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Flanking structures

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Abstract

Flanking structures are deflections of planar or linear fabric elements in a rock alongside a cross-cutting object such as a vein, fracture or burrow. Flanking structures are divided into flanking-folds and flanking shear-bands. Both structures can develop by a range of mechanisms including intrusion or in situ formation of veins that bisects existing fold trains or shear-bands along the axis of the structure; flow partitioning alongside an active fault in a ductilely deforming rock; passive rotation of a vein with attached narrow rim of wall rock formed by alteration of the wall rock during intrusion of the vein; development of a shear zone in or along a pre-existing vein; and passive amplification of small deflections alongside a vein or burrow. Flanking structures can be used to establish a sequence of deformation and intrusion or partial melting, and some types of flanking structures can be used as shear sense indicators or to determine finite strain. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Many deformed rocks contain cross-cutting sets of straight planar or linear fabric elements (Fig. 1). Elements such as faults or veins (referred to in this paper as cross-cutting elements) cut older and more pervasive elements such as layering, foliations or older vein sets (referred to in this paper as the host-fabric element). If the cross-cutting element (CE) and the host fabric element (HE) have been subject to the same ductile deformation, the orientation of the HE is in most cases straight all the way up to the contact with the CE. In some cases, however, the orientation is deflected in a zone close to the CE and apparently associated with the presence of the CE (Fig. 1). These narrow zones of deflected HE flanking the CE, here named flanking structures, are the subject of this paper. The next section is a general summary of the geometry of flanking structures based on the literature and on observations by the author (Figs. 2 and 3) as described in Sections 3 and 5.

2. Geometry of flanking structures

Flanking structures are mostly isolated features in a host rock with straight foliation or lineation. The CE is central to every type of flanking structure and is usually developed as an intrusive vein with sharp boundaries, derived from an external magma source (Figs. 1, 2a and 4a). Less commonly the CE are locally derived vein-shaped leucosomes (Fig. 2b–d); veins with fibrous or massive quartz or carbonate deposited from a migrating fluid (Fig. 3c,d); or even faults (Fig. 2e), joints or linear features such as burrows (Fig. 4c).

The HE of a flanking structure is usually a foliation or several foliations cross-cutting each other at a small angle, compositional layering, or another penetratively developed planar structure in the rock (Figs. 2 and 3). Occasionally, the HE may be an isolated layer or vein in a non-foliated rock that is cut by the CE. Although no examples were observed by the author, the HE might also be a linear fabric of some sort (Fig. 4b).

In flanking structures, the angle between the CE and HE changes when approaching the CE. It may decrease; increase; or increase to orthogonality and decrease again. The first case leads to a geometry similar to that of shear-bands, hence such structures are here named *flanking shear-bands* (Fig. 1). If the angle increases towards the CE, or increases to orthogonality and then decreases, an isolated fold-train or *flanking-fold* structure (Fig. 1) results that is bisected by the CE (Hudleston, 1989). In both flanking shear-bands and -folds, part of the HE close to the CE with deviant orientation is referred to as the *internal HE*; that further away and unaffected in orientation is referred to as the *external HE* (Fig. 1).

In all flanking structures associated with a CE of limited lateral extent, the deviation in orientation of the foliation in the internal HE decreases towards the tips of the CE, and

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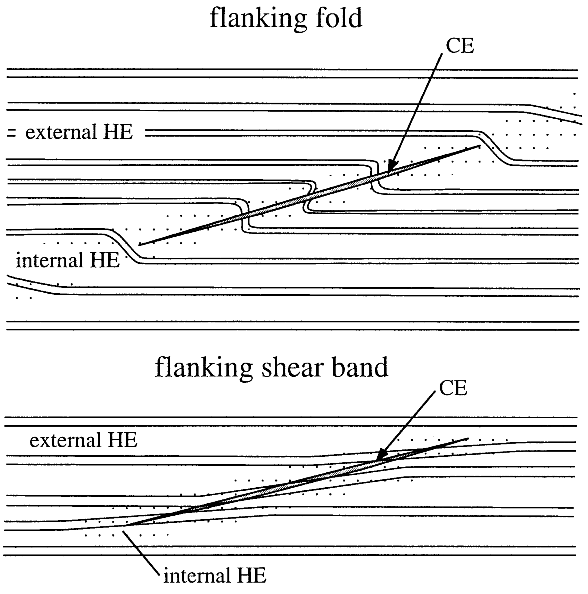

Fig. 1. Schematic drawing of two types of flanking structures: flanking-folds and flanking shear-bands. In both cases, the host fabric element (HE—here a layering) is deflected close to the cross-cutting element (CE—here a vein). This deflected part is the internal HE. The HE further away (external HE) is undisturbed.

may die out in the wall rock either beyond the tip (Figs. 2d,e; 3a and 5a) or, less commonly, before the tip is reached (Fig. 5b; cf. Grasemann et al., 1999). If the vein is deformed but straight, the maximum deviation in orientation of the foliation tends to lie in the center of the CE (Fig. 5). If a CE such as a vein is boudinaged, *boudin-related flanking structures* may occur in which the internal HE shows a gradient in orientation and a switch in the facing of flanking-folds along the side of each individual boudin (Figs. 3c,d and 6; Fig. 9 in Druguet et al., 1997). The orientation of the internal HE in the middle of the side of each boudin can have the geometry of a flanking shear-band (Fig. 6c), flanking-fold (Figs. 3d-centre and 6a), or be straight (Figs. 3c-central boudin and 6b).

Flanking structures usually lie oblique to the external HE at angles of 10–70° (Figs. 2 and 3). Commonly, several flanking structures of the same geometry are parallel or lie at a small angle to each other in the same volume of rock. The vergence of HE-deflection is usually the same for all flanking structures in a particular volume of rock, a fact that earmarks them as potential indicators of shear sense if the rock is deformed by non-coaxial progressive deformation (Hudleston, 1989) and if the mechanism of formation is taken into consideration.

Where a CE transects markers in the HE such as recognisable single layers, flanking structures can be shown to be of three geometric types. (1) Those that have no displacement along the CE, and those that have either (2) synthetic or (3) antithetic displacement. (n-, s- and a-Type flanking structures, respectively: Fig. 7a). Synthetic displacement in this sense means a displacement along the CE in the same direction as a hypothetical rotational movement of the deflected, internal HE with respect to the external HE (Fig. 7a). Displacement is measured relative to a marker line normal to the CE since a vein that intrudes a foliation obliquely by wall rock displacement normal to the CE will cause an optical illusion that can be confused with displacement (Fig. 7b). Flanking-folds are the most common type of flanking structures observed by the author and are the main theme of this paper.

3. Geometry of flanking-folds

Flanking-folds were first described in detail by Gayer et al. (1978) and Hudleston (1989), and further examples are shown in papers by Druguet et al. (1997), Passchier (1997a), Zubriggen et al. (1998) and Grasemann et al. (1999). Gayer et al. (1978) described flanking-folds along dolerite dykes formed in pelitic and psammitic meta-sediments at lower amphibolite facies conditions. Hudleston (1989) referred to flanking-folds as "paired hook-shaped folds" and showed examples along veins and fractures in glacial ice and in several high-grade rocks. The structures shown by Druguet et al. (1997) are discussed below. Zubriggen et al. (1998) showed examples of flanking-folds in gneissic layering formed at amphibolite facies conditions centered on intrusive vein-CE (Fig. 2a; their Fig. 6c), but did not give a description. Graseman et al. (1999) referred to the structures as "fringe folds" and described n-Type flanking-folds adjacent to quartz-filled tension gashes in a low-grade quartz–feldspar mylonite, discussed their development and used them to determine kinematics of deformation.

Flanking-folds of n- and a-Type have been observed by the author in a large number of geological settings, mostly along intrusive granitoid and mafic veins (Figs. 2a,f and 3a–c,e,f) or partial melt veins (Fig. 2b–d) in medium-to-high-grade gneiss terrains, but also along massive or fibrous carbonate veins in marbles (Fig. 3d) and slates (Passchier and Urai, 1988). Flanking-folds seem to be most common in medium-to-high-grade metamorphic rocks. From my observations and descriptions in the literature (op. cit.), the following general statements can be made.

Flanking-folds occur from mm- to at least metre-scale and can be open to isoclinal. If the HE is penetratively developed in the rock, flanking-folds occur in fold-trains that trend closely parallel to a central CE. The axial plane is usually parallel to the CE (Figs. 2a,c,f, and 3e,f, Gayer et al., 1978; Grasemann et al., 1999). The folds in the fold-train have remarkably little variation in amplitude, shape and wavelength, even in layers of different thickness (Fig. 2a,f). Folds are normally of parallel shape, but in the case of tight flanking-folds, similar fold-shapes are occasionally observed (Gayer et al., 1978; Hudleston, 1989). Large angles between the CE and the internal HE are common

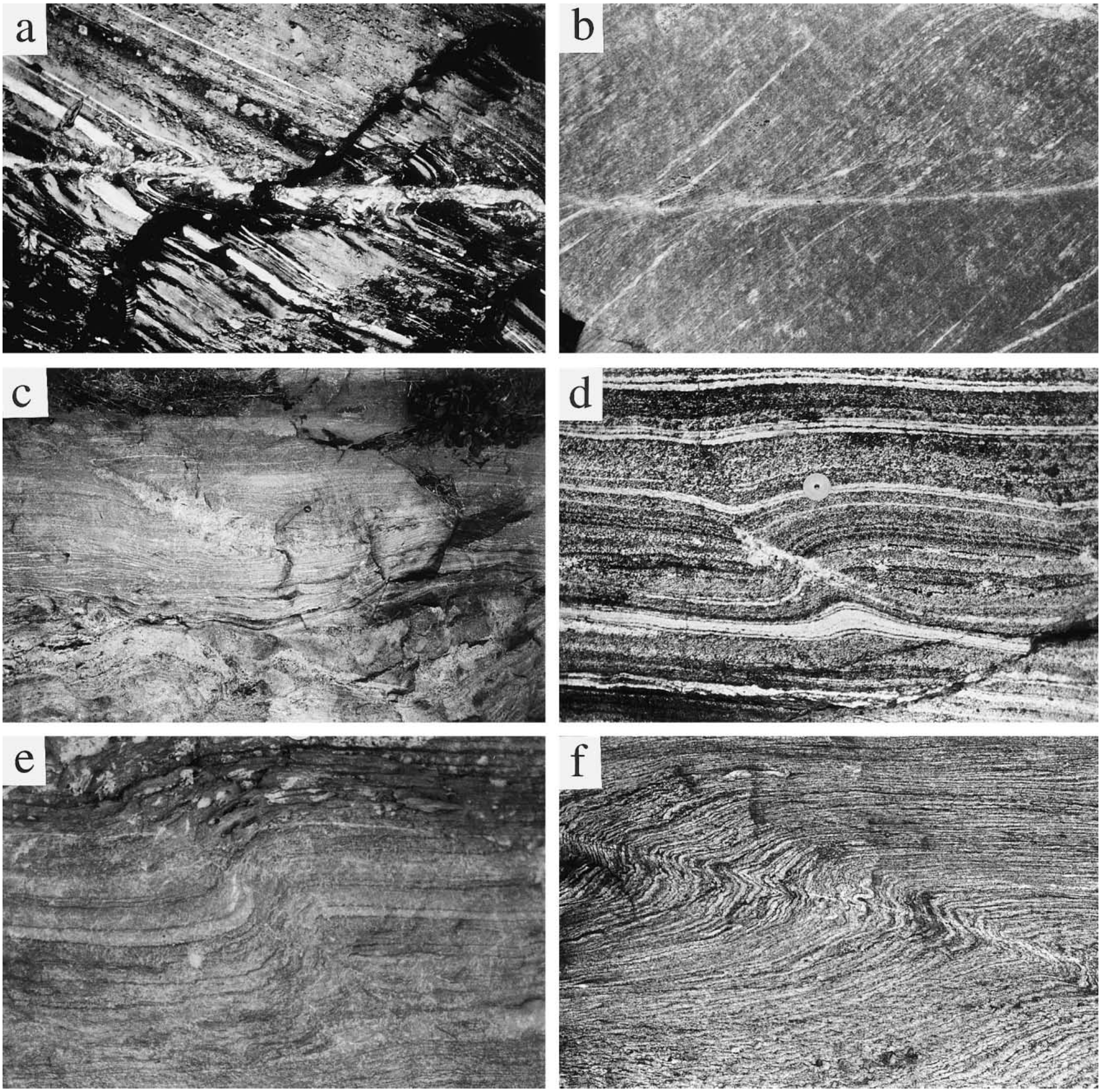

Fig. 2. (a) Flanking-fold train in gneissic layering with a granodiorite dyke as CE. Nivetta, Strona–Ceneri Zone, Italian Alps. Width of view 2 m. (b) Flanking shear-band in granitic gneiss with leucosome-CE. Ponte Brolla, Valmaggia, Italian Alps. Width of view 1 m. (c) Flanking-fold train in high-grade gneiss with leucosome-CE. Central Sri Lanka. Width of view 6 m. (d) Short a-Type flanking-fold with leucosome-CE in banded high-grade gneiss. Nordre Stromfjord, Nagssogtoquidian orogen, W Greenland. (e) a-Type flanking-fold with a brittle fracture-CE. Ogden Rocks, Kaoko belt, Namibia. Width of view 1.4 m. (f) Flanking-fold train in micaschist with pegmatite vein-CE, Cap-de-Creus, Eastern Pyrenees. Width of view 15 cm.

(Hudleston, 1989; Grasemann et al., 1999; Gayer et al., 1978). Flanking-folds usually occur as a single fold pair, but occasionally more irregular parasitic folds occur as well (Fig. 2f).

Some flanking-folds occur along migmatite vein-CE that have diffuse boundaries with the wall rock (Fig. 2c,d). These folds usually have a less regular geometry than those close to intrusive veins.

4. Development of flanking-folds

4.1. Mechanism (I)—CE formed during or after folding

An intuitive interpretation of the development of flanking-folds is that of a drag-fold train that is formed in non-coaxial flow, followed by development of the CE by fracturing, intrusion or partial melting in the core of the

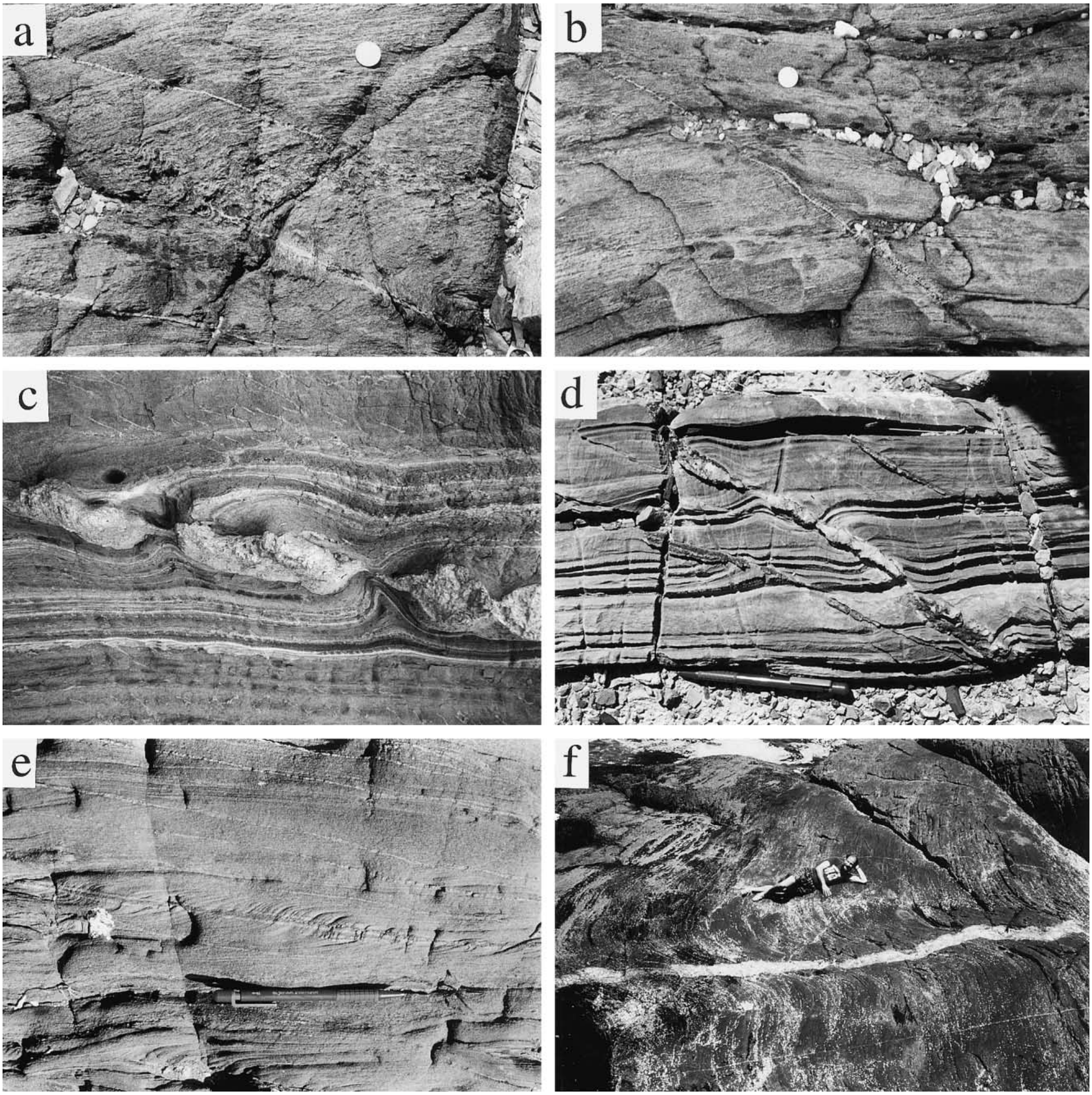

Fig. 3. (a) Tips of three subparallel pegmatite veins cutting micaschist. The middle vein has an alteration rim where micaschist has been replaced by a quartz–tourmaline rock. The lower vein has no alteration rim, the upper one has a small alteration patch below the coin only. Flanking-folds are only associated with the alteration rims of the upper and middle veins. Cap-de- Creus, Eastern Pyrenees. (b) Tip of a pegmatite vein cutting micaschist. The lower part of the vein has an alteration rim where micaschist has been replaced by a quartz–tourmaline rock. The upper part of the vein left of the coin has no alteration rim. Flanking-folds are only associated with the altered lower part of the vein. Cap-de-Creus, Eastern Pyrenees. (c) Boudinaged pegmatite vein in banded metapelite. The layering is deformed into a boudin-related flanking structure. Lower Khan River, Namibia. Width of view 60 cm. (d) Boudinaged carbonate vein in a metamorphic limestone. Layering in the limestone is deformed into a boudin-related flanking structure with flanking-folds against the centre of the boudins. Rhino Wash north of the Ugab Valley, Kaoko Belt, Namibia. Pencil for scale. (e) Swarm of parallel thin pegmatite veins cutting micaschist. Flanking-folds only form around the central and lowermost pegmatite veins that have an alteration rim. 5 km NE of the Doros Crater, Kaoko Belt, Namibia. (f) m-Scale flanking-fold structure associated with a deformed pegmatite vein-CE in layered granitic gneiss. Thin, parallel pegmatite veins at top and bottom of the photograph lack flanking-folds. Rio de Janeiro, Brazil. Rudolph Trouw for scale.

fold-structure (Fig. 8-I). According to Hudleston (1989) this mechanism operates for at least some partial melt-CE. This could happen in several ways; partial melting could be late and entirely passive because of a local concentration of mica in the core of the fold structure, or of water being present in a small fault or shear zone (Fig. 8-Ia and b). Partial melt-CE formed in this way have irregular, frayed boundaries to the wall rock and are internally undeformed (Hudleston, 1989).

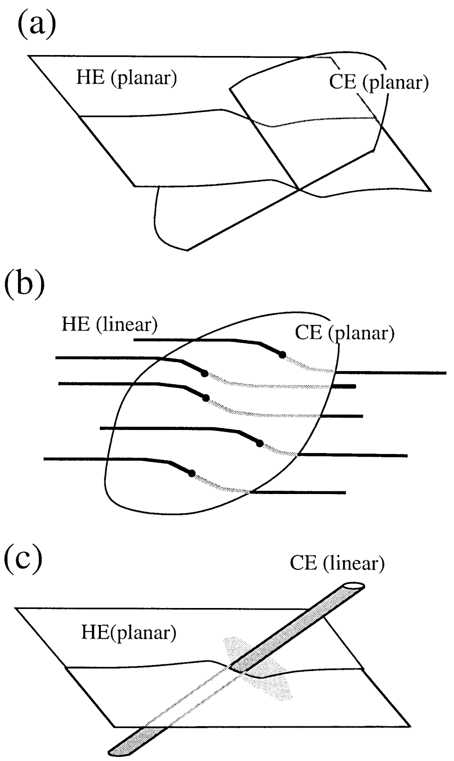

Fig. 4. Inferred three dimensional geometry of flanking-folds with: (a) planar CE and HE; (b) planar CE and linear HE; and (c) planar HE and linear CE (burrow).

It is also possible that the CE starts developing *during* the folding process, in which case the vein should be partly deformed (Fig. 8-Ic). This could happen in rocks deformed at a high metamorphic grade in which a small volume of melt was present at grain boundaries. The rock will maintain its cohesion when the melt percentage is less then 30–35% (Van der Molen and Paterson, 1979), but in the core of a fold train porosity might increase and melt can accumulate until cohesion between grains is lost, and a local melt vein develops (Fig. 8-Ic).

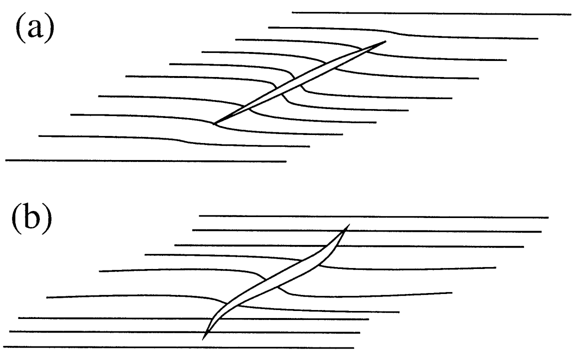

Fig. 5. (a) Flanking-fold structure with an internal HE that extends beyond the tips of the CE. (b) Flanking-fold structure where the tips of the CE extend beyond the internal HE domain.

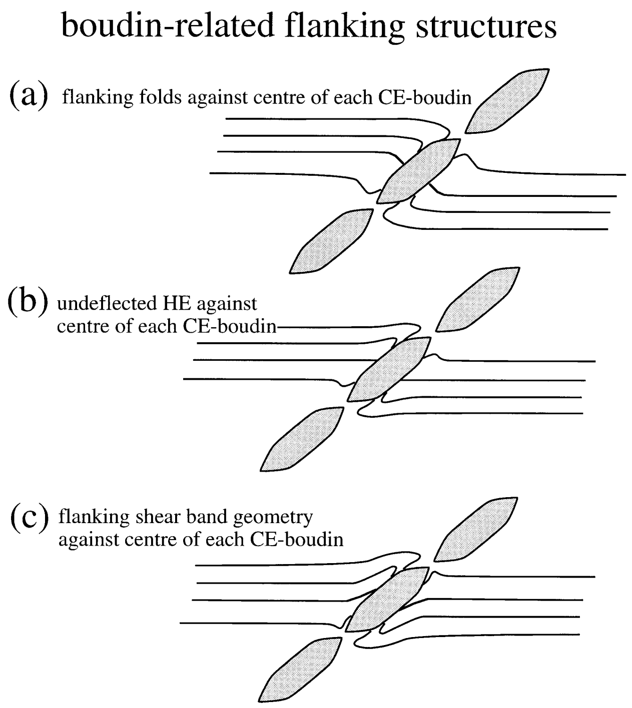

Fig. 6. Three types of boudin-related flanking structure around a boudinaged vein. (a) Flanking-fold central to each boudin. (b) No deflection of the HE central to each boudin, but folds associated with boudin necks on both sides. (c) Flanking shear-band geometry central to each boudin.

Flanking-folds with partial melt-CE observed by the author and described by Hudleston (1989) are of n-, s- or a-Type. n-Type flanking-folds could form by passive partial melting in the core of a pre-developed flanking-fold (Fig. 8-Ia), or if the critical resolved shear stress over a vein was close to zero, e.g. in veins subparallel to the extensional instantaneous stretching axis of the flow (cf. Passchier, 1997b). s-Type flanking-folds could either form before partial melting, e.g. by the presence of a small shear zone or fault in the core of the structure that is erased by the melt patch (Fig. 8-Ib); or by active slip in the melt patch itself (Fig. 8-Ic). a-Type flanking-folds with local partial melt CE (Fig. 2d) probably form by mechanism (II) described below.

Although the scenario described above centers on melt veins, similar flanking-folds could develop at a lower metamorphic grade if fluid pressure in the rock is relatively high and quartz or carbonate veins develop by precipitation from solution along fluid-filled fractures. Fluids could preferentially deposit material in the core of fold trains if porosity is locally enhanced by small-scale fracturing, causing fuzzy hydrothermal veins to develop. Alternatively, fractures might form in the core of a fold train where strain rate is high, or where a strong fabric anisotropy develops (Hudleston, 1989).

4.2. Mechanism (II)—folding associated with active faults

Although mechanism (I) can explain some flanking-fold types, Hudleston (1989) proposed another mechanism for

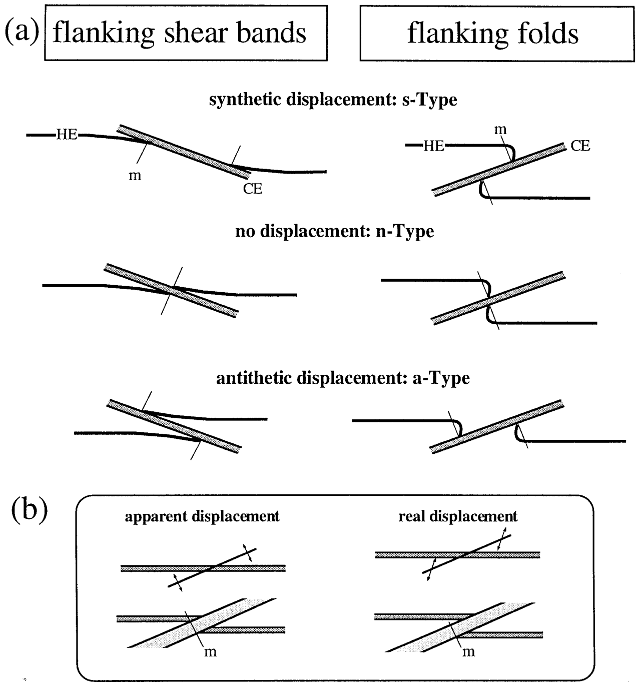

Fig. 7. (a) Three different types of flanking-folds and flanking shear-bands, respectively, based on displacement of HE along the CE as indicated by a thin marker line (m); s-Type—synthetic displacement; n-Type—no displacement and; a-Type—antithetic displacement. "Antithetic" and "synthetic" refer to the relative rotation sense of the internal HE section with respect to the external HE, compared with displacement sense on the CE. (b) Difference between apparent displacement of the HE by a vein-CE (left) and true displacement (right) caused by a shear component along the CE; 'm' is a marker line.

a-Type flanking-folds in glacier ice with ice-filled vein-CE and in rocks with partial melt-filled vein-CE. Similar examples of a-Type flanking-folds were observed by the author along local melt veins in high-grade gneiss in the Nagssogtoquidian Orogen of W Greenland (cf. Fig. 2d) and in lower amphibolite-facies mylonites in the Kaoko Belt of Namibia, where they are centred on relatively short fault CE (Fig. 2e). Based on observations of these structures in glacial ice and on experiments using plasticene, Hudleston (1989) concluded that a-Type flanking-folds develop as follows (Fig. 8-II): a (tensile or shear) fracture develops at a high angle to the foliation in a rock where ductile non-coaxial progressive deformation is in progress. Such fractures will tend to rotate with progressive deformation, and can become partly filled with melt or vein material (Hudleston, 1989). If the fault remains unsealed during its rotation, flow can be partitioned into (antithetic) slip on the fault and low-vortical progressive deformation (close to pure shear) in the rock immediately adjacent to the active fault (cf. Lister and Williams, 1983). As a result of this type of flow partitioning, the original angle between the CE and HE is modified to a different extent close to the fault (creating the internal HE) and further away (external HE), leading to development of a-Type flanking-folds (Fig. 8-II insets; Hudleston, 1989).

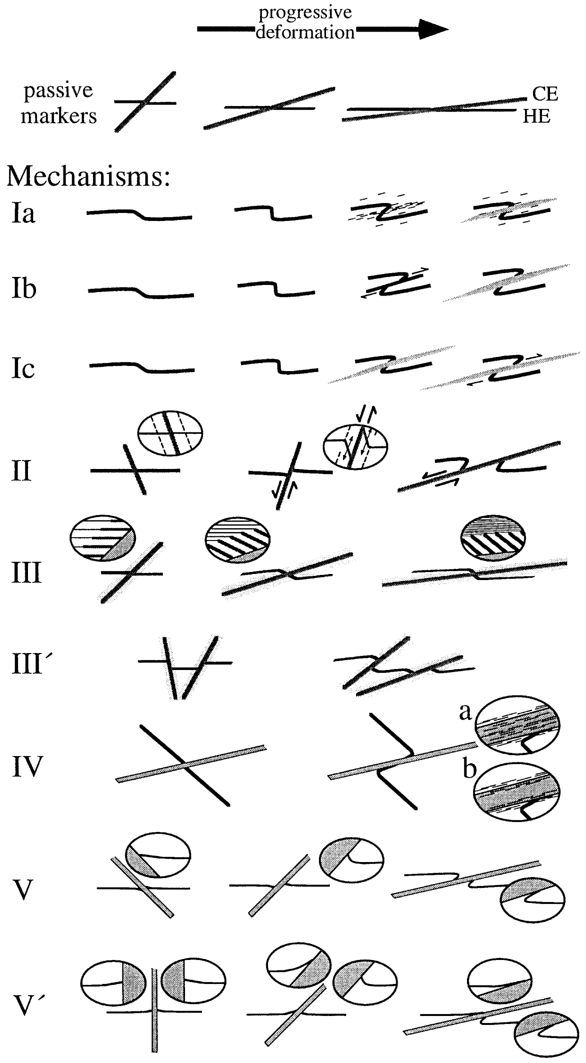

Fig. 8. Schematic presentation of several mechanisms by which flanking-folds can develop. All structures are shown in a section normal to planar CE (gray) and HE (black). The top of the diagram shows deformation of a CE and HE that act as passive markers. (Ia) Development of a fold train, and later passive development of a vein in the mica-rich core of the structure caused by preferential partial melting. (Ib) Development of a fold train, followed by generation of a fault or shear zone in the core of the structure. This fault or shear zone is passively erased by a local melt vein. (Ic) Development of a fold train, and concentration of melt in the core of the structure at an early stage. Both Ib and Ic can show synthetic displacement along the melt vein-CE (s-Type flanking-folds). (II) Development of a flanking-fold by slip on an active fault which rotates in bulk ductile non-coaxial flow. Caused by flow partitioning, deformation alongside the fault is close to pure shear, leading to development of an internal HE with deviant orientation from the external HE. (III) Development of an n-Type flanking-fold caused by passive rotation of a vein-CE with attached narrow strip of wall rock (insets) caused by alteration of the wall rock during intrusion of the vein. The rotated strip of wall rock develops into the internal HE. (III′) Development of a- and s-Type flanking-folds by mechanism (III) from pre-existing offset on conjugate sets of veins. (IV) Development of flanking-folds by preferential non-coaxial flow along a CE. Insets show two possible types, with flow in the entire CE (IVa) or in a chilled margin and/or altered wall rock rim (IVb). (V) Development of flanking-folds by passive amplification of asymmetric deflections in the HE close to the CE. (V′) Development of a flanking-fold- and shear-band pair by passive amplification of a symmetric deflection along a CE (after Fúnez, pers. comm.).

4.3. Mechanism (III)—development associated with an alteration rim on the CE

4.3.1. Introduction

n-Type flanking-folds along faults or intrusive veins cannot easily be explained by the previously discussed mechanisms. Hudleston (1989) reported some n-Type flanking-folds and the author observed them in several settings (Figs. 2a,f and 3a,b,e). Geometrically, these flanking-folds resemble cleavage refraction in, for example, turbidites or other layered pelitic rocks. Cleavage refraction develops because of differences in progressive deformation in layers of different lithology, which leads to relative rotation of the foliation in adjacent layers (e.g. Treagus, 1988). Despite the geometric similarity, however, there seems to be no reason why flanking-folds would develop by such relative rotation of foliations since the major difference in lithology is between the CE and the wall rock, while the folds develop *within* the wall rock at some distance from the CE. In fact, most veins cross-cutting older planar structures that are deformed together in extension in medium-to-high-grade metamorphic rocks are stretched or even boudinaged and cut by foliations, but develop no flanking-folds despite the fact that the angle between them must have changed during the deformation. Special conditions are therefore required to form n-Type flanking-folds (Passchier, 1997a), as illustrated by an example from the Pyrenees.

4.3.2. Tourmaline rims

Flanking-folds are common in micaschist from the Cap-de-Creus area in the eastern Pyrenees, Spain (Figs. 2f and 3a,b). Here, early-Proterozoic pelites were deformed, metamorphosed and intruded by pegmative veins during the Variscan orogeny (Druguet et al., 1997). The pelites have a generally E–W trending subvertical foliation S_1 subparallel to bedding. Pegmatite veins intruded subvertically, early during a second deformation event D_2 and cut through S_1 and bedding (Druguet et al., 1997). Along many of the pegmatite veins, the wall rock has been altered. The micaschist consists of quartz, biotite, plagioclase and minor K-feldspar and white mica, but a rim of up to 2 cm wide along the edge of many pegmatite veins consists of quartz, tourmaline and minor white mica (Fig. 3a,b; Druguet et al., 1997, their Fig. 11). A gradual transition exists between the micaschists and these tourmaline rims, and individual biotite-rich lamellae grade into tourmaline-rich lamellae which form a ghost-foliation close to the surface of the pegmatite veins. Where pegmatite veins transect an alternation of psammitic and pelitic layers, tourmaline rims only occur in the metapelites. The tourmaline rims are therefore inferred to have formed by metasomatism of micaschist under the influence of a Boron-rich fluid that infiltrated the micaschist from the veins (Druguet et al., 1997).

D_2 led to strong deformation of both micaschist and pegmatite veins. Adjacent to many of the veins S_1, bedding and quartz veins are all deflected into flanking-folds of D_2 age. The internal HE of the flanking-folds coincide with the tourmaline rims and are up to 2 cm wide, while the pegmatite veins constitute the CE (Druguet et al., 1997, their Fig. 11). Close to the vein the angle between the internal HE and CE varies between 70 and 120°, but is commonly orthogonal (Fig. 3a,b). In three dimensions, the flanking-folds are close to cylindrical in shape, and fold axes are parallel to the intersection lineation of the foliation and the veins (Druguet et al., 1997).

At first sight, the presence of flanking-folds might be explained by the growth of tourmaline-rich rims orthogonal to pegmatite veins as a curious kind of fibrous vein; however, sandstone, quartzite and calcsilicate layers of the bedding parallel to S_1 are deflected into the flanking-folds and run up to the veins without a change in thickness, composition or internal structure, some even preserving sedimentary structures close to the veins. The flanking-folds must therefore have developed by a relative rotation of pegmatite-vein CE and the attached tourmaline-rim internal HE with respect to the external HE. This is supported by observations at the tip of intruded pegmatites on horizontal outcrop pavements normal to the intersection line of S_1 and the pegmatite veins (Fig. 3a,b). At these sites, pegmatite veins taper to a width of less than 1 mm, and even to non-filled joints. Along most of these thin veins and joints, tourmaline rims as described above are developed. The development of the rims, however, is relatively patchy and some parts of the veins and joints are devoid of tourmaline rims, even where they cut through micaschist (Fig. 3a,b). If one traces the occurrence of flanking-folds along a single vein, these are seen to be clearly linked to the presence of tourmaline rims: where these are lacking, no flanking-folds develop (Fig. 3a,b). This is a clear indication that the presence of tourmaline rims is a prerequisite for the development of flanking-folds in these rocks.

From the observed geometry, the following sequence of events leading to development of the flanking-folds is proposed (Fig. 8-III). Pegmatite veins intruded into micaschist highly oblique to S_1 and bedding, and tourmaline-rims developed locally by metasomatic alteration of the micaschist. Subsequently, during D_2 the rock was strongly deformed at amphibolite facies conditions and the foliation and pegmatites rotated relative to each other; the tourmaline rims and the pegmatites, however, deformed less than the bulk micaschist except for local boudinage (Fig. 9 in Druguet et al., 1997). The tourmaline-rich selvages and coarse-grained pegmatite were probably more competent than the surrounding micaschist during D_2. In this way, a relatively high angle was preserved between the CE and internal HE, although the angle between the CE and external HE is now generally less than 30° (Fig. 8-III insets). Total relative rotations between internal- and external-HE of up to 120° have been observed, although 60–80° is most common. It is unlikely, though, that the steep angles between the CE and internal HE, as seen in tourmaline rims in Fig. 3a and b, represent the exact original angle of pegmatite intrusion since quartz in the tourmaline rims is commonly undulous and some tourmaline selvages are slightly folded; the angles must have been modified to some extent.

Similar modifications in the angle between the CE and internal HE are possible in other flanking-folds. The internal HE can rotate from the instantaneous extension into the instantaneous shortening field of flow in non-coaxial progressive deformation. Therefore, the internal HE may locally develop small-scale buckle-folds with axial planes parallel to that of the main flanking-fold (Fig. 2f). If the relative rotation of the internal and external HE is large enough, the internal HE may even rotate back into the extension field. In this case, a flanking-fold could have both limbs in the extension field, leading to tight folds with straight limbs, and even to similar folds (Gayer et al., 1978; Hudleston, 1989).

The Cap-de-Creus area is not the only locality where flanking-fold development is associated with alteration. Thin veins of pegmatite intruding a Neoproterozoic micaschist in Northern Namibia at the Doros Crater show development of flanking-folds along veins that have clear alteration rims, while others, where such rims are lacking, have the wall rock foliation run straight up to the veins (Fig. 3e). A mechanism similar to that in the Cap de Creus rocks is envisaged for the development of these flanking-folds. Investigation of this structure is still in progress.

Mechanism (III) could also apply for n-Type flanking-folds where no difference in composition can be seen in the field between the internal and external HE (e.g. Figs. 2a and 3d-centre). Small changes in composition or microstructure in the wall rock adjacent to a vein, caused by fluid exchange with the wall rock or contact metamorphism, may produce a sufficient deviation in strain rate or flow geometry to cause the onset of flanking-fold development.

4.3.3. a- and s-Type flanking-folds formed by mechanism (III)

The mechanisms of intrusion–alteration–rotation for the development of flanking-folds, as proposed for n-Type structures above, may also work for some a- or s-Type flanking-folds around fault- or vein-CE. In deformed subvertical Neoproterozoic carbonate–turbidite beds in the Ugab valley of Namibia, a large number of subvertical fault or carbonate vein-CE occur at an angle of 30–60° with bedding, most of them associated with flanking-folds (Fig. 3d). In the carbonate beds, the angle between the CE and bedding is strongly variable, and both a- and s-Type flanking-folds were observed, where a-Type dominate for the steeper angles and s-Type for the shallower angles (Fig. 8-III′ at right). Comparison of carbonate beds with different intensities of deformation shows that displacement of the HE along the CE does not increase with deformation of the CE and surrounding carbonate layers, but seems to predate this deformation. The most likely explanation for this type of structure is that the CEs were originally brittle conjugate structures with opposite displacement on the two members of the set, which were subsequently rotated (Fig. 8-III′). Therefore, all types of flanking-folds can develop by mechanism (III), n-Type for tension veins, and a- or s-Type for faults or shear-veins that formed before the rotation stage.

4.4. Mechanism (IV)—enhanced deformation in a CE or along a CE-boundary, and drag

An alternative mechanism for the development of flanking-folds has been proposed by Gayer et al. (1978) for flanking-folds observed along mafic dykes in the Caledonides of northern Scandinavia. If a vein-CE that cuts the HE obliquely is weaker than the wall rock during subsequent deformation, the vein could act as a ductile shear zone in which flow is concentrated, with a strain rate gradient into the wall rock. Theoretically, this mechanism could lead to development of flanking-folds (Fig. 8-IVa). Alternatively, the alterated wall rock or chilled margin of a dyke could act as a nucleation site for ductile shear zones: depending on the angle between the dyke and the HE, this could also lead to the development of flanking-folds (Fig. 8-IVb). Gayer et al. (1978) proposed mechanism (IVa) for their flanking-folds because not only the HE, but also an older foliation within the mafic dyke-CE were deflected in the same direction, similar to deflection in a shear zone with its core along the dyke-margin. Activity of mechanism (IVa) or (IVb) can therefore be recognised by strong deformation of the vein and/or its adjacent wall rock.

4.5. Mechanism (V)—passive amplification without partitioning

Hudleston (1989) suggested that flanking-folds can also develop at high finite strain by passive amplification of a minor bend in the HE formed during vein-intrusion (Fig. 8-V). If such a minor bend is formed in a passive marker line and the whole rock is deformed by homogeneous simple shear flow, for example, it will indeed amplify into a flanking-fold at high strain; however, no clear field examples that could be attributed to this mechanism have been presented yet. A curiosity of mechanism (V) is than an a-Type displacement could be generated from the apparent displacement of the HE over a vein-CE, simply by stretching of the vein (Fig. 8-V). Finally, if symmetric minor bends are formed along an intrusion or burrow, homogeneous deformation could theoretically amplify the structure into a flanking-fold and shear-band pair (Fúnez, pers comm.; Fig. 8-V′). In contrast to mechanism (II), Mechanism (V) can lead to formation of flanking structures by homogeneous deformation of the CE and the wall rock, without flow partitioning.

4.6. Boudin-related flanking structures

The geometry of boudin-related flanking structures is shown in Figs. 3c,d and 6. They apparently develop in response to complex flow around developing boudins by deflection of the HE into boudin necks during boudin formation, and in some cases (Fig. 3a,c) by the additional development of flanking-folds or flanking shear-bands along the sides of the boudins. Boudin-related flanking structures are common in the Cap-de-Creus area where tourmaline rims are present at the edge of the boudins, and deflection of the HE into flanking-folds can be observed at the center of the boudins (Fig. 9 in Druguet et al., 1997). This structure has been attributed to mechanism (III) by Druguet et al., (1997). Similar geometries have been observed around boudinaged pegmatite veins in banded metapelite from the Khan River, Namibia (Fig. 3c) and around boudinaged carbonate veins that transect marble beds in the Ugab Valley, Namibia (Fig. 3d). The HE either runs up straight to the side of the boudins (Fig. 6b), or shows small flanking-folds as in Fig. 6a. Geometries as shown in Fig. 6c have not been observed by the author, but are theoretically possible.

5. Flanking shear-bands

Since only a few examples of flanking-shear-bands are known to the author, they are only treated briefly here. Examples of flanking shear-bands can be observed in high-grade gneisses (Fig. 2b), usually associated with partial melt veins. Only n-Type flanking shear-bands have been observed by the author. By analogy with flanking-folds, development mechanisms of flanking-shear-bands can be grouped into two basic types based on overprinting relationships observed in the field or in thin section, with late- or early-CE.

Late-CE flanking shear-bands form in the high-strain core of a shear zone, e.g. by local fracturing caused by high fluid pressure or high strain rate, and by subsequent vein filling. In high-grade rocks they can develop by a local concentration of melt that was present at grain boundaries, and local loss of cohesion and development of melt veins. Alternatively, a partial melt vein may preferentially develop in a mica-rich shear-band core, or an intrusive vein could follow the anisotropy of a shear-band core. This mechanism is therefore equivalent to mechanism (I) of flanking-fold formation, and has been proposed for development of flanking-shear-bands at Ponte Brolla, Switzerland (Fig. 2b; Merle et al., 1989).

In early CE-flanking shear-bands, the deflection in the HE post-dates the CE. In such cases there should be field or microstructural evidence for development of the CE over a planar HE, followed by the development of flanking shear-bands. This will be the case where a vein or its contact zone channel a developing shear zone. This can happen if the rheology of the vein or its margin is considerably different from that of the host rock. If the vein is weaker, concentration of flow in the vein and slight deformation in the adjacent wall rock creates the shear-band geometry (mechanism IVa or IVb). An example of such structures are pegmatite veins with biotite-rich selvages that intrude high-grade gneiss in the Vestfold Hills, Antarctica. During later greenschist-facies regional deformation, small shear zones nucleate in these biotite selvages, creating flanking shear-band geometries (Passchier et al., 1991). Early-CE flanking shear-bands can be recognised by deformation of apophyses that cut the HE, or by deformation of the vein core (cf. Fig. 4.38 in Passchier et al., 1990).

6. Flanking structures as potential shear-sense indicators

6.1. Introduction

This paper mainly serves to draw attention to the large range of flanking structures in existence, the several ways in which they can form, and the potential of these structures to reconstruct the sequence and nature of progressive deformation, intrusion and partial melting in rocks. However, flanking structures may also carry information on shear sense, and possibly on other aspects of progressive and finite deformation (Grasemann et al., 1999). In the light of this potential, modeling studies are needed before flanking structures can be interpreted in a useful way, either by numerical analysis or by analogue experiments. As yet, only Hudleston (1989) carried out relevant analogue experiments.

According to Hudleston, flanking-folds can be used to determine shear sense, but it may be premature to generally use them as shear sense indicators. At least three, and possibly five, different mechanisms seem to be responsible for the development of flanking-structures, and it will be necessary to know by which mechanism a particular structure formed before a shear-sense analysis can be attempted. This point is outlined below for flanking-folds attributed to mechanism (III) as an example.

6.2. Example—mechanism (III)

Flanking-folds formed by mechanism (III) are unlikely to become reliable indicators of shear sense or other kinematic data, unless a lot of additional information can be obtained from the rock. This is because of the large number of variables involved; in triclinic flow, for example, there are six variables describing the bulk flow type, and four to describe the orientation of the two surfaces involved. An example of higher symmetry flow is sufficient to illustrate the complexity of the situation. Consider monoclinic flow, in which the intersection line of the planar HE and CE is parallel to the flow-rotation axis. The situation can be completely described by 2D-flow in a plane normal to the intersection line of the HE and CE.

In 2D-flow material lines, i.e. both the HE and CE, rotate towards an attractor line of the flow, the extensional eigenvector or fabric attractor (Passchier, 1997b). Depending on the flow type and the initial orientation of the CE and HE, this means that the CE and HE can either rotate in the same direction but at different rates, or rotate in opposite directions. As a result, the developing flanking-fold vergence will be either S-, or Z-shaped (Fig. 9). This simple situation may be representative for many shear zones, especially those where veins develop in tension in a shear zone where the HE has rotated towards the fabric attractor. Three variables are sufficient to describe this system:

1. The original angle β between the HE and CE;
2. The orientation (α) of the HE with respect to the fabric attractor at the onset of deformation; and
3. The kinematic vorticity number W_k of the flow (ratio of pure shear to simple shear).

Using a Mohr circle construction for flow, it is possible to determine the relative rotation direction of the HE and CE and thereby the developing flanking-fold vergence. In some situations, vergence switches are possible at low strain values, but Fig. 9 shows the final flanking-fold vergence at high finite strain for a dextral flow, where α, β and W_k are plotted in α—β sections for three W_k-values. The diagram shows that S-, or Z-vergence of flanking-folds are equally common for mechanism (III), and that they are therefore generally unreliable shear sense indicators. In practice, the situation is even worse since foliations are not passive markers and will tend to fold or boudinage in some orientations. However, if flanking-folds formed along tension-gash veins that developed parallel to the instantaneous shortening axis of the flow (Passchier 1997b) during the same deformation event that developed the flanking-folds, the geometry of the system plots on the bold line in Fig. 9. This line is always in the field of Z-shaped flanking-folds for dextral shear sense, provided that $\alpha + \beta < 135°$. For flanking-folds on tension-gash veins it may, therefore, be possible to determine shear sense in many cases. Graseman et al. (1999) use this principle to determine the kinematics of flow in a shear zone from the Himalayas, and even derive a flow W_k-number from the flanking-fold CE. This is done using the angle between vein-CE tips and the external HE, arguing that these directions represent the orientation of the instantaneous shortening axis and the fabric attractor of flow, respectively. Assuming that this attribution is correct, W_k can be calculated from this angle.

6.3. Other mechanisms

Similar difficulties that hamper the use of flanking-folds

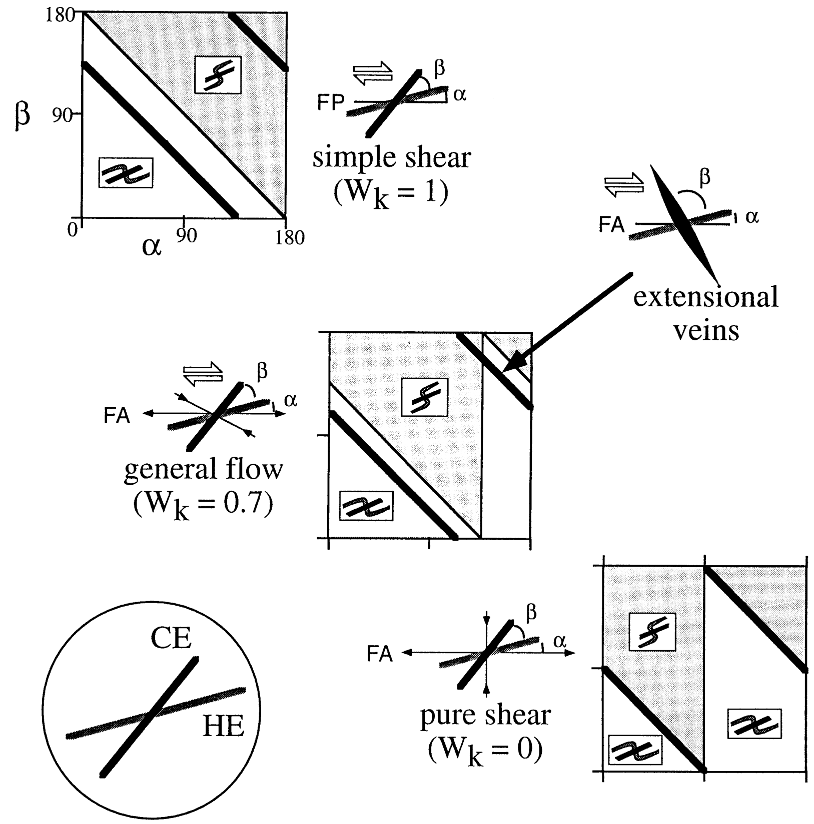

Fig. 9. Diagram showing the vergence of flanking-folds in a section normal to planar CE and HE as they will develop at high-finite strain by invariable monoclinic progressive deformation at three different kinematic vorticity numbers: 0 (pure shear), 0.7 (general flow), and 1 (simple shear). α and β are angles between CE, HE and the extensional eigenvector of flow (fabric attractor—FA, or flow plane—FP) at the onset of deformation. The bold line in the diagrams is the combination of α and β for tension-gash-CEs that develop parallel to the instantaneous shortening axis of the flow.

of mechanism (III) to determine shear sense apply to the other mechanisms. A straightforward interpretation is only possible in special cases, e.g. if the HE is rotated into near parallelism with attractor-eigenvectors of flow caused by strong non-coaxial progressive deformation, if flow is monoclinic, and if the flanking-fold axis is approximately normal to the stretching lineation in the rock.

Flanking-folds that developed by mechanism (I) in non-coaxial progressive deformation and which have their fold axis approximately normal to the stretching lineation in the rock should be reliable shear sense indicators since the development of the folds is either an effect of passive amplification of a minor bend, or of flow partitioning (Fig. 8-I). Therefore, the vergence of rotation of the internal HE with respect to the external HE is the same as that of the sense of shear. This category incorporates most n- and s-Type flanking-folds with a partial melt-CE, but care must be taken with a-Type flanking-folds with melt-CE: these structures probably develop by mechanism (II) and must be interpreted differently. Flanking shear-bands that develop by mechanism (I) are equally reliable as shear sense indicators (cf. Merle et al., 1989).

Mechanism (II) can lead to the development of flanking-folds in both coaxial and non-coaxial flow, and such structures are therefore less reliable as shear sense indicators, unless additional information is present on the flow type in the rock and the nature of the veins. If the veins are tension gashes formed parallel to the instantaneous shortening axis of monoclinic flow (Passchier 1997b), they will be reliable shear sense indicators as shown by Hudleston (1989). a-Type flanking-folds of this type indicate non-coaxial flow in which the vergence of rotation of the internal HE with respect to the external HE reflects the sense of shear (Hudleston, 1989). However, if the veins have another origin, it is presently not clear whether similar structures could not form by an opposite shear sense: modelling experiments will be needed to establish this. In all cases, it is necessary to check whether assumptions regarding simplicity of the initial geometry of the HE and CE, flow geometry and deformation history are reliable.

Little can be said as yet about the reliability of structures that formed by mechanisms (IV) or (V) to determine shear sense in the absence of sufficient field observations and modelling studies.

6.4. Strain measurement

Although it is disappointing that flanking-folds are not generally reliable shear-sense indicators, flanking-folds that develop by mechanism (III) may be used to determine the two-dimensional finite strain ratio for the plane in which they are observed, provided that the orientation of the strain ellipse is known in the form of a shape-fabric foliation plane (Fig. 10a; Passchier, 1990). Also, the original angle between

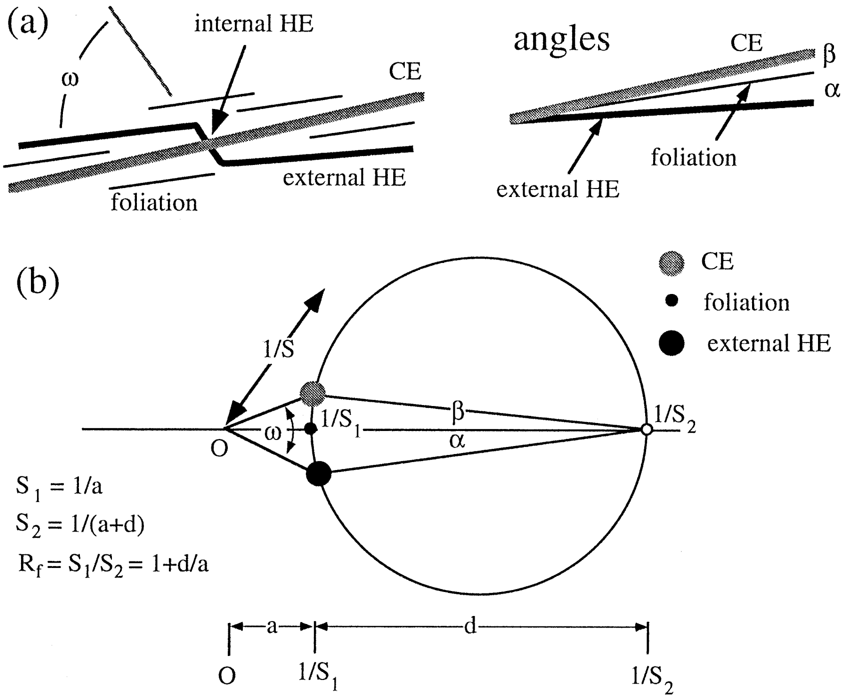

Fig. 10. Mohr circle construction to determine finite strain ratio R_f from a flanking-fold. The angles between CE, HE and the foliation in the rock (a), and the angle ω between the internal and external HE are plotted in a Mohr diagram for finite deformation (b). R_f can be determined from the dimensions of the diagram using the equations in the figure. O—origin of the reference frame. S_1 and S_2—principal stretch values. The point where S_1 plots on the Mohr diagram (small black dot) represents the position of the foliation. The positions of the CE and external HE are given by large grey and black dots, respectively. This method will only give reliable results if the foliation and the flanking-fold are of the same age and if the angle between the internal HE and CE preserves the original angle between the HE and CE before development of the flanking-fold.

the CE and HE must be known, for example from the internal HE (provided it is internally undeformed) or, better, from an elongate undeformed xenolith in a vein-CE. The finite orientation of the CE, external HE and the local shape-fabric foliation (Fig. 10a) are plotted on a Mohr circle of finite deformation (dePaor and Means, 1984; Fig. 10b). A line through the centre of the circle and the point representing the foliation gives the line on which the origin of the diagram should lie. The position of the origin on this line is found from the difference ω between the original and final angles separating the CE and HE (Fig. 10a). The strain ratio R_f can now be calculated from line-lengths a and d as:

$$R_f = 1 + d/a \qquad (1)$$

This type of strain measurement is independent of the orientation of flanking-folds in the rock or of volume change.

7. Conclusions

Flanking structures, both flanking-folds and flanking shear-bands, are common structures in deformed rocks that form by at least five different mechanisms. With care and under specific circumstances, if the mechanism responsible for a particular flanking structure is known, it is possible to determine sense of shear and finite strain of the deformation responsible for development of flanking structures. Flanking-folds and flanking shear-bands have a potential as a data source of deformation in rocks, e.g. to determine kinematic vorticity, but more detailed field observations and modelling studies are needed to develop the potential of these structures.

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