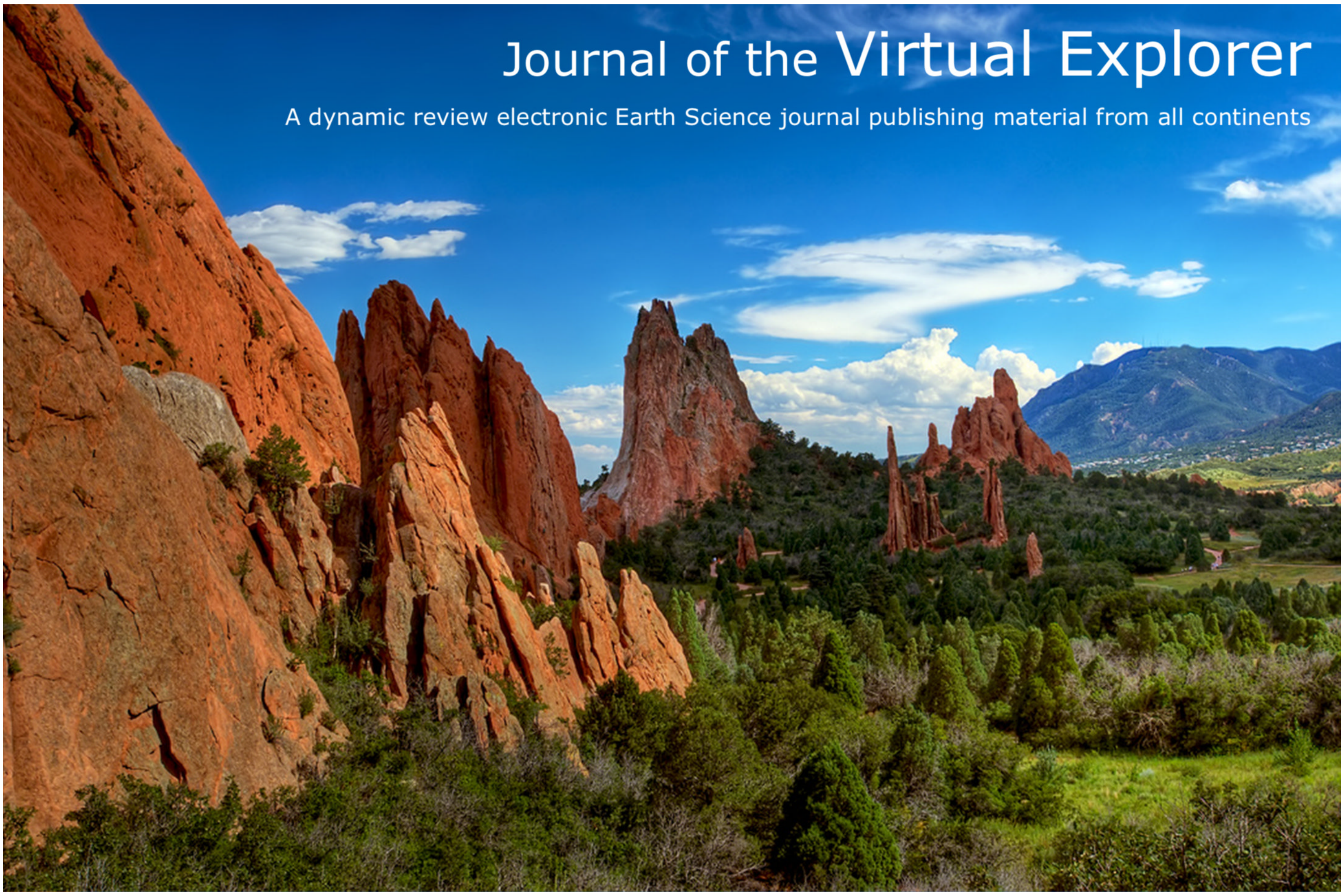


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**Abstract**: The offset of marker planes along slip surfaces results in monoclinic or triclinic structures, which have been frequently used as shear sense criteria (e.g. shear bands, C'-type foliation, flanking structures). However, instantaneous extensional or contractional offset along slip surfaces is determined only by the spatial relationship between the slip surface and the offset marker line with respect to the principal stress directions in the arbitrarily chosen reference frame. In the different quadrants of the maximum and minimum principal stress directions the shear sense along the slip surface is reversed. Within the same reference frame and along the same slip surface, differently oriented marker lines may record either extensional or contractional offset. Two perpendicular marker lines across the same slip surface always show contrary types of instantaneous offset, i.e. one is contractional while the other one is extensional, although the sense of slip is necessarily identical. Furthermore, if during progressive deformation a slip surface rotates with respect to the principal stress axes, the shear sense may be inverted and the offset of marker lines may change from contraction to extension and vice versa. Dividing extensional and contractional slip surfaces into different deformation events with opposite kinematics may lead to misinterpretation of the bulk shear sense and erroneous conclusions on the deformation history. Structures which form by offset of two perpendicular marker layers along a slip surface look very different at small shear strain. At large shear strains these two structures become qualitatively very similar when all structural elements form small angles with the fabric attractor.

http://virtualexplorer.com.au/article/2008/203/offset-of-markers-along-slip-surfaces

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## Introduction

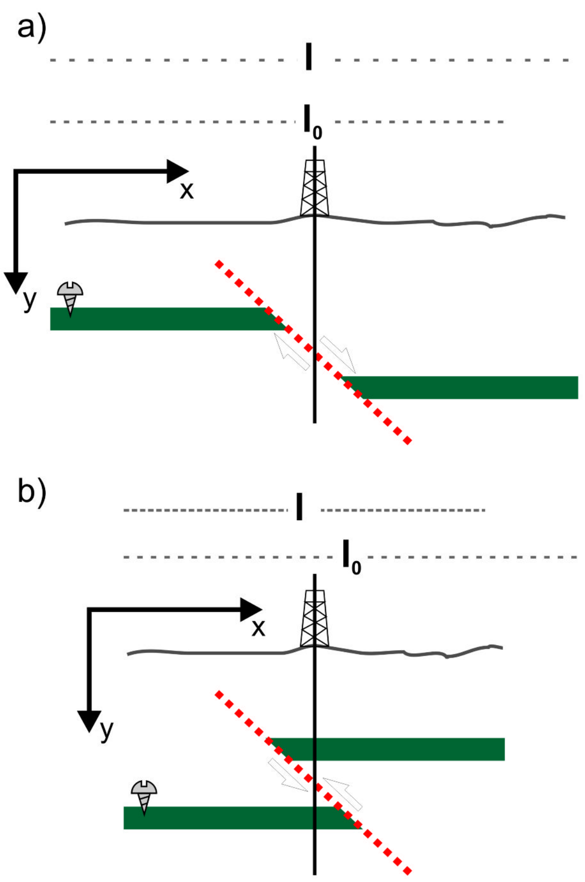
Slip surfaces or discontinuities may act as the nucleation site of secondary shear zones and eventually develop monoclinic or triclinic structures, which have been used to derive the overall shear sense of ductile flow (for a compilation of literature see Passchier and Trouw, 2005). In greenschist facies shear zones, one of the most successful kinematic indicators are secondary slip surfaces or so-called shear bands, which make an angle of about 15-35° with the shear zone margin and record a synthetic shear sense (e.g. Berthé et al., 1979; White, 1979; Platt and Vissers, 1980; Lister and Snoke, 1984; Platt, 1984). Usually, only one set of shear bands is developed, but occasionally a second conjugate set is described (Harris and Cobbold, 1985; Behrmann, 1987). These structures, together with other recently described geometries of different sense-of-slip and foliation drag were merged into a group called flanking structures (Passchier, 2001). What these structures have in common is that markers in the host rocks (e.g. foliation) are deflected near the slip surface, whereas the host rocks are undisturbed in the far field (Grasemann and Stüwe, 2001). The heterogeneous deformation field near the slip surface (i.e. perturbation strain) is controlled by the displacement gradient along the slip surface (Grasemann et al., 2005; Passchier et al., 2005). A number of numerical and analogue models demonstrated the complex progressive development of these structures. They caution the use of single isolated structures as kinematic indicators but highlight the potential of quantitative kinematic interpretation if several structures with variable geometries are considered (Grasemann et al., 2003; Exner et al., 2004, 2006; Wiesmayr and Grasemann, 2005; Kocher and Mancktelow, 2005, 2006; Mulchrone, 2007). Kocher and Mancktelow (2006) demonstrated that the slip surface induces a perturbation flow field in the host rocks, but this perturbation flow does not influence the rotational behavior of the fracture as a passive marker line. This observation holds for anisotropic Newtonian material and therefore it follows that the only stable (i.e. non-rotating) orientations attained by slip surfaces are those parallel to the stretching and shortening eigenvectors of the flow field.

The kinematics along the slip surface can be either syn- or antithetic with respect to the far field shear sense, dependent on the orientation of the slip surface to the principal stress direction. Furthermore, Wiesmayr and Grasemann (2005) demonstrated that the offset along the slip surface can be both contractional and extensional for all boundary conditions varying between simple shear and pure shear in narrowing (transpression) and broadening (transtension) shear zones. However, all above cited references implicitly assume a reference frame and marker lines which are parallel to the shear zone boundary (i.e. the stretching eigenvector for narrowing shear zones and the shortening eigenvector for broadening shear zones, Simpson and De Paor, 1993). In this work we demonstrate that offset is strongly dependent on the chosen reference frame or the orientation of the marker line with respect to the slip surface. Extensional and contractional offset along slip surfaces in ductile simple shear zones may co-exist and opposite kinematics should not be used a priori to discriminate between different deformation events.

## Definition of extensional and contractional offset

In structural geology dip-slip faults can be classified into reverse and normal faults. Considering the Earth's surface as a reference frame with zero shear stress, Anderson´s fault theory predicts that normal faults occur where the greatest principal stress is vertical and reverse faults occur where the least principal stress direction is vertical (Anderson, 1951). A normal fault occurs when the crust is extended and a marker horizon sub-parallel to the Earth's surface reference frame (x – horizontal, y - vertical downwards, Fig. 1) would record extensional offset (the length $l_0$ before deformation is shorter than the length l after faulting, Fig. 1a). In hydrocarbon exploration missing sections identified in wells are traditionally interpreted as the expression of a normal fault (Tearpock and Bischke, 2003). A reverse fault is indicative of shortening of the crust, and the marker horizon records contractional offset ($l_0 > l$). A repetition of the stratigraphy in well data is generally considered to be indicative of reverse faults (Fig. 1b).

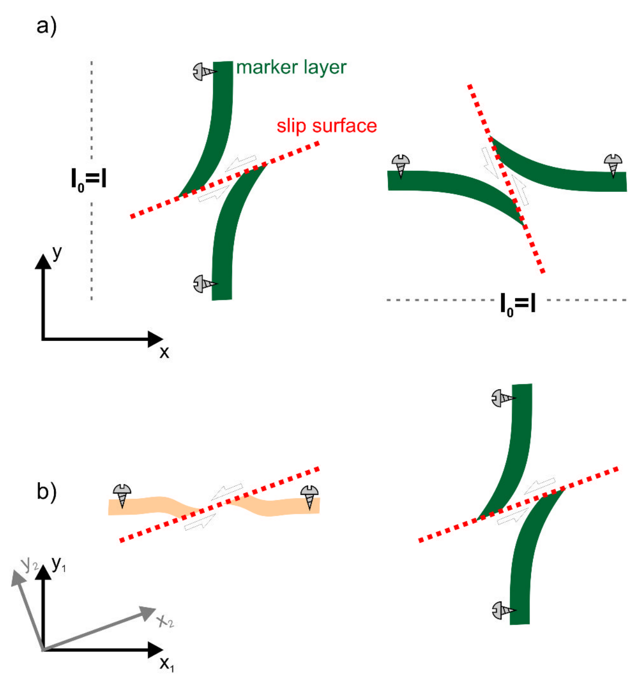
**Figure 1. Extensional (normal) and contractional (reverse) offset**




a) Extensional (normal) and b) contractional (reverse) offset of a stratigraphic layer parallel to the Earth's surface. The reference frame is generally considered to be the Earth's surface. In subsurface geology, normal faults record a missing section, whereas along thrust (reverse) faults the section is repeated.

The discrimination between extensional and contractional offset along secondary finite slip surfaces in ductile flow is more ambiguous because the offset is strongly dependent on the chosen reference frame and the angle between the marker and the slip surface. Considering the offset along an isolated slip surface, which creates a heterogeneous perturbation strain in the otherwise homogeneously deforming host rocks (Passchier et al., 2005), an offset marker line would experience neither extension nor shortening in the far-field (except from deformation by the homogeneous background strain). Whether the structure resembles a normal or reverse fault is strongly dependent on the chosen reference frame (Fig. 2a). Quantitative kinematic and mechanic studies of shear sense indicators in ductile shear zones (e.g. Ramberg, 1975; Simpson and De Paor, 1993; Schmid and Podladchikov, 2004 and many others as well those cited above) frequently consider a reference frame, where the Cartesian coordinate system is parallel to the shear zone boundary ($x_1$-$y_1$ in Fig. 2b). In these studies marker lines are generally considered to be parallel to the shear zone boundary. Using such a reference frame the left structure in Figure 2b would indicate an extensional offset. Other mathematical solutions, which are for examples based on linear elastic fracture mechanics theory (e.g. Pollard and Segall, 1987; Martel, 1997), consider a Cartesian coordinate system, which is parallel to the slip surface or to the long axis of an elliptical inclusion ($x_2$-$y_2$ in Fig. 2b). Whether a marker horizon is missing or repeated in a section parallel to the y-axis of the coordinate system is again determined by the chosen reference frame (compare the right structure in Fig. 2b choosing $x_1$-$y_1$ or $x_2$-$y_2$ for coordinate system).

**Figure 2. Offset along a slip surface observed in a Cartesian x-y coordinate system**



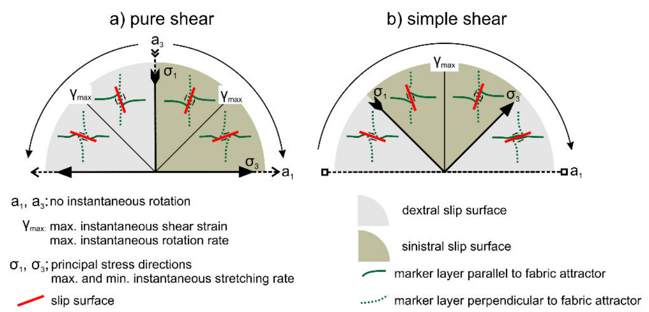

a) Extensional (left) and contractional (right) offset along a slip surface observed in a reference frame defined by a Cartesian x-y coordinate system. Note, that there is no length change of the marker in the far field. b) In a reference frame defined by a Cartesian $x_1$-$y_1$ coordinate system, both, the left and the right structures, record an extensional offset of the marker layers. However, in a reference frame defined by a Cartesian $x_2$-$y_2$ coordinate system (i.e. parallel to the slip surface), the left structure records a “missing section”, whereas the right structure creates a repeated marker layer.

In quantitative kinematic interpretations the frequently used assumption of a reference frame parallel to the shear zone boundary is certainly a good choice since this is always a non-rotating direction (i.e. eigenvector of flow, Bobyarchick, 1986). All material lines rotate toward the constant length (simple shear) or extending line (general shear) of no instantaneous angular velocity. This vector is also sometimes referred to as either extensional flow apophysis (Ramberg, 1975) or the fabric attractor (Passchier, 1997). Therefore marker lines parallel to this direction are also a plausible assumption but it is important to note, that the fabric attractor is only parallel to the shear zone boundary in simple shear or narrowing shear zones. In broadening shear zones or dilatant flow, the shortening eigenvector of flow is parallel to the shear zone boundary but the fabric attractor is oblique to this direction, at an angle which depends on the kinematic vorticity number of the flow (Simpson and De Paor, 1993; Passchier, 1997). Additionally, other markers like veins or secondary foliations, which make an angle with the shear zone boundary, may be offset by slip surfaces. We therefore discuss first the instantaneous deformation of two marker lines, one parallel and the other perpendicular to the shear zone boundary. Furthermore, we demonstrate structures that develop during progressive deformation where the slip surfaces and marker lines, which are perpendicular to the fabric attractor, rotate and where the slip surface may change the local sense of shear depending on their orientation to the principal stress directions.

## Instantaneous offset of marker lines

Slip along a fault causes a local heterogeneous displacement and stress field and can be studied by elementary elastic crack theory (Pollard and Segall, 1987). We investigate the two-dimensional, instantaneous deformation of two perpendicular marker lines, which are offset along a slip surface of finite length embedded in an elastic medium, following the procedure outlined by Grasemann et al. (2005). We restrict our discussion of far field boundary conditions to the end members of homogeneous deformation, i.e. pure and simple shear (Fig. 3). The sense of slip is controlled by the orientation of the slip surface with respect to the principal stress directions dividing the range of possible orientations into four quadrants, two of which have a dextral and the other two have a sinistral slip. A slip surface parallel to the principal stress directions does not experience instantaneous shear strain. The rotational behavior of the slip surface and the marker lines is controlled by the orientation of the principal stress directions ($\sigma_1$ and $\sigma_3$) with the eigenvectors of the deformation tensor ($a_1$ and $a_3$), which are directions of no instantaneous rotation (Bobyarchick, 1986). We restrict this discussion to marker lines, which are parallel and perpendicular to $a_1$.

**Figure 3. Instantaneous offset of two perpendicular marker layers**




Instantaneous offset of two perpendicular marker layers along a slip surface and the orientation of the fabric elements with respect to the kinematic axes in a) pure shear and b) simple shear.

Coaxial deformation (i.e. pure shear) has two perpendicular eigenvectors, which are parallel to the principal stress direction (Fig. 3a). A slip surface, which is oblique to the stretching eigenvector $a_1$ will instantaneously rotate into the direction of $a_1$, i.e. the fabric attractor. Two material lines, which are parallel and perpendicular to the fabric attractor, do not rotate instantaneously. However, the line parallel to $a_1$ will stretch and the line parallel to $a_3$ will shorten. At 45° and 135° with respect to $a_1$ the slip surface experiences its maximum instantaneous shear strain and rotation rate.

Simple shear has only one direction which is not instantaneously rotating, i.e. the fabric attractor parallel to the shear zone boundary (Fig. 3b). Fabric elements of any other orientation will rotate into the shear plane and therefore the mylonitic foliation of strongly strained rocks is considered to represent the orientation of the flow plane. The minimum and maximum principal stress directions are oriented at 45° and 135° respectively (measured from the fabric attractor counterclockwise). Slip surfaces with orientations larger than 135° and less than 45° will slip synthetically while the sense of slip between 45° and 135° is antithetic. At 45° and 135° the slip surfaces experience no instantaneous shear strain. Material lines perpendicular to the flow plane have the maximum instantaneous shear strain and rotation rate.

This short discussion about slip surface and two perpendicular material lines can be easily extended to general shear deformation and marker lines of any arbitrary orientation. For narrowing shear zones, $\sigma_1$ will vary between 90° (pure shear) and 135° (simple shear). For broadening shear zones, $\sigma_1$ will vary between 135° (simple shear) and 180°. In the following we extend this discussion to finite deformation including the heterogeneous perturbation strain generated by the slip plane including a homogeneous background strain.

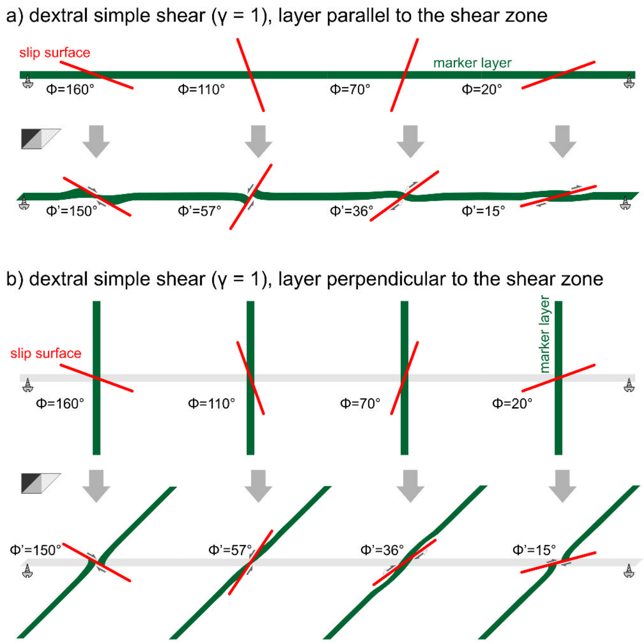
## Finite offset of marker lines

We modelled the slip surface as a rigid elliptical object with a high aspect ratio (50) embedded in a zero Reynolds number linear Stokes flow. The Newtonian material is decoupled from the object, which allows slip between the matrix and the inclusion. Similar to fractures modelled as weak inclusion with high aspect ratios (Kocher and Mancktelow, 2005), the slip surface in our model has no stable position except parallel to the fabric attractor and the rotation rate is almost identical to a passive marker (Exner et al., 2004). Although slip along the inclusion induces a perturbation flow field in its vicinity, the flow field does not influence the rotational behavior of the object itself.

The model is based on Jeffery's (1922) well-known solution for a rigid ellipsoid in free-space Stokes flow where the interfacial velocities equate. An applied velocity field is greatly perturbed close to the ellipsoid but this perturbation vanishes at great distances from the ellipsoid. To adapt this model to account for slip at the interface, normal velocities at the boundary are equated and a free-slip boundary condition is applied by setting tangential surface tractions to zero. The latter can be achieved by setting internal tractions to zero and equating these with the external tractions yielding a solution for the ellipsoid velocity gradient tensor (see Appendix A in O'Connor, 2008). For a complete derivation of this model in two-dimensions see Mulchrone (2007).

Figure 4a shows the deformation of a passive marker layer, which is deformed by dextral simple shear with a shear strain of $\gamma = 1$. Similar to previous physical and numerical models (e.g. Grasemann and Stüwe, 2001; Grasemann et al., 2003; Exner et al., 2004; Kocher and Mancktelow, 2005; 2006), the marker layer is parallel to the shear zone boundary (i.e. the fabric attractor). Slip surfaces are oriented with an angle of $\Phi$ = 160°, 110°, 70° and 20° with respect to the shear direction (measured anticlockwise). During simple shear deformation the slip surfaces rotate to orientations of $\Phi'$ = 150°, 57°, 36° and 15°. For detailed discussion of the resulting structures including general shear boundary conditions, Non-Newtonian and anisotropic materials, the reader is referred to the modelling studies cited above. Note that in both Cartesian reference frames (x-axis either parallel to the shear zone boundary or parallel to the slip surface) the structures developed along the slip surfaces with $\Phi'$ = 150°, 57° would record a "missing section" and would be classified by most structural geologists as extensional. On the contrary the slip surfaces with $\Phi'$ = 15° would be recognized as a "thrust" recording a "contractional" offset of the marker layer. The structure with $\Phi'$ = 15° records essentially no offset (or more accurately, a small thrusting component) because it initiated with antithetic slip but during progressive rotation of the slip surface, it crosses the principal stress direction $\sigma_3$ where the shear sense is reversed to synthetic. However, it is important to emphasize that the modelled deformation is simple shear and since the green marker layer is parallel to the shear zone boundary, its total elongation is zero. The local thickness change and offset of the marker layers in the vicinity of the slip surface is only controlled by the heterogeneous perturbation deformation, which diminishes at some distance to the fault.

**Figure 4. Finite deformation (dextral simple shear, $\gamma$ = 1) of a marker layer**



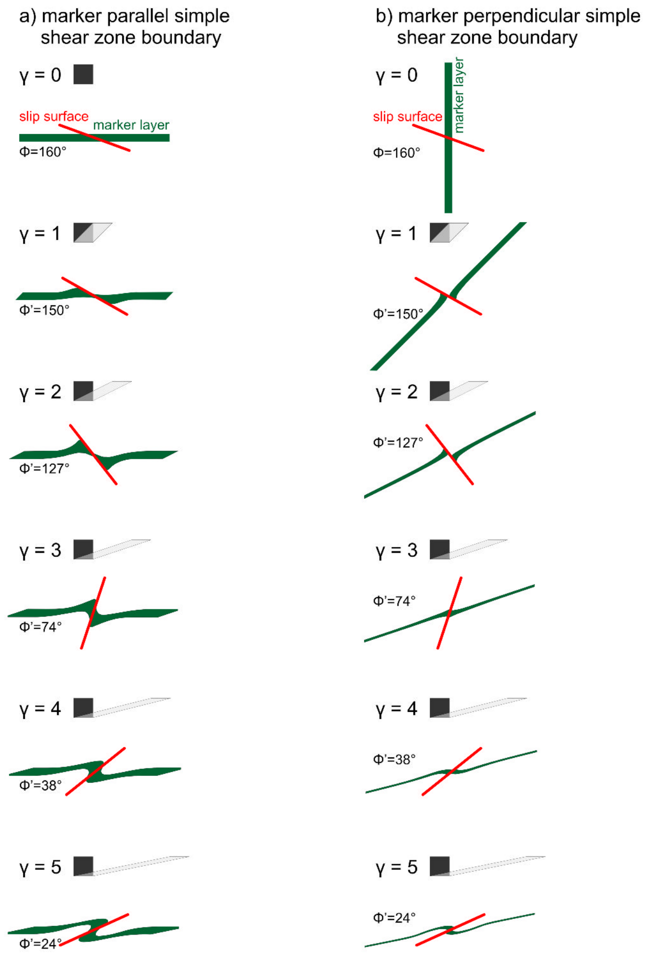

Finite deformation (dextral simple shear, $\gamma = 1$) of a marker layer along a slip surface with different initial orientations. a) layer parallel to the shear zone. b) layer perpendicular to the shear zone.

The model in Figure 4b has exactly the same boundary and initial conditions except that the green marker layers are oriented perpendicular to the shear zone boundary. This has a major influence on how the structure develops during progressive shearing, because the layer does not remain parallel to the fabric attractor but rotates together with the slip surface (but at a different rate) into the shear direction. While the slip surface with $\Phi' = 150°$ has a clear extensional offset, the description of the slip of other structures is more complex and partly dependent on the chosen reference frame. In the frequently used Cartesian reference frame, where the x-axis is parallel to the shear zone boundary, the slip surface with an initial angle of $\Phi = 110°$ will start to develop as an antithetic “back-thrust”. After rotation through the perpendicular, the slip surface acts as an antithetic extensional fault. However, if the reference frame is chosen with the x-axis parallel to the slip surface, the perturbation strain is causing a local extensional offset of the green marker horizon. Similarly, the structure with an initial orientation of the slip surface of $\Phi = 70°$ starts to develop in a shear zone parallel reference frame as an antithetic normal fault. When it rotates through the principal stress direction $\sigma_3$ at 45°, the shear sense is reversed and the slip surface would be interpreted as a synthetic thrust. In a slip surface parallel reference frame the perturbation strain causes a local contractional offset of the green marker horizon, which reverses to an extensional offset after rotation through the principal stress direction. The slip surface oriented initially with $\Phi = 70°$, causes a clear local extensional offset of the green marker horizon, but observed in a shear zone parallel reference frame, the slip surface acts as a synthetic thrust.

Considering the complex structural development of slip surface in ductile shear zones, which may change their local shear sense and which may rotate at different rates than marker horizons, which are offset along the slip surface, it is interesting to observe the development of such structures at larger magnitudes of shear strain. Note, that we restrict our discussion to simple shear background strain. General shear boundary conditions may create even more complex deformation histories because slip surfaces and marker layers may both or individually rotate against the shear direction.

In what follows we investigate the structural development of a shear zone parallel (Fig. 5a) and perpendicular (Fig. 5b) green marker layer cut by a slip surface initially oriented at $\Phi = 160°$. During shearing the slip surface rotates into the shear direction changing the instantaneous shear sense from syn- to antithetic at 135° (i.e. $\sigma_1$) and from anti- to synthetic at 45° (i.e. $\sigma_3$). The rotation rate is indistinguishable from that of a passive marker line. The progressive development of the structures up to a shear strain of $\gamma = 5$ in Figure 5a is well understood and similar models have been described by means of analogue forward and dynamic reverse numerical modelling (Exner et al., 2004; Kocher and Mancktelow, 2005). However, the structure in Figure 5b has a distinctly different evolution. The physical parameters, mathematical model, boundary conditions, initial orientation and progressive rotation of the slip surface are identical to the model in Figure 5a. The only difference is that the deformation of a passive marker layer with the same thickness but oriented perpendicular to the shear zone has been observed. The major differences during progressive shearing are, that the initially perpendicular passive marker layer is subjected to rotation and to stretching and thinning. The maximum rotation rate is at the beginning of the model, when the layer is oriented at 90° with respect to the shear zone boundary. During rotation towards the fabric attractor (i.e. the direction parallel to the shear zone boundary) the rotation rate decelerates. At the same time, the green marker layer is stretched during rotation. The maximum instantaneous stretching rate is at an orientation of 45° with respect to the shear zone boundary, when the layer is parallel to $\sigma_3$. The structures resulting from shear zone parallel and normal markers at low shear strain (e.g. $\gamma = 1$ in Fig. 5a and b) look qualitatively totally different. For example the structure in Figure 5a at a shear strain of $\gamma = 1$ would be classified as a shear band. However, the structure developed under exactly the same parameters and boundary conditions but with an initial shear zone perpendicular marker (Fig. 5b) would be referred to as negative slipped flanking fold. Interestingly, the structures become qualitatively more and more similar at larger shear strains: at $\gamma = 4$ both structures in Figure 5a and b are no slip flanking folds and at $\gamma = 5$, positive slipped flanking folds.

**Figure 5. Progressive deformation (dextral simple shear, $\gamma$ = 1-5) of a marker layer**




Progressive deformation (dextral simple shear, $\gamma$ = 1-5) of a marker layer a) parallel and b) perpendicular to the shear zone boundary. The slip surface has an initial orientation of 160° with respect to the fabric attractor. Note, that the structures in a) and b) become increasingly similar with increasing strain.

## Discussion

The model results in Figure 4 and 5 have some important implications, which should be considered when interpreting the kinematics of flow from slip surfaces in ductile shear zones. In order to keep the discussions of the complex behavior of rotating slip surfaces in ductile flow as clear as possible, we restrict our models to simple shear boundary conditions, which have the important simplification of only one non-rotating direction, which is parallel to the shear zone boundary and which experiences no length change during deformation. All markers and the slip surface, which creates a heterogeneous perturbation strain but behaves as a passive marker in terms of rotation rate, are rotating into the shear direction.

One of the major results of previous numerical and analogue models of slip surfaces deforming in ductile shear zones is that contractional and extensional offset along the slip surfaces is just a function of its orientation to the instantaneous stretching axes (i.e. the principal stress directions) of the background deformation (Wiesmayr and Grasemann, 2005). Therefore, extensional and contractional offset along slip surfaces may occur during the same deformation event within a shear zone, if slip surfaces form at different angles (e.g. as conjugate systems) or form at different increments and therefore rotate into different orientations (Exner et al., 2006). Moreover, when the slip surfaces rotate through a principal stress direction of the background deformation, the shear sense reverses and extensional offset may be “reactivated” with contractional offset and vice versa (Exner et al., 2004; Kocher and Mancktelow, 2005). Conjugate sets of slip systems (mostly shear bands) and possible reactivations have been observed in natural rocks leading to different and sometimes conflicting kinematic interpretations (e.g. Harris and Cobbold, 1985; Behrmann, 1987; several examples in Snoke et al., 1998). This study extends this previous work and emphasizes that extensional versus contractional offset along slip surfaces is furthermore a function of the orientation of the marker line with the slip surface and the chosen reference frame. Although the assumption that the foliation in highly strained rocks forms a marker parallel to the shear zone boundary is in many cases justified (e.g. Passchier and Trouw, 2005), the fabric attractor in broadening general shear zones is oriented oblique to the shear zone boundary (Simpson and De Paor, 1993). Additionally other markers like secondary foliations or veins, which may form at high angles with respect to the shear zone boundary, can be offset by slip surfaces. Therefore the interpretation of local extensional or contractional offset along slip surfaces in terms of narrowing and broadening shear zones independent of other structural observations should be avoided. Furthermore we suggest to avoid terms like extensional crenulation cleavage (Platt and Vissers, 1980) and preferentially use non-genetic terms like C’-type cleavage (Passchier and Trouw, 2005). Similarly, positive and negative slip (Coelho et al. 2005) along slip surfaces may be misleading, and should only be used if the reference frame is clearly defined and/or the markers are parallel to the shear zone boundary.

Slip systems with various orientations may be used in combination with the recorded offset and rotational behavior in order to estimate the rotational quality of the flow type (e.g. Wiesmayr and Grasemann, 2005). Such quantitative kinematic investigations are based on the fact that (Simpson and De Paor, 1993): (i) the non-rotating eigenvectors of flow separate sectors where material lines either co- or counter-rotate with respect to the shear direction; (ii) the principal stress directions separate quadrants where the slip surfaces record syn- and antithetic shear with respect to the overall shear sense. Kocher and Mancktelow (2005) demonstrated that structures developed around a single slip surface can be backward restored using a dynamic reverse model based on analytical solutions derived by Schmid and Podladchikov (2003), even if the structure records large shear strain. However, this technique requires the knowledge or (justified) assumptions about the initial configuration of the marker lines. As shown by the two simple models in Figure 5, the structures outlined by marker layers parallel and perpendicular to the shear zone boundary look qualitatively very similar and without the knowledge of the initial orientation of the layer before deformation, mechanic or kinematic backward balancing techniques will probably result in plausible but not necessarily unique solutions.

## Conclusions

1) The orientation of the reference frame is essential for defining extensional and contractional offset along a finite slip surface deforming in a ductile shear zone. Traditionally, Cartesian coordinate systems with axes either parallel to the shear zone boundary or parallel to the slip surface have been used.

2) Extensional and contractional offset along a slip surface are also a function of the orientation of marker layers. The same slip surface may cause extensional and contractional offsets in two perpendicular marker layers.

3) The sense of slip along a slip surface is dependent on its orientation to the principal stress directions of the deformation in the shear zone. Therefore, differently oriented slip surfaces may cause extensional and contractional offset within the same deformation increment.

4) Marker layers parallel to the fabric attractor do not rotate and the local deformation in the vicinity of the slip

surface is only controlled by the heterogeneous perturbation strain caused by the slip surface. Marker layers oblique to the fabric attractor additionally experience the background strain of the shear zone and will therefore rotate.

5) Two structures which form by offset of two perpendicular marker layers along a slip surface look very different at small strains. However, in simple shear zones the structures become qualitatively very similar at larger shear strains because all fabric elements have been rotated into the direction of the fabric attractor.

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