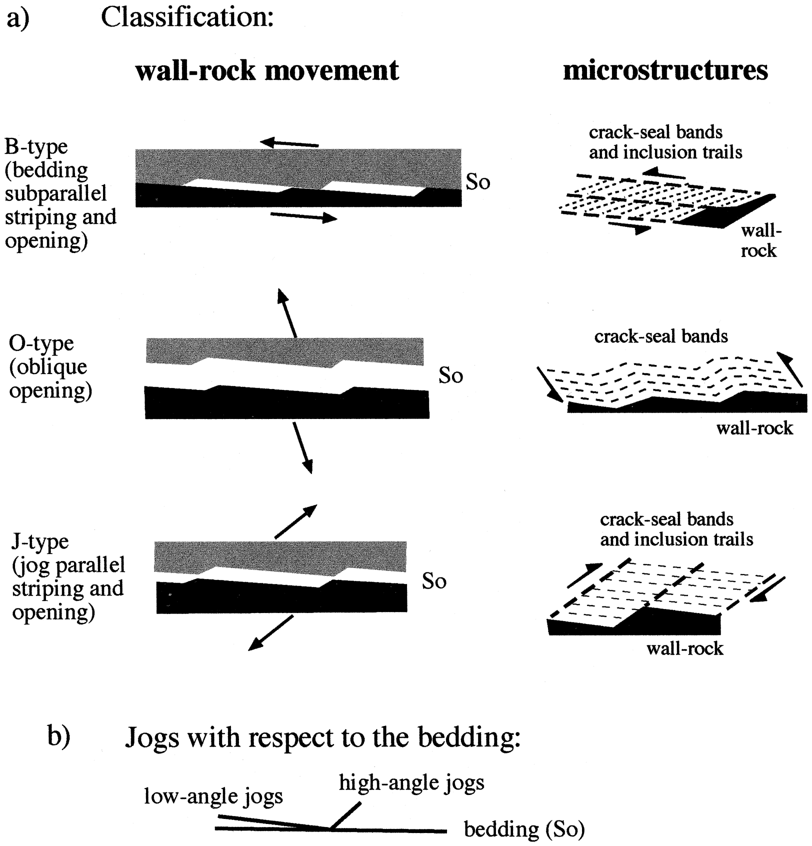

Fig. 10. (a) A proposed classification for striped bedding-veins. B–type striped bedding-veins open along low-angle jogs subparallel to the bedding, J-type veins open parallel to high-angle jogs on the bedding and O-type veins open with an angle that lies between B- and J-type veins. O-type striped bedding-veins develop only crack–seal band whereas J- and B-type striped bedding-veins can have both inclusion trails and crack–seal bands. (b) Orientation of low-angle and high-angle jogs with respect to bedding for a striped bedding-vein.

have crack–seal bands only. Striped bedding-veins from the Orobic Alps, of Cox and Etheridge (1983), Gaviglio (1986), Cox (1987), Labaume et al. (1991), de Roo and Weber (1992) and Jessell et al. (1994) are all of type B whereas the striped bedding-veins of Mawer (1987) are of type O. Veins of J-type are rare, but have been observed in sediments of the southern Pyrenees (Passchier, unpublished data). The distinction is important, since type B and type J veins represent a different shear sense.

The best way to classify striped bedding-veins in our scheme is to make sections parallel to the vein lineation and to identify any inclusion trails that form continuous bands from one side of the vein to the other. If there is no lineation in the veins, they probably contain no inclusion trails at all and are likely to be of type O. Kinematic analysis of the veins can be attempted as follows: The best tool to determine sense of shear is the 'sense' of attachment of inclusion trails to the wall-rock (Fig. 10). Displacement is parallel to inclusion trails, if present. If only crack–seal bands are present, jogs of similar shape in the bands should be identified and displacement is parallel to the line connecting the jogs (Fig. 10). The stair-stepping geometry of jogs in the wall-rock can also be used to determine the shear sense. If the steps in the hanging wall are downwards to the left, the displacement is sinistral for striped bedding-veins of type B and most O-types. O-types approaching J and J-type striped bedding-veins have the opposite sense of shear (Fig. 10). If, due to later deformation or metamorphic overprint, the original crystals and crack–seal bands have been destroyed, movement direction and shear sense can still be determined from the inclusion trails connecting both wall-rocks. Obviously, either large thin sections or favourable outcrop surfaces are necessary for such observations.

Cleavage orientation next to the veins cannot be used to determine the shear sense since the orientation of the cleavage with respect to the vein may vary depending on the location of the vein in different fold limbs, as it does in the Orobic Alps.

Finally, the thickness of striped bedding-veins may be used as a measure of finite strain in a rock pile: with increasing displacement on the veins, their thickness will gradually increase. This means that, if data can be obtained on the shape and size of the jogs, and spacing and number of the inclusion trails, the thickness of the veins can be used to measure the amount of total slip along the vein.

6. Conclusion

This study shows how striped bedding-veins can be used to determine the direction and amount of displacement of sedimentary layers during layer-parallel slip. Three types of striped bedding-veins can be distinguished, B, O and J depending on the opening direction. All types may contain crack–seal bands but only B- and J-types contain solid inclusion trails. Steps in the wall-rock, the orientation and form of the inclusion bands and trails, and vein thickness can be used to evaluate the sense of shear and the amount of displacement. Elongate fibrous-looking crystals in striped bedding-veins are not tracking the displacement direction and cannot be used to determine the opening trajectory of the veins.

The vein lineation that is visible in hand specimen is formed by the inclusion trails and can be used to determine the direction of movement. To evaluate the sense of shear one has to look at the orientation of crack–seal bands with respect to inclusion trails in thin sections that are cut parallel to the vein lineation (Fig. 10). It is difficult to determine the sense of shear in hand specimen, as the angle between crack–seal bands and the bedding is commonly very small and obscured by deformation, and it is hard to see stair-stepping in the wall-rock. As a result, it is not easy to establish from which side of the wall-rock the lineation starts. The opening of the veins is parallel to the lineation, but the sense of shear is not always clear. If crack–seal bands are absent, jogs in the wall-rock are the only sense of shear indicators in this type of vein.

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