ELSEVIER

Journal of Structural Geology 28 (2006) 1139–1145

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

Flanking structure development in anisotropic viscous rock

Thomas Kocher *, Neil S. Mancktelow

Geological Institute, ETH Zurich, CH-8092 Zurich, Switzerland

Received 24 November 2005; received in revised form 15 March 2006; accepted 21 March 2006
Available online 19 May 2006

Abstract

Flanking structures typically occur in foliated or banded rock, and this marked planar structure implies a significant mechanical anisotropy, which has not been considered in previous mechanical models of flanking structure development. Both analytical and numerical techniques are used to investigate the influence of anisotropic viscosity on flanking structure formation. Reorientation of the principal stress axes in anisotropic materials can cause the sense of shear along a fracture in certain orientations to be opposite to that expected in an isotropic material. Applying the principle of stress reorientation in anisotropic rocks to natural flanking structures allows a qualitative estimation of the degree of anisotropy during flanking structure formation. It is shown that a strong foliation or banding does not necessarily imply a strong mechanical anisotropy, which calls for caution in inferring mechanical anisotropy directly from the structure of rocks without additional rheological information.

Keywords: Flanking structure; Anisotropy; Foliation boudinage; Reverse drag

1. Introduction

The origin and evolution of deflections of planar markers (e.g. foliation or layering) in the vicinity of a rheological discontinuity in rocks, termed flanking structures by Passchier (2001) and Grasemann and Stüwe (2001), have been the subject of a number of studies in recent years. The geometrically simple setup of a planar element cross-cut by a discontinuity, e.g. a fracture or a dyke, and subsequently deformed in general shear flow, was found to develop a wide variety of different structures, such as normal or reverse shear bands, s-type, or a-type flanking structures (see Grasemann et al. (2003, fig. 1) for an in-depth explanation of the terminology used throughout this paper). Further studies showed that these structure types can be subdivided into extensional or contractional structures (Exner et al., 2004), and even more detailed terminology based on the curvature of marker lines was recently suggested by Coelho et al. (2005). Flanking structures are potentially important in kinematic analysis of deformation because they may provide qualitative information (Wiesmayr and Grasemann, 2005) and, under special circumstances, even quantitative data (Kocher and Mancktelow, 2005) on the flow field in which they were formed.

Studies on flanking structures by Hudleston (1989), Reches and Eidelman (1995), Passchier (2001), Grasemann and Stüwe (2001), Grasemann et al. (2003, 2005), Exner et al. (2004), Wiesmayr and Grasemann (2005) and Kocher and Mancktelow (2005) applied numerical, analogue and analytical methods to explain the development of flanking structures around a discontinuity. Most of these studies were restricted to linear viscous or linear elastic rheology. However, it is widely accepted that rocks behave according to nonlinear stress–strain relationships and only approach linear viscous behaviour if the deformation is dominated by diffusion creep, typically at very low stress levels (e.g. Ranalli, 1995; Turcotte and Schubert, 2002; Barnhoorn, 2003). Grasemann and Stüwe (2001) briefly addressed the formation of flanking structures for a power-law viscous rheology and from their results argued that there is no significant difference compared with linear viscous rheology, except for a tendency to localize deformation closer to the fracture. These results confirm earlier work by Barr and Houseman (1996), who had addressed deformation fields around faults in nonlinear materials, but only for the case of a simple shear bulk flow field and not for blind faults isolated in the surrounding media.

Most natural examples of flanking structures are found in rocks that show a strongly developed planar structure caused by foliation, metamorphic banding or sedimentary layering. In fact, the presence of these planar elements is a prerequisite for

* Corresponding author. Tel.: +41 44 632 36 71; fax: +41 44 632 10 30.
E-mail addresses: thomas.kocher@alumni.ethz.ch (T. Kocher), mancktelow@erdw.ethz.ch (N.S. Mancktelow).

0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.03.035

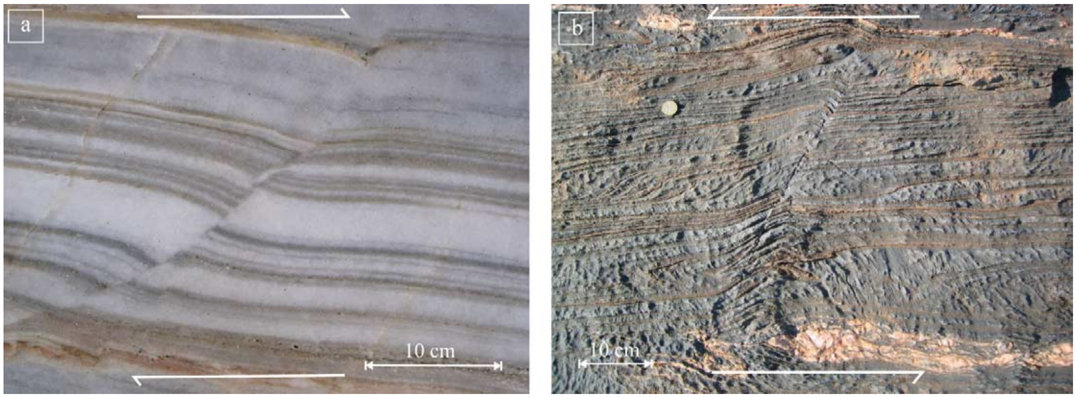

Fig. 1. Natural examples of reverse a-type flanking structures in (a) calcite–dolomite marble, Naxos, Greece (N36°58′22.8″/E025°24′21.6″), and (b) finely foliated marbles from the Goantagab region, Kaoko Belt, Namibia (S20°40′33.0″/E014°25′49.7″).

the flanking structure to be visible (see Fig. 1 for two natural examples). One might intuitively conclude that the strong foliation also indicates a significant mechanical anisotropy, the effects of which have not been included in any of the previous studies.

This paper presents theoretical considerations and numerical results on the influence of anisotropic rock rheology on the development of flanking structures. In nature, by far the most common flanking structures are associated with a brittle fracture; this study therefore focuses on such a discrete weak discontinuity. Reches and Eidelman (1995) noted that reverse drag along a fracture occurs due to reduced or non-existent friction, which in turn induces a perturbation strain or perturbation flow field in the fracture vicinity (Passchier et al., 2005). This perturbation is the cause of flanking structures. It is therefore of particular interest to establish (1) whether anisotropic rock properties modify this flow field and promote or inhibit the formation of flanking structures, and (2) whether natural flanking folds provide any constraint on the degree of anisotropy in natural rocks.

2. Numerical techniques and model setup

Numerical results were calculated using the finite element code FLASH written by the first author. The code solves Stokes equations (mass and linear momentum balance) for incompressible anisotropic Newtonian fluids in two dimensions. The balance equations are formulated and solved in a mixed (velocity–pressure) Galerkin formulation (Zienkiewicz and Taylor, 2000). The incompressibility condition poses problems in the numerical calculations, which are overcome by discretizing the velocities with triangular seven-node Crouzeix–Raviart elements (Cuvelier et al., 1986). Pressure is approximated discontinuously using three degrees of freedom, as described, for example, by Poliakov and Podladchikov (1992). A discrete penalty algorithm with pressure elimination (Cuvelier et al., 1986) is applied to iterate for the unknown velocities. The fracture is approximated as a very thin, weak, elliptical isotropic inclusion surrounded by an anisotropic but homogeneous matrix. The matrix behaviour is described by a transversely isotropic viscous constitutive law, characterized by a single orientation along which the shear viscosity of the material is weak (as caused by a foliation). The orientation of the plane of weakness is given by its normal, called the ‘director’ $\vec{n}$ (Mühlhaus et al., 2002). The material behaviour is then described by two viscosities: a normal viscosity μ_N describing the behaviour of the material in foliation-parallel stretching or shortening, and a shear viscosity μ_S describing the behaviour under foliation-parallel shear. The degree of anisotropy δ is given by $\delta = \mu_N/\mu_S$ and is assumed to be always ≥ 1. A detailed description of the finite element method that was implemented in FLASH is available in Kocher (2006).

3. Flanking structure development in anisotropic rock

The perturbation displacement or perturbation velocity field in the vicinity of a fracture is determined by the shear stress drop $\Delta\sigma$ caused by that fracture, as implied by Schmid and Podladchikov (2003) for isotropic linear viscous material and explicitly shown by Grasemann et al. (2005) for isotropic linear elastic material (the two formulations are equivalent according to the correspondence principle of Biot (1965)). The instantaneous flanking structure develops as a consequence of this perturbation flow field and is therefore only determined by the stress drop along the fracture for the given bulk deformation field. The instantaneous sense of shear along a fracture is determined by the shear stress that would act along the trace of the same fracture in a homogeneous material. In other words, if the angle between a fracture and the minimum principal stress axis σ_2 is positive, the offset along the fracture will be sinistral, whereas a negative angle between the fracture and σ_2 leads to a dextral offset (note that angles are positive if measured in a counter-clockwise direction and that compressive stresses and strain rates are negative; σ_2 is therefore the direction of maximum compression). In isotropic material, the axes of principal stress σ_1 and σ_2 are parallel to the principal strain rate axes $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ at all times (e.g. Altenbach and Altenbach, 1994). For this reason, the fields of different types of flanking structure that develop at low strain according to Grasemann et al. (2005, figs. 5 and 6), are separated by the orientation of the strain rate axes. However, in anisotropic

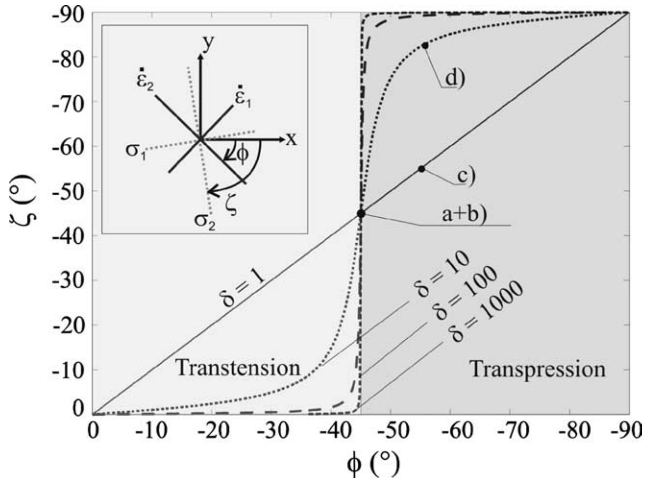

Fig. 2. Orientation ζ of the minimum principal stress axis σ_2 as a function of the orientation ϕ of the minimum principal strain rate axis $\dot{\varepsilon}_2$ for different anisotropy factors δ in dextral general shear (modified after Weijermars (1992, fig. 4)). Angles are defined in the insert box. As the material becomes more anisotropic, the difference in orientation between the principal stress axes and strain rate axes increases. The letters a–d mark the positions of the four corresponding plots in Fig. 3.

material, σ_1 and σ_2 and the strain rate axes $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are no longer parallel, with the angular discordance a function of the anisotropy factor δ. Cobbold (1976) derived an analytical formula that describes the orientation of the principal stress axis σ_2 in anisotropic material relative to the orientation of the principal strain rate axis $\dot{\varepsilon}_2$ (=axis of maximum shortening). Assuming that the plane of anisotropy (the foliation) lies parallel to the x-axis of the coordinate system, the equation is (reformulated after Weijermars, 1992):

$$\varsigma = \begin{cases} \dfrac{1}{2}\arctan\left(\dfrac{\tan(2\phi)}{\delta}\right) & \text{if} \quad \phi \in [0^\circ, \ -45^\circ) \\ \dfrac{1}{2}\arctan\left(\dfrac{\tan(2\phi)}{\delta}\right) - \pi/2 & \text{if} \quad \phi \in (-45^\circ, \ -90^\circ] \end{cases} \tag{1}$$

where ϕ is the angle between the x-axis and the principal strain rate axis $\dot{\varepsilon}_2$, ς the angle between the x-axis and the principal stress axis σ_2, and δ the anisotropy factor.

Values of the angle ζ for different degrees of anisotropy are plotted in Fig. 2. This figure demonstrates that already at degrees of anisotropy of $\delta = 10$, σ_2 will be oriented at either very low ($\approx 0°$) or very high ($\approx -90°$) angles to the plane of anisotropy for most of the possible orientations of $\dot{\varepsilon}_2$, depending on whether the flow field is transpressive or transtensive. Only for perfect simple shear bulk deformation (i.e. with no shortening or stretching component parallel to the plane of anisotropy, $\phi = -45°$) or perfect pure shear bulk deformation ($\phi = 0$ or $-90°$) are the stress axes parallel to the strain rate axes and their orientations therefore independent of δ. Keeping this in mind, and recalling that the sense of shear along the fracture is determined by the shear stress along the fracture, we can conclude that the type of flanking structure

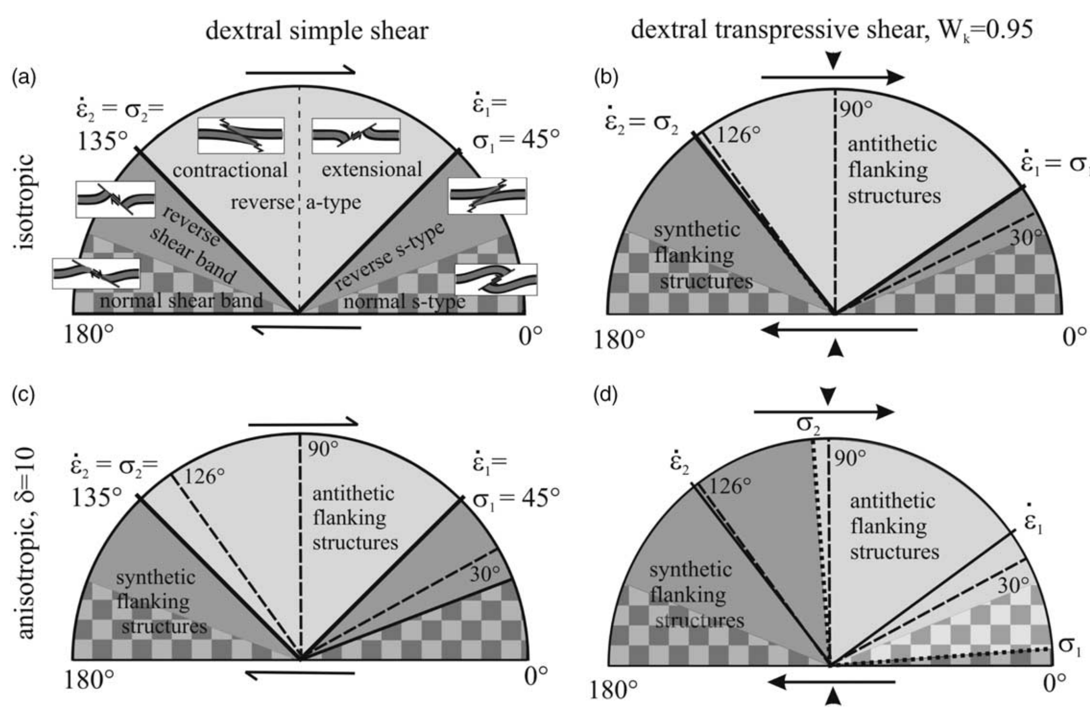

Fig. 3. Effect of anisotropic viscous rock properties on instantaneous flanking structure development, modified after Exner et al. (2004). Solid black lines mark the orientation of the principal strain rate axes, dotted lines the orientation of the principal stress axes. $\dot{\varepsilon}_1$ =instantaneous stretching axis, $\dot{\varepsilon}_2$ =instantaneous shortening axis, σ_1=maximum principal stress axis, σ_2=minimum principal stress axis (=axis of maximum compressive stress because of convention that compressive stress is negative). The dashed lines mark the initial orientation of the three fractures shown in Fig. 4, a–c. Dark grey shading indicates synthetic flanking structure development, while light-grey shaded areas indicate antithetic flanking structure development. In the chequered areas, flanking structures show normal drag, whereas structures in the rest of the diagram have reverse drag.

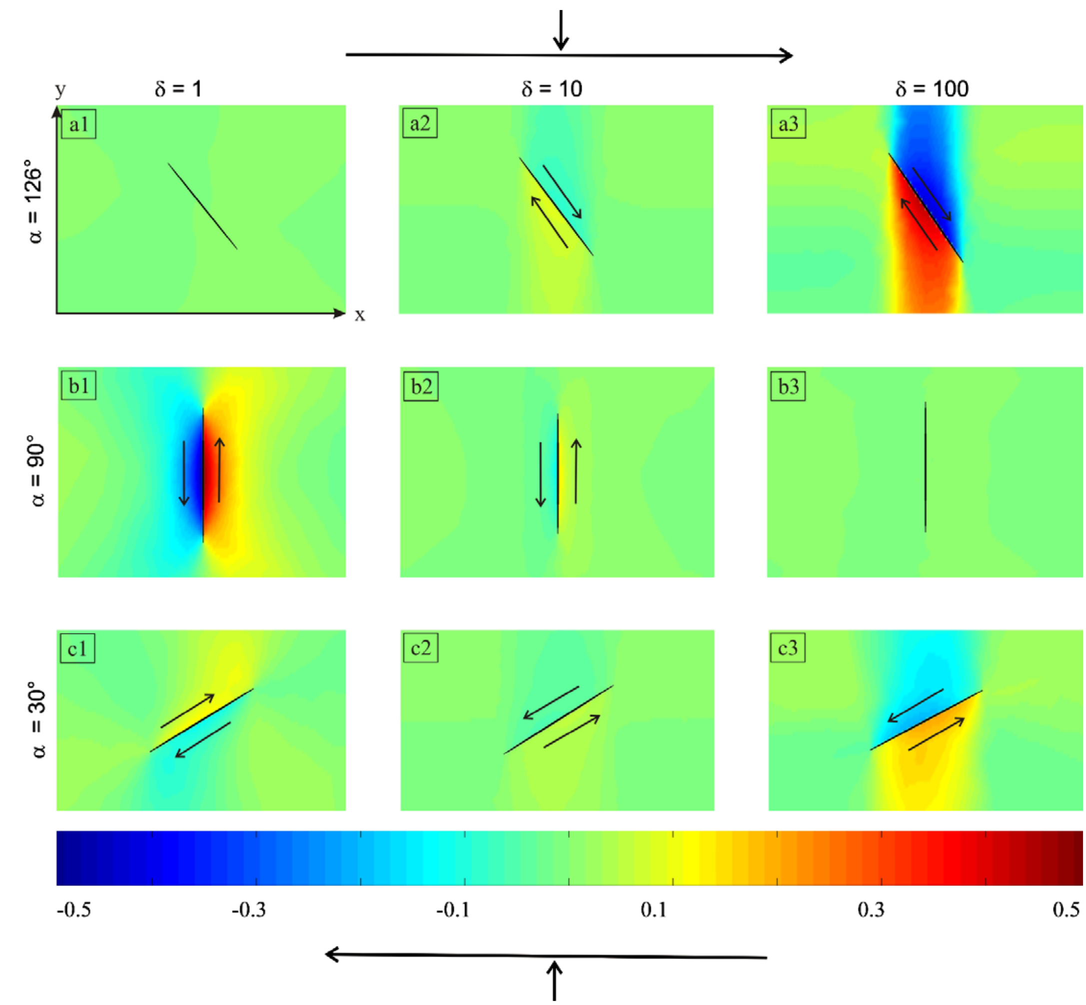

Fig. 4. Plots of the dimensionless vertical perturbation velocity around a weak Newtonian inclusion embedded in a Newtonian anisotropic matrix under weakly transpressive dextral shear (vorticity number $W_k = 0.95$, fracture length $= 1$). α gives the fracture orientation with respect to the x-axis; δ is the ratio of normal to shear viscosity μ_N/μ_S. The plane of anisotropy is aligned parallel to the x-axis and the extensional flow eigenvector (= fabric attractor; Passchier, 1997).

(i.e. whether a- or s-type) that develops instantaneously in anisotropic rock is determined by the fracture orientation with respect to σ_1 and σ_2 and not with respect to the axes of instantaneous stretching or shortening.

Stress reorientation due to anisotropy therefore leads to a change in the distribution of the types of flanking structures that are expected to develop at small finite deformations. Figs. 3a and c show the different types of flanking structures that develop in isotropic and anisotropic material in simple shear bulk flow. Since the principal strain rate axes $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ and the principal stress axes σ_1 and σ_2 are parallel (Fig. 2), they separate the fields of synthetic and antithetic structure development. However, in a weakly transpressive flow (vorticity number $W_k = 0.95$), this is only true in the case of isotopic rheology (Fig. 3b), whereas an anisotropy of $\delta = 10$ causes a shift of σ_2 to an almost vertical position (Fig. 3d). As a result, any fracture oriented at an angle larger than 98.4° will develop an s-type structure, whereas fractures at smaller angles develop a-type structures.

The theoretical results in Figs. 2 and 3 were checked by numerically calculating perturbation velocity fields around a fracture in anisotropic linear viscous material. Fig. 4 shows a series of plots of the vertical perturbation velocity field around three fractures oriented at angles of 126, 90 and 30° to the plane of anisotropy in weakly transpressive dextral shear ($W_k = 0.95$), for three different degrees of anisotropy of the matrix ($\delta = 1$, 10, 100). The fracture orientations are chosen such that the changes become clearly visible.

In isotropic rock, a fracture oriented at 126° lies almost parallel to the minimum principal stress axis σ_2 in a flow field of $W_k = 0.95$ (Fig. 3b). Therefore, the shear stress along the trace of the fracture is almost zero and no significant perturbation flow field is induced (Fig. 4, a1). As the matrix around the same fracture becomes anisotropic, σ_2 becomes almost perpendicular to the plane of anisotropy (in the case of $\delta = 10$, the angle of σ_2 to the x-axis is 98.4°). The consequence is a dextral (= synthetic) shear sense along the fracture (Fig. 4, a2), which is opposite to the sense of shear predicted by Fig. 3b for a fracture of the same orientation in isotropic material.

If a fracture in isotropic material is initially oriented at 90° and therefore perpendicular to the plane of anisotropy, a strong perturbation flow field is present in its vicinity (Fig. 4, b1). However, if the matrix around the fracture is anisotropic, σ_2 is reoriented to lie almost parallel to the fracture, which results in a decrease of the shear stress on the plane of the fracture. For large values of δ, the perturbation velocity field virtually disappears (Fig. 4, b3).

A fracture at a shallow angle of 30° to the shear plane develops a synthetic flanking structure in isotropic material according to Figs. 3b and 4, c1. With increasing anisotropy, however, the maximum principal stress axis σ_1 is reoriented and crosses the fracture orientation, which leads to a reversal in the sense of shear along the fracture. The structure that develops is then an a-type flanking structure and no longer an s-type structure (Fig. 3d).

Theoretical and numerical results are consistent and demonstrate that the most significant changes are already caused by anisotropy factors $\delta < 10$. An increase from $\delta = 10$ to $\delta = 100$ does not change the results significantly, but only influences the absolute value of the perturbation velocities (Fig. 4, a3–c3).

The finite shape of the flanking structures is also influenced by how fast the fracture that induces the perturbation flow field rotates and shortens or stretches during deformation. Kocher and Mancktelow (2005) and Exner (2005) showed that a fracture that is fully embedded in viscous isotropic material behaves like a passive marker line. Additional numerical experiments, carried out in the frame of the present study, have shown that this is also true if the mechanical properties of the surrounding matrix are anisotropic. This has important implications when addressing the frequency and stability of flanking structures during deformation.

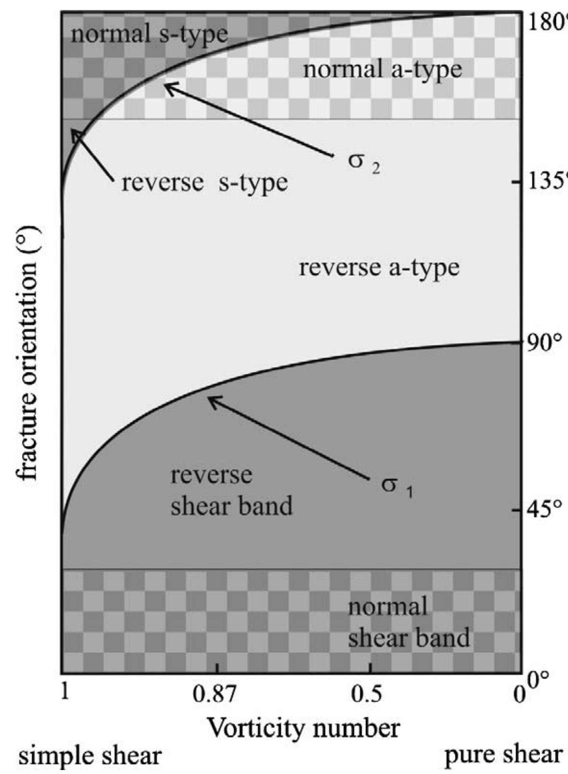

Fig. 5. Instantaneous flanking structure development (after Grasemann et al., 2003, fig. 5), modified for anisotropic matrix material ($\delta = 10$) under transpressive dextral shear. The orientation of the fracture (vertical axis) is measured positive in a clockwise sense from the horizontal axis to allow direct comparison with the original diagram of Grasemann et al. (2003). Antithetic structures develop in light-grey areas, synthetic structures in dark-grey areas; normal drag structures develop in chequered areas. A- and s-type structures are now separated by the principal stress axes σ_1 and σ_2. Anisotropy favours the formation of certain types of flanking structures, for example reverse shear bands and reverse a-type structures, but suppresses the formation of both normal and reverse s-type structures.

4. Discussion

The theoretical considerations and numerical experiments demonstrate that anisotropy can have significant effects on the instantaneous development of flanking structures. They show that the principal strain rate axes (the orientation of which is determined by the applied bulk flow field) and the principal stress axes are no longer parallel, which can lead to an inversion of the sense of shear along a fracture dependent upon the anisotropy factor δ. This result therefore requires a modification of the flanking structure maps presented by Grasemann et al. (2003, figs. 5 and 6) for anisotropic material. In the modified diagram (Fig. 5), the fields of synthetic and antithetic flanking structures are now separated by the orientation of the principal stress axes σ_1 and σ_2 instead of the strain rate axes.

The results presented here only address the type of flanking structure that develops in anisotropic rock (i.e. whether a- or s-type). Although a comparison of the magnitude of the perturbation velocity fields for the same fracture in anisotropic and isotropic material shows differences in the perturbation flow field characteristics, which might indicate differences in drag development between the two rheologies, the drag effects were assumed to be the same in both materials. Given the complex dependency of the drag (i.e. the curvature pattern of the marker lines) on several factors such as distance from the fracture, angle between fracture and marker line and finite deformation (Grasemann et al., 2005), simple statements about drag development are not possible from our experiments and would require further, preferably analytical, work. This complex dependency on several parameters is expressed in natural flanking structures by the fact that the drag can be difficult to classify unambiguously, whereas the shear sense along the fracture is always easily determined.

The observation by Kocher and Mancktelow (2005) that a fracture behaves like a passive marker still holds in anisotropic Newtonian material. It is important to note that the presence of the fracture induces a perturbation flow field in its vicinity, but the perturbation flow field does not influence the behaviour of the fracture as a passive marker line. The additional deformation around the fracture is a completely passive reaction to the reduced shear stress along the embedded fracture. From this it follows that no stable (i.e. non-rotating) orientation exists for an isolated fracture embedded in anisotropic rock except for the stable orientations parallel to the stretching and shortening eigenvectors of the flow field (Kocher and Mancktelow, 2005). Stability of a flanking structure during deformation can therefore be ruled out as an explanation for the abundance of certain structure types, e.g. isolated shear bands, in high-strain zones.

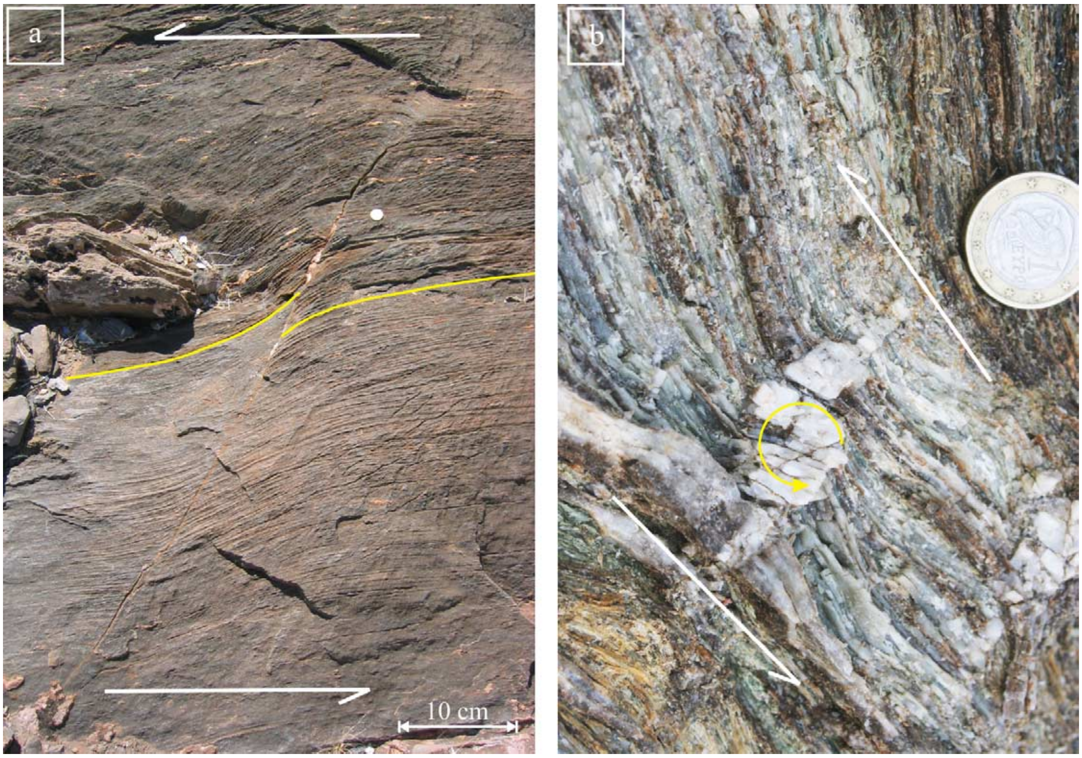

Fig. 6. (a) Reverse a-type flanking structure from a NW–SE-trending shear zone (same outcrop as Fig. 1b). The solid lines mark two corresponding planes of foliation on either side of the fracture. A comparison with the theoretical results indicates that mechanical anisotropy in this rock was low during formation of the flanking structure, even though a strong foliation is observed in the rock. (b) Quartz vein in strongly foliated (and strongly anisotropic) schists on the island of Folegandros, Greece (N36°36′40.45″/E024°57′04.85″). Note for convenience this photo is rotated 90° clockwise; the field shear sense is top down to the north.

Of particular interest is whether any statement can be made about rock anisotropy by comparing the results from this study with natural examples. To assess this possibility, we consider a natural example of a reverse a-type flanking structure developed in finely foliated marble (Fig. 6a). The sinistral shear sense in the outcrop surrounding Fig. 6a was determined independently from sigma clasts. The calcite filling of this and several other fractures in the same outcrop, with fibres perpendicular to the vein walls, suggests that they formed as mode I fractures oriented close to or parallel to the minimum principal stress axis (remember that compressive stresses are negative). Its current orientation is at approximately 55° to the foliation. The strong foliation is axial planar to isoclinal folds and makes the rock look anisotropic. Whether this also indicates a mechanical anisotropy is uncertain.

If anisotropy had been important during the formation of the fracture and related flanking structure, a mode I fracture would have formed either almost parallel (in transtensional flow) or almost perpendicular (transpressional flow) to the foliation (i.e. the plane of anisotropy). However, a strongly anisotropic rock in transtensional flow (with a σ_2 axis almost parallel to the plain of anisotropy) would quickly become internally unstable (Biot, 1965; Fletcher, 2004) and develop strong chevron folding or kink bands. This possibility can therefore be excluded. If the rock had been strongly anisotropic under sinistral transpression, a mode I fracture would have formed almost perpendicular to the foliation. However, the current position of the fracture in Fig. 6a excludes this option because the fracture cannot rotate against the (sinistral) sense of shear due to its behaviour as a passive material line.

A third option—though less likely—is that the fracture formed as one of two conjugate mode II fractures in strongly anisotropic rock in transpression, symmetrically arranged about σ_2. In this case, theory would predict one of the fractures to be oriented at approximately 60° to the foliation, which is close to the current fracture orientation. However, in this scenario, the sense of shear along the fracture should be sinistral, which is the opposite of what is actually observed in Fig. 6a. From the above considerations and from the observation that smaller fractures with similar orientations, but less offset, are found in the same outcrop, we conclude that anisotropy did not play an important role in the formation of the flanking structure in Fig. 6a.

In contrast, an example where anisotropy appears to have been important during fracture formation is given in Fig. 6b. The tips of the quartz vein propagate as mode I fractures perpendicular to the foliation, whereas the central part of the vein that was formed earlier has already been rotated, indicating a significant rotation component to the bulk deformation. In isotropic material under pure shear (with a fabric attractor parallel to the foliation), the central vein part would not rotate, whereas in isotropic rock under simple shear deformation, the fracture would propagate at 45° to the foliation. The implication that anisotropy is important in this sample is further supported by the fact that there is no significant perturbation strain around the tips of the fracture, which agrees well with the results in Fig. 4, b3.

The reorientation of the stress axes in anisotropic rock has further consequences for the deduction of kinematic data (e.g. Kocher and Mancktelow, 2005) and dynamic information (e.g. paleostress analysis) from geological structures. If the rock is strongly anisotropic, the stress and strain fields are almost completely decoupled and a large number of different flow fields will lead to very similar stress patterns in the rock, which in turn govern the fracture formation. Statements about the kinematics are therefore only possible if anisotropy is not important. One way to assess the degree of anisotropy qualitatively is from the type of flanking structure that develops, as discussed above.

5. Conclusions

The instantaneous sense of shear along a brittle fracture is determined solely by the orientation of that fracture with respect to the principal stress axes. In strongly anisotropic rock, the principal stress and principal strain rate axes are not parallel as in isotropic material, but at an angle to each other that is determined by the anisotropy factor δ. Reorientation of the principal stress axes changes the relative frequency of the different types of flanking structures that can theoretically form around fractures of different orientations. This requires a modification of the flanking structure maps presented by Grasemann et al. (2003). Strong anisotropy favours the development of reverse shear bands and reverse a-type structures, whereas normal or reverse s-type flanking structures almost disappear. The stress reorientation in strongly anisotropic rock also restricts the possible orientation of mode I fractures to be either sub-parallel or sub-perpendicular to the foliation.

Comparison of these theoretical results with a natural flanking structure developed in strongly foliated marble suggests that rock with a pronounced planar structure does not necessarily have a correspondingly strong mechanical anisotropy. In contrast, the quite common development of extensional veins in mode I fractures almost perpendicular to foliation ('foliation boudinage') in an overall shear environment clearly establishes that these examples do involve strong mechanical anisotropy. By integrating field data with knowledge gained from the mechanical models it is possible to make qualitative statements about the anisotropy of a rock at the time of formation of a particular structure. Discrimination between flanking folds in anisotropic and isotropic rock is therefore possible.

Acknowledgements

Jean-Pierre Burg is thanked for comments on an earlier version of this manuscript. TK was supported by ETH project 0-20998-02. Reviews by P. Cobbold and T. Bell are gratefully acknowledged.

References

Altenbach, J., Altenbach, H., 1994. Einführung in die Kontinuumsmechanik. Mechanik, Teubner Studienbücher.

Barnhoorn, A., 2003. Rheological and microstructural evolution of carbonate rocks during large strain torsion experiments. PhD thesis No. 15309, ETH Zürich. Available at: http://e-collection.ethbib.ethz.ch/ecolpool/diss/fulltext/eth15309.pdf.

Barr, T.D., Houseman, G.A., 1996. Deformation fields around a fault embedded in a non-linear ductile medium. Geophysical Journal International 125, 473–490.

Biot, M.A., 1965. Mechanics of Incremental Deformations. Wiley and Sons, New York.

Cobbold, P.R., 1976. Mechanical effects of anisotropy during large finite deformations. Bulletin de la Société Géologique de France 18, 1497–1510.

Coelho, S., Passchier, C., Grasemann, B., 2005. Geometric description of flanking structures. Journal of Structural Geology 27, 597–606.

Cuvelier, C., Segal, S., van Steenhoven, A., 1986. Finite Element Methods and Navier-Stokes Equation. D. Reidel Publishing Company, Dordrecht, Holland.

Exner, U., 2005. Analogue modelling of flanking structures. PhD thesis No. 16061, ETH Zürich. Available at: http://e-collection.ethbib.ethz.ch/ecolpool/diss/fulltext/eth16061.pdf.

Exner, U., Mancktelow, N.S., Grasemann, B., 2004. Progressive development of s-type flanking folds in simple shear. Journal of Structural Geology 26, 2191–2201.

Fletcher, R.C., 2004. Anisotropic viscosity of a dispersion of aligned elliptical cylindrical clasts in viscous matrix. Journal of Structural Geology 26, 1977–1987.

Grasemann, B., Stüwe, K., 2001. The development of flanking folds during simple shear and their use as kinematic indicators. Journal of Structural Geology 23, 715–724.

Grasemann, B., Stüwe, K., Vannay, J.-C., 2003. Sense and non-sense of shear in flanking structures. Journal of Structural Geology 25, 19–34.

Grasemann, B., Martel, S., Passchier, C., 2005. Reverse and normal drag along a fault. Journal of Structural Geology 27, 999–1010.

Hudleston, P.J., 1989. The association of folds and veins in shear zones. Journal of Structural Geology 11, 949–957.

Kocher, T., 2006. FLASH—code description. Available at: http://e-collection.ethbib.ethz.ch/cgi-bin/show.pl?type=bericht&nr=459.

Kocher, T., Mancktelow, N.S., 2005. Dynamic reverse modelling of flanking structures: a source of quantitative kinematic information. Journal of Structural Geology 27, 1346–1354.

Mühlhaus, H.B., Dufour, F., Moresi, L., Hobbs, B., 2002. A director theory for visco-elastic folding instabilities in multilayered rock. International Journal of Solids and Structures 39, 3675–3691.

Passchier, C.W., 1997. The fabric attractor. Journal of Structural Geology 19, 113–127.

Passchier, C., 2001. Flanking structures. Journal of Structural Geology 23, 951–962.

Passchier, C.W., Mancktelow, N.S., Grasemann, B., 2005. Flow perturbations: a tool to study and characterize heterogeneous deformation. Journal of Structural Geology 27, 1011–1026.

Poliakov, A., Podladchikov, Y., 1992. Diapirism and topography. Geophysical Journal International 109, 553–564.

Ranalli, G., 1995. Rheology of the Earth, 2nd ed. Chapman and Hall, London.

Reches, Z., Eidelman, A., 1995. Drag along faults. Tectonophysics 247, 145–156.

Schmid, D.W., Podladchikov, Y.Y., 2003. Analytical solutions for deformable elliptical inclusions in general shear. Geophysical Journal International 155, 269–288.

Turcotte, D.L., Schubert, G., 2002. Geodynamics, 2nd ed. Cambridge University Press.

Weijermars, R., 1992. Progressive deformation in anisotropic rocks. Journal of Structural Geology 14, 723–742.

Wiesmayr, G., Grasemann, B., 2005. Sense and non-sense of shear in flanking structures with layer-parallel shortening: implications for fault-related folds. Journal of Structural Geology 27, 249–264.

Zienkiewicz, O.C., Taylor, R.L., 2000. The Finite Element Method, 5th ed., Vol. 1–3 Elsevier Butterworth-Heinemann.