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Geometric constraints on the development of shear bands in rocks

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Abstract

Shear bands in ductile shear zones have been used to determine sense of shear, but they also contain information on the flow pattern and flow history in shear zones. A simple geometric analysis of two types of shear bands, S-C fabrics and extensional crenulation cleavage (ECC) fabrics, is used to delimit possible flow patterns and flow history in shear zones where such structures develop. S-C fabrics can form in bulk simple shear during the entire active period of a shear zone. Development of ECC-fabrics as observed in nature, however, is favoured by bulk extension of the shear zone as a whole. This means that such fabrics preferentially develop in an extensional tectonic setting, or in a constrictional tectonic setting during late stages of activity on ductile shear zones, when flow in the zone develops from bulk simple shear to bulk non-coaxial extension.

Introduction

Ductile zones are important structures in crustal tectonics since they can accommodate a large fraction of the locally imposed bulk deformation. Knowledge of the movement direction and sense of shear in exhumed large-scale ductile shear zones is essential for the reconstruction of the regional tectonic history in orogenic belts. In order to correctly interpret the role of shear zones in regional tectonics, it is important to know whether the wall rocks were deforming while the shear zone was active, i.e. whether flow in the zone deviated from simple shear. In theory, shear zones may be stretching or shortening during their active periode (Fig. 1). Fabric elements in natural shear zones which can give information on flow conditions are therefore of great interest to geologists. This paper concentrates on one such fabric element – shear bands.

Shear bands

Shear bands are sets of regularly spaced minor shear zones which truncate an older fabric in deformed rocks. Two types have so far been distinguished in the geological literature; S-C fabrics (Berthé et al. 1979, Lister & Snoke 1984) and extensional crenulation cleavage (ECC-fabrics; Platt & Vissers 1980, Platt 1984, Dennis & Secor 1987).

(1) S-C fabrics

An S-C fabric (Fig. 2a) consists of a foliation or S-planes (abbreviated from the French 'Schistosité-foliation), transected at regular intervals by parallel minor shear bands or C-planes (from the French 'Cisaillement'-shear). S-planes show a characteristic deflection into the C-planes in response to displacement along the latter (Fig. 2a).

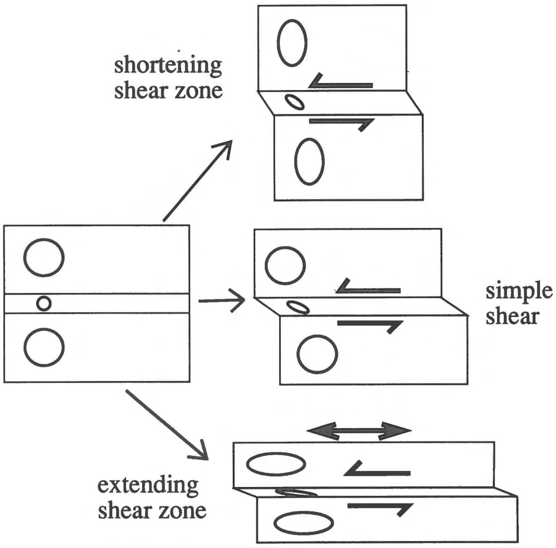

Fig. 1. Three basic types of ductile shear zones.

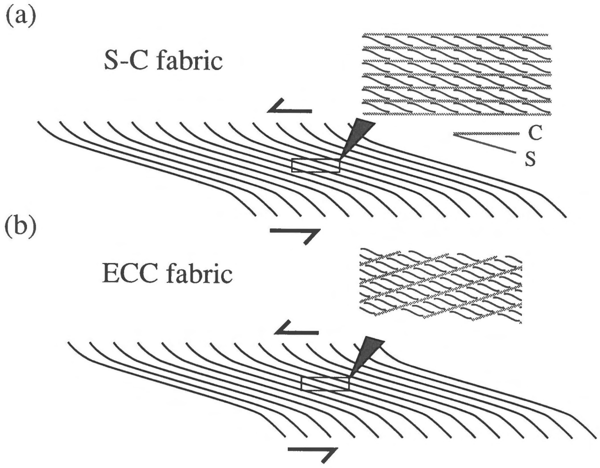

Fig. 2. Two types of shear bands. S-C fabric has shear bands parallel to shear zone boundaries. ECC-fabric has shear bands oblique to shear zone boundaries. Solid lines; foliation in shear zone. Grey lines; shear bands.

C-planes are subparallel to the edge of the major shear zone in which they are generated. Where several stages in the development of an S-C fabric can be observed, S and C-planes can be seen to develop synchronously, although the S-planes may start to develop first. S-C fabrics seem to be a result of flow partitioning in a shear zone, with alternating zones of high strain rate (C-planes) and low strain rate (domains in which S-planes are visible).

(2) Extensional crenulation cleavage

Extensional crenulation cleavage (or ECC-fabric) was described by White (1979) and Platt & Vissers (1980) as a regularly spaced set of minor shear bands oblique to an older foliation (Fig. 2b). The name derives from the observation, that displacement on the shear bands induces a bulk extension in the direction of the older foliation planes (Platt & Vissers 1980). ECC-fabrics differ from S-C fabrics by the orientation of the shear bands, which are oblique to the edge of the shear zone in which they develop (Fig. 2b), and which are usually shorter and of a more anastomosing nature than C-planes. Such anastomosing shear bands tend to divide the rock into lozenge-shaped domains. Although conjugate sets of shear bands do occur in some cases (Harris & Cobbold 1984, Behrmann 1987), one set is usually dominant. This set has a characteristic orientation with respect to the foliation and kinematic framework of the shear zone; it dips in the opposite direction to the main foliation at an angle to the edge of the zone (Fig. 2b). This symmetry can be used to determine shear sense. In addition, sense of shear in both ECC and S-C fabrics can be determined from the arrangement of the small angle between the older foliation and the shear bands, and by the deflection of the older foliation into the shear bands (Fig. 2b). Contrary to S-C fabrics, ECC-fabrics seem to develop only during the very last stage of shear zone activity (Platt & Vissers 1980). ECC-fabrics are most common in well-foliated rocks such as schists and phyllites, but have also been observed in quartzites with a strong crystallographic preferred orientation (Gapais & White 1982).

Development of extensional crenulation cleavage

Shear bands are not restricted to rocks, but are also common in metals, where they have been studied extensively. ECC-type shear bands develop in response to hardening in highly deformed metal samples with a strong crystallographic preferred orientation, at an angle of approximately 35° to the surface of flattened metal sheets (Fargette & Whitwham 1976, Dillamore et al. 1979, Malin & Hatherly 1979). Their number increases with progressive deformation, and they may replace most of the old deformed fabric in the sample (Fargette & Whitwham 1976). Geometric softening is considered to be the main reason for shear band growth (Dillamore et al. 1979).

In rocks, ECC-fabrics also seem to develop in response to hardening by flow localisation in a shear zone (Platt & Vissers 1980, Gapais & White 1982). The fact that usually only one shear band set develops instead of a conjugate set can be put down to the asymmetric orientation of the anisotropy in the rock with respect to the potential shear bands; the shear bands which lie at a small angle to the anisotropy develop preferentially (Platt & Vissers 1980). One important difference between ECC-fabrics in rocks and in metals is, that in rocks they develop in the last stage of shear zone activity and rarely, if ever, destroy a large volume of the older fabric. In the past, studies of shear zones in rocks have concentrated on the rheological aspects of shear band genesis, and little attention has been paid to the geometry of progressive deformation by which shear bands develop; bulk simple shear is often assumed (Dennis & Secor 1987, McCaig 1987). Nevertheless, spectacular shear bands in metals are formed in rolling, not in simple shear. The fact that shear bands in rocks develop only in late stages of shear zone activity has been attributed to increasing strain and associated fabric buildup and hardening (Platt & Vissers 1980, Gapais & White 1982). However, changes in the geometry of the instantaneous flow field with time may also play a role.

As yet, little is known about flow geometry associated with ECC-fabrics in rocks. This is mainly due to the fact, that it is difficult to obtain reliable data from natural shear zones on factors such as deformation history in the shear zone, initial orientation of shear bands, bulk and local finite strain, and bulk and local volume change. As a result, too few parameters are constrained to successfully model shear band development in the laboratory or in computer simulations. One way to proceed from this point would be the study of shear zones with an ECC-fabric, in which special circumstances help to constrain deformation and flow parameters; for example, where quartz veins form during shear band growth, or intrusions transect the shear zone at various stages of ECC-development. In the absence of any reported natural shear zones of this sort, the second best approach is to see which restrictions on possible flow patterns and deformation history sequences are implied by the geometry of ECC-fabrics observed in nature. This approach is followed here.

Geometric constraints on ECC-development

Consider the following simple two-dimensional model (Fig. 3). A planar shear zone between wall rock blocks is subdivided into two sets of elongate domains, shear bands and relic domains. During ECC-development in this model, flow patterns in shear bands and relic domains are different, but are homogeneous in both. Flow patterns are constrained by the fact that relic domain and shear band share a common material line. Bulk flow in the shear zone is defined by the rotation rate and stretching rate of the lines *a* (parallel to the shear zone boundary) and *b* (the boundary of shear bands and relic domains); the deformation of *a* and *b* represents the 'mean deformation' measured over both shear bands and relic domains. A 'space problem' exists at the edge of the shear zone in this model, but since no mean volume loss or detachment of shear zone and wall rock is implied, and a change in length of *a* is balanced by identical stretch in the wall rock, it does not affect the results of this study. In natural deformation or in a more complex model, a deformation gradient towards the edge of the shear zone would accommodate this space problem. Additional constraints on the model, based on observations on natural ECC-fabrics, are as follows;

(1) flow in shear band and relic domain must be such that after deformation the strain in shear bands exceeds that in relic domains;
(2) sense of shear in shear bands should be of the same sign as in the bulk zone;

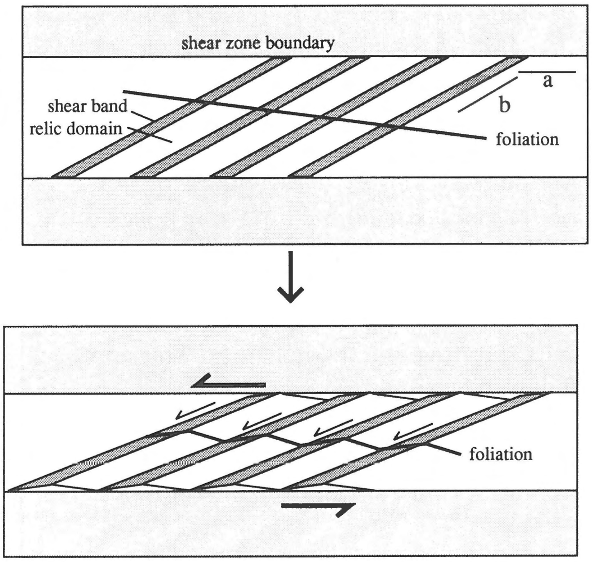

Fig. 3. Model of shear band development as used in this study. The shear zone is divided into two sets of domains; shear bands, and relic domains. a and b are material lines used to calculate bulk deformation in the shear zone. a is parallel to the shear zone boundary; b is parallel to shear bands.

(3) a material line representing the foliation in the rock should stretch under all circumstances, both in shear bands and in relic domains;

(4) area change in the plane of observation (volume change in 3D-plane strain) is allowed.

The model can be used to study the geometric consequences of the development of ECC-fabrics. It only models part of the total deformation history of a shear zone, from the moment shear bands start developing. Two end-members in a range of possible deformation patterns can now be distinguished (Fig. 4);

(1) The relic domains remain undeformed, and all deformation is concentrated in the shear bands (Fig. 4a). In this case, the entire shear zone must stretch, and the wall rock will be deformed. The angle between shear bands and edge of the shear zone decreases with progressive deformation; the shear bands rotate in opposite direction to local sense of shear.

(2) The wall rock of the shear zone remains undeformed (Fig. 4b). This situation was investigated by Dennis & Secor (1987) in the case of simple shear flow parallel to foliation planes in the relic domains. Here a more general approach is taken, because the actual flow patterns in natural shear bands and relic domains are unknown. Whatever the flow patterns and flow history involved, the geometry of ECC-fabrics as seen in nature can only be formed between rigid wall rocks if both relic domains and shear bands shorten parallel to their long axis. In this case, the angle between shear bands and the edge of the shear zone *increases* with progressive deformation. Although this type of deformation pattern should be common if bulk flow in shear zones is by simple shear during ECC-fabric development, it seems to be uncommon in nature (S. White 1990, pers. comm). In order to investigate this enigma, a more quantitative approach to the problem of ECC-fabric development is outlined below.

Fig. 5 illustrates deformation in a simple system of an adjacent shear band (SB) and relic domain (RD) where the shear zone boundary (and thus the wall rock) remains undeformed, as for progressive bulk simple shear parallel to shear zone boundaries. An undeformed shear zone boundary is modelled by a diagonal Z which has the same length in the deformed and undeformed state. It is now possible to derive simple equations which express the amount of shear strain possible on shear bands in a shear zone with undeformed wall rock as a function of volume change, stretch on shear bands, and the angle between shear bands and the shear zone boundary. The equation:

$$\gamma = \frac{-R^2\cos\alpha \pm \sqrt{R^2 - V^2\sin^2\alpha}}{R\sin\alpha} \qquad (1)$$

expresses the amount of *permissible* shear strain ($\gamma = g/q$) on shear bands referred to the undeformed state as a function of volume change

$$V = \frac{ac}{pq}$$

(deformation is assumed to be by plane strain), stretch on shear bands $R = c/p$ and an angle α. α is a constant, the initial angle between the shear band and the shear zone boundary at the onset of shear band activity. Using equation (1), a shear zone with

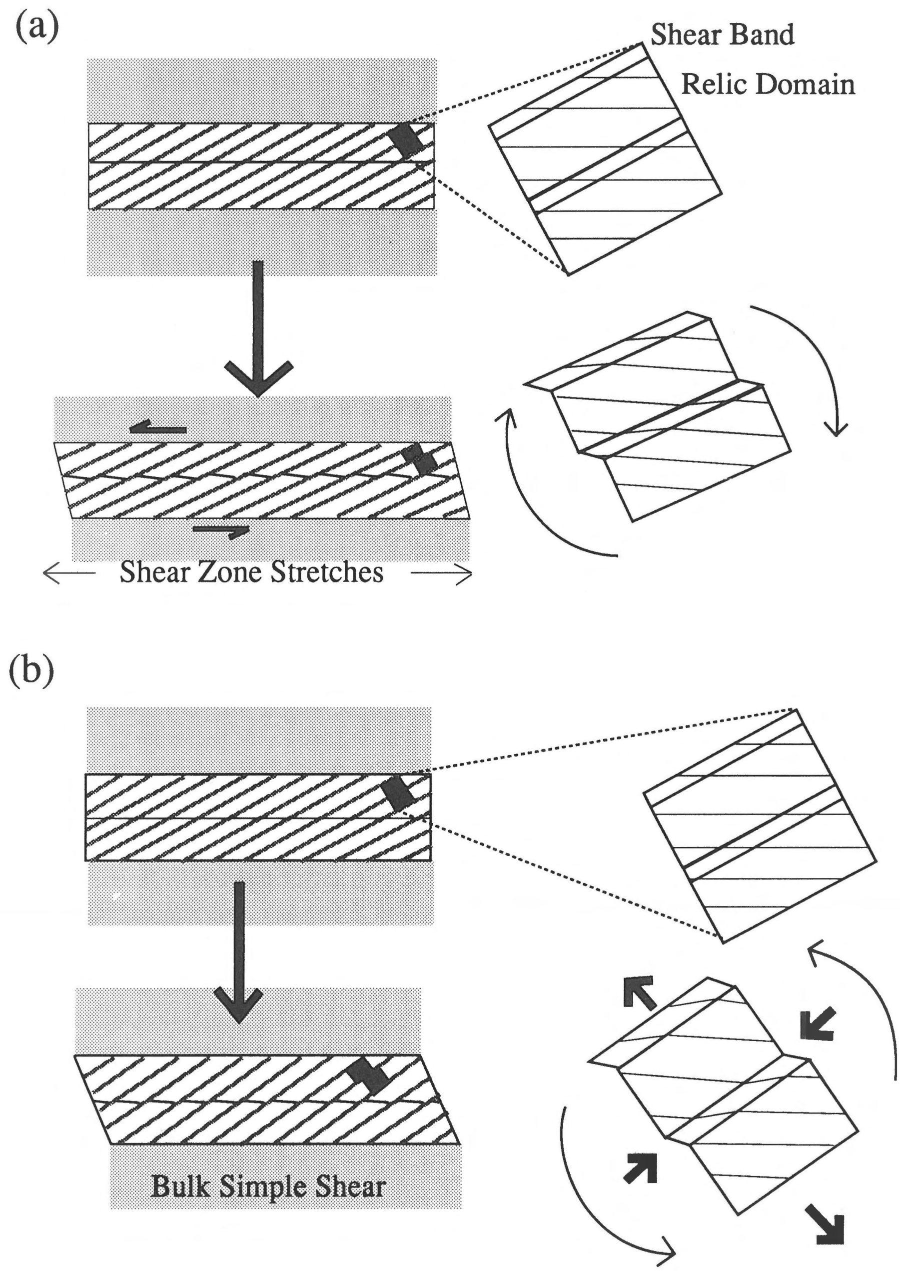

Fig. 4. Two end-member situations in the development of an ECC-fabric. Deformation geometry in the shear zones enlarged at right; (a) relic domains remain undeformed, the shear zone stretches and shear bands rotate against bulk sense of shear; (b) deformation in the zone is by bulk simple shear – the relic domains and shear bands are shortened and shear bands rotate in same direction as bulk sense of shear.

undeformed wall rocks (such as bulk simple shear) can be illustrated as a surface in $R - \alpha - \gamma$ space (Fig. 6). Shear bands in the model only have sinistral shear sense, as in the natural situation, for positive values of γ; for this reason, only possitive values of γ are plotted in Fig. 6. The three surfaces in the graph represent three different values of V. The volume above the graphs represents a bulk

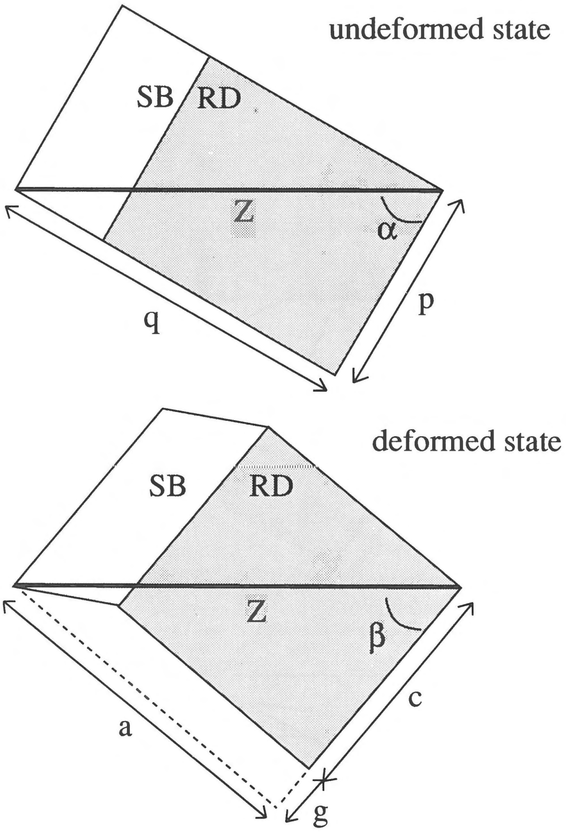

Fig. 5. Geometry of shear band (SB) and relic domain (RD) used to calculate the relationship of stretch on shear bands, volume change and shear strain along shear bands in a shear zone deforming by bulk simple shear. Line Z is parallel to the shear zone boundary and does not stretch. Explanation in text.

extending shear zone; the volume below the graphs a bulk shortening shear zone (Fig. 1). The following conclusions can be drawn from Fig. 6:

(1) If shear bands are initially inclined to the shear zone boundary (α≠0), an increasing amount of relic domain-shortening is necessary with increasing shear strain on shear bands, in order to maintain compatibility in bulk simple shear.

(2) For increasing values of α, the maximum amount of shear strain which can be reached in a shear zone decreases. Notice that this statement refers to changes in the initial angle α, not to changes in the angle between shear bands and shear zone boundary with progressive deformation; such changes cannot be read from the graph. If α exceeds 45°, no simple shear flow is possible parallel to shear zone boundaries in isochoric flow. In the case of volume increase, this critical initial angle decreases; in the case of volume decrease, it increases.

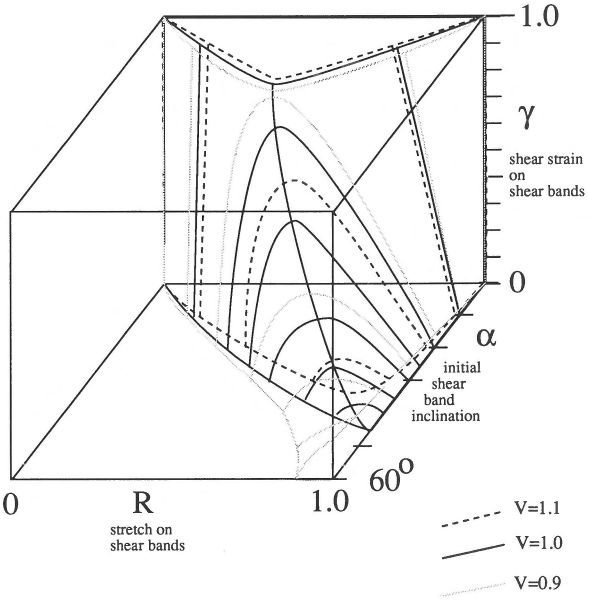

Fig. 6. Surfaces of bulk simple shear in a three dimensional space where shear strain on shear bands (γ) is plotted against stretch on shear bands (R) and initial shear band inclination (α). Three surfaces are shown for three values of volume change in plane strain.

(3) If relic domains are not, or little deformed (R≈1), deformation in a situation with inclined shear bands (α≠0) is *only possible in a shear zone which is undergoing bulk extension.*

(4) The influence of volume change on the effects described above is limited, except in the case of very steep bands and/or small amount of shear strain on shear bands.

In natural ECC-fabrics, the foliation in relic domains and shear bands is rarely buckled but is either unaffected by shear band development, or is extended (Platt & Vissers 1980). It is interesting to investigate the effect of imposing this additional constraint on the model described above. If it is stipulated that the foliation must extend both in shear bands and relic domains, it turns out that only a very limited amount of deformation is possible on shear bands in the case of gently dipping foliations. It is unlikely, that such a weak deformation would actually be noticable in a deformed rock. If the foliation is parallel to shear zone boundaries, bulk simple shear in the shear zone is *not possible at all* for inclined shear bands. In that case, shortening of the relic domains would always lead to shortening of the foliation.

Natural ECC-fabrics

Equation (1) and Fig. 6 are interesting for modelling purposes, but of little use to the geologist who wishes to investigate natural shear zones. In the latter case, the angle β between shear band and shear zone boundary in the *deformed* state should be used in the equation. Equation (1) can be rewritten to serve this purpose to give:

$$\delta = \frac{V\cos\beta \pm R\sqrt{V^2 - R^2\sin^2\beta}}{V\sin\beta} \qquad (2)$$

where $\delta = g/a$ (Fig. 5) and β is the angle between the shear bands and the shear zone boundary in the deformed state. Using this equation, a shear zone with undeformed wall rocks (bulk simple shear) can be illustrated as a surface in $R - \beta - \delta$ space (Fig. 7). Only positive values of δ are plotted, as for γ in Fig. 6. Again, the three surfaces in the graph represent three different values of V, the volume above the graph represents a bulk extending shear zone, the situation below the graph a bulk shortening shear zone.

In natural shear zones, ECC-fabrics can show many different geometries, but most commonly single sets of shear band are developed at an angle of 15–30° to the shear zone boundary (Fig. 2b; Platt & Vissers 1980, Gapais & White 1982). Spectacular examples of ECC-fabric as observed in the Betic Cordilleras (Platt & Vissers 1980) and the Merens shear zone (McCaig 1987) are characterised by large values of shear strain on the shear bands (exceeding 0.5 in many cases). It will be clear from Fig. 7, that for β-values exceeding 20° such shear bands can only be compatible with an undeformed wall rock if relic domains are strongly deformed during shear band activity. In many cases, as in the Merens mylonites (McCaig 1987) changes in mineral composition or chemistry take place preferably along shear bands, not in relic domains. If these reactions are aided by deformation-enhanced diffusion, it suggests that relic domains were little or not deformed. Bulk simple shear therefore seems unlikely; an actively *extending* shear zone could explain the observed geometry much better. Volume increase, observed in some cases where ECC fabrics have been studied in detail, enlarges the extension domain in Fig. 7 and makes an extensional nature of these shear zones even more likely.

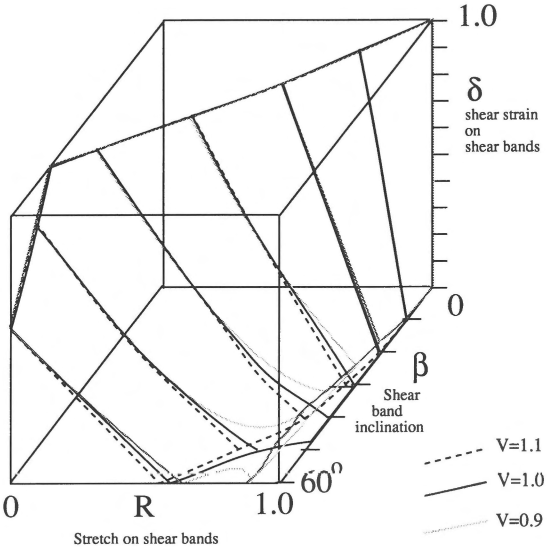

Fig. 7. Surfaces of bulk simple shear in a three dimensional space where shear strain on shear bands (δ) referred to finite length is plotted against stretch on shear bands (R) and final shear band inclination (β). Three surfaces are shown for three values of volume change in plane strain.

Discussion

The previous sections lead to the suggestion, that spectacular examples of extensional crenulation cleavage are restricted to situations in which the shear zone is stretching actively. Obviously, bulk simple shear is an ideal situation which is unlikely to dominate in nature, but why, in that case, would stretching shear zones dominate over shortening ones? In large scale extension terrains like the Basin-and-Range, a shear zone may be actively ex-

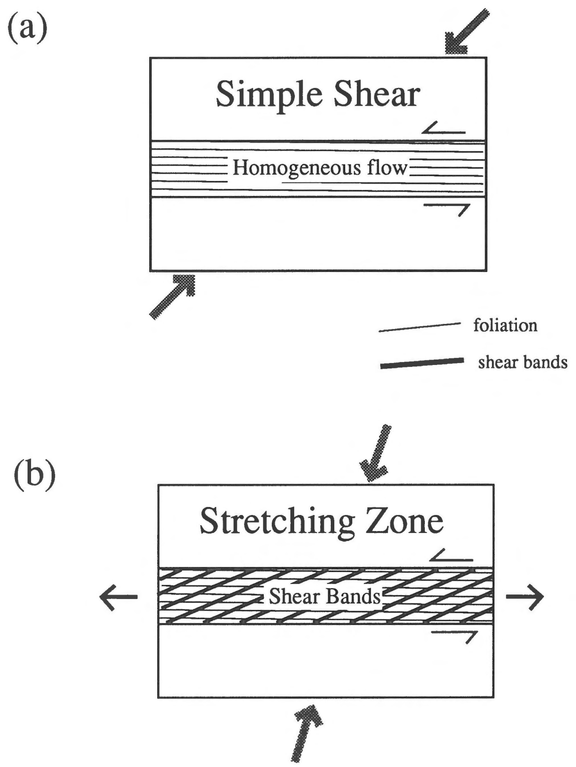

Fig. 8. A change in the orientation of the bulk shortening direction can induce deformation in the walk rock of a shear zone, and thereby shear band development if a foliation was present at a small angle to the shear zone boundary.

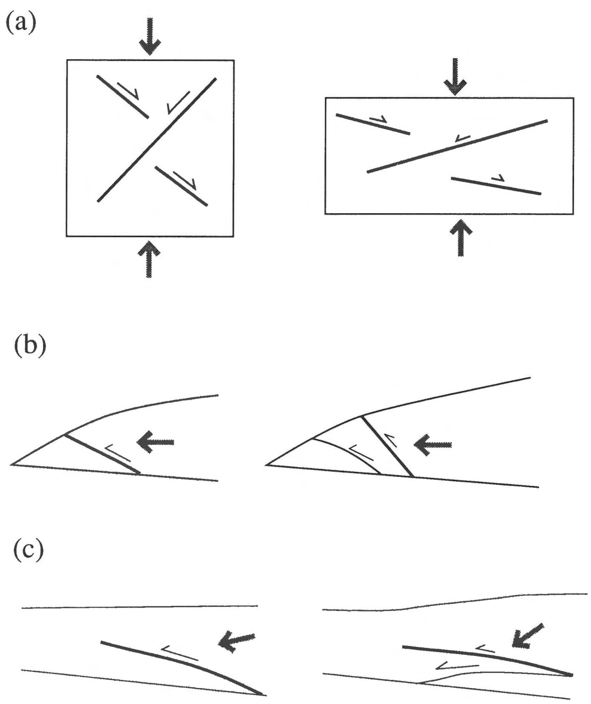

Fig. 9. Three tectonic settings in which rotation of shear zones is associated with an increasing angle between the bulk instantaneous shortening direction (grey arrows) and the shear zone boundary; (a) conjugate shear zones in bulk pure shear; (b) shear zones in an accretionary prism, uplifted by imbricate stacking at the front of the wedge and; (c) shear zones uplifted by imbricate stacking at the back of the wedge, leading to local horizontal extension in the active prism.

tending during its entire active life, and an ECC-fabric may develop in a late stage when hardening sets in (e.g. Malavielle & Cobb 1986, Davis et al. 1987, Saltzer & Hodges 1988). Indeed, spectacular ECC-fabrics are very common in such settings (Lister & Snoke 1984). Many ECC-fabrics, however, can be found in transcurrent or constrictional mobile belts. These must be explained in another way.

The fact that ECC-fabrics develop late in the history of most shear zones may mean, that a change in conditions causes the shear zone to develop from an approximately simple shear zone to an extending one. One effect, hardening in the shear zone (due to strain hardening, changing P-T conditions or fluid composition) can cause a late deviation from simple shear if ductile deformation is initiated in the wall rock. This, however, cannot explain the common occurrence of extending shear zones, since the stress field would be reoriented in such a way upon hardening that bulk *shortening* of the shear zone would be favoured. Displacement along shear zones, however, causes the zones to rotate with respect to the bulk (regional) shortening field, and this factor may be responsible for ECC-fabric development. If a shear zone would rotate away from the bulk shortening direction (Fig. 8), bulk imposed strain rate may not all be accomodated along the zone, and either new steep zones are activated, or the wall rock will have to deform to accommodate imposed deformation. The shear zone will stretch in this situation before its active life is ended, and an ECC-fabric may develop in response to the presence of a strong crystallographic preferred orientation or foliation (Fig. 8). Three common settings of shear zones in constrictional situations are used as examples to illustrate this effect (Fig. 9).

(1) Displacement on conjugate sets of shear zones in bulk coaxial shortening will cause rotation of the zones away from the bulk shortening direction (Fig. 9a).

(2) Shear zones which delimit imbricates in the toe of a constrictional wedge may become uplifted and steepened when new imbricates are accreted. As a result, the angle between the zone and the bulk shortening direction increases (Fig. 9b).

(3) Shear zones with a relatively shallow dip in the back of a constrictional wedge may become extended in a late stage of their activity when new material is accreted to the bottom of the wedge; the entire wedge, including the shear zone will stretch at this stage due to a decrease in the surface slope of the wedge (Fig. 9c; Platt 1986).

Conclusions

Well developed ECC-fabrics with a large shear strain on shear bands can develop more easily in stretching shear zones than in shear zones with bulk simple shear flow. In shear zones with undeformed wall rocks they are expected to be uncommon. Shear zones in extensional tectonic belts are expected to show spectacular ECC-fabrics. Shear zones in transcurrent or constrictional orogenic belts may develop as simple shear zones, but end their active life as stretching shear zones. In this final stage, ECC-fabrics may develop.

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