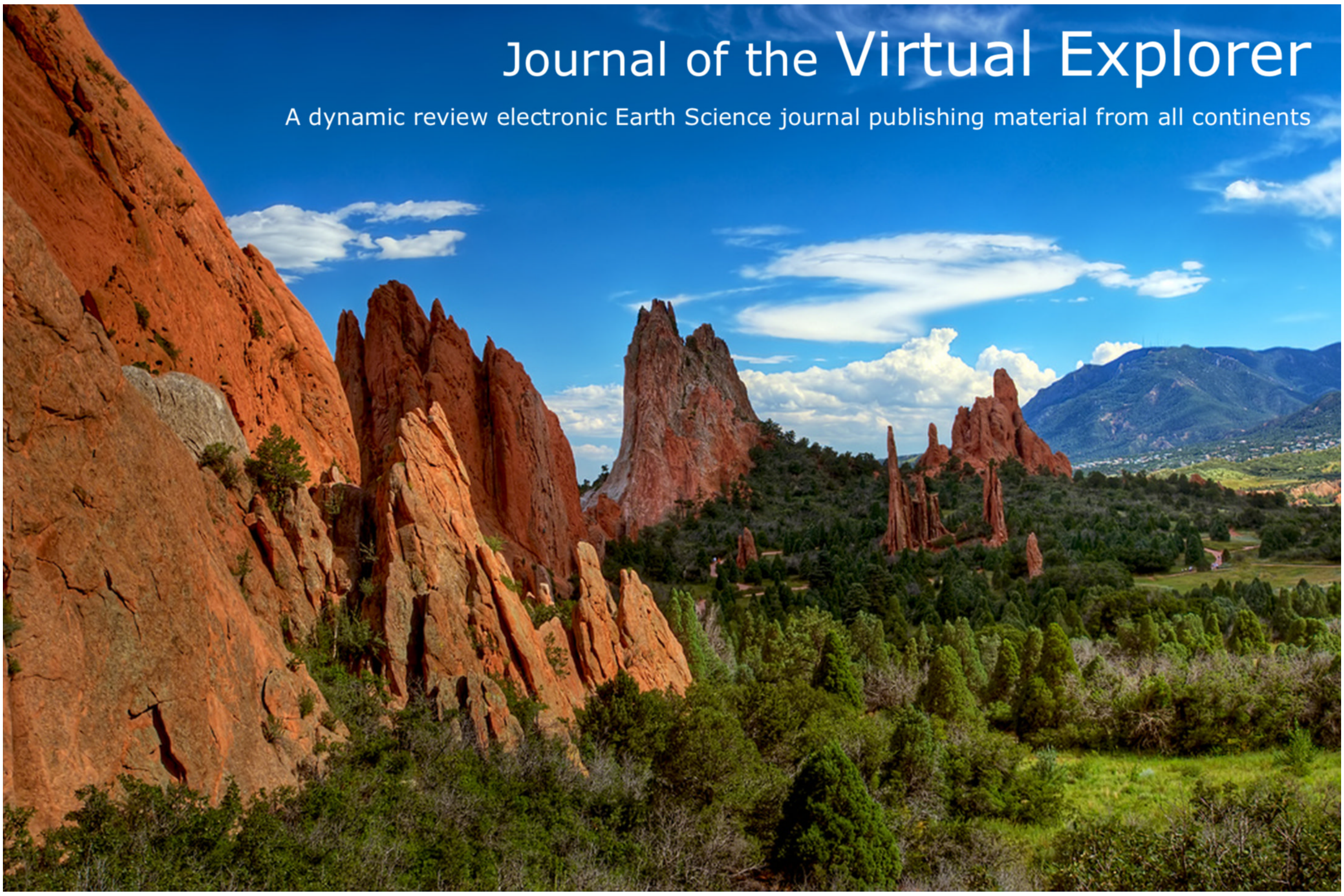

Two mechanisms for forming flanking folds

Cees Passchier, Vincent Heesakkers, Sara Coelho

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume 30, paper 6
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Abstract: Flanking folds are fold trains or shearband-like structures in layered rocks that are symmetrically arranged around a cross-cutting element (CE) such as a vein, alteration zone, or fault. The folds only occur close to these CE and seem to "flank" them, hence the name. Most flanking folds form by either of two very different mechanisms, although the structures produced can be very similar: (1) Disc-shaped planar high-viscosity CE such as veins, dykes or alteration zones around faults or thin veins can partly protect the adjacent part of the host rock from ductile deformation (object-related flanking folds). If the CE are originally oblique to a marker horizon such as layering, and if the entire assemblage is deformed in non-coaxial flow, flanking folds will develop in the marker horizon because of the difference in flow geometry in the far field and close to the CE. (2) If a brittle fault is active during ductile non-coaxial flow in the wall rock, principal stresses along the fault must be oriented parallel or normal to the fault surface because of the Anderson principle (which states that principle stress must be parallel or perpendicular to a "free" surface not to a fault surface). As a result, flanking folds develop in the marker horizon (Andersonian flanking folds). The presence of flanking folds along a fault plane without alteration zones are therefore an indication that a brittle fault was active during ductile deformation. Analogue experiments and field examples from Namibia are used to illustrate both types of flanking folds.

http://virtualexplorer.com.au/article/2009/209/mechanisms-for-forming-flanking-folds

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Introduction

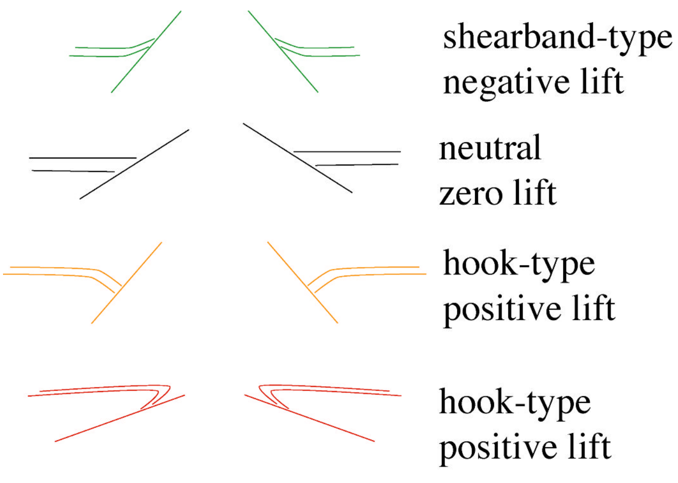
Flanking folds, first extensively described by Gayer *et al.* (1978) and Hudleston (1989), are fold trains in a primary planar or linear structure, such as a foliation, layering or lineation, which are "flanking" isolated secondary planar structures, such as faults, fractures or veins, which lie oblique to the primary one. Some of them are traditionally referred to as "drag folds", but we prefer to use the term "flanking folds" (Passchier 2001) because of its non-genetic connotation and the option to use it for all fold and deflection structures close to secondary elements in rocks, including shear bands. Flanking folds have been the subject of extensive experimental and field research over the last years, including the effects of flow conditions, strain, initial geometry and orientation on the final geometry (Passchier, 2001; Grasemann and Stüwe, 2001; Grasemann *et al.*, 2003; Exner *et al.*, 2004; Grasemann *et al.*, 2005; Wiesmayr and Grasemann, 2005; Coelho *et al.*, 2005; Kocher and Mancktelow, 2006; Gomez *et al.* 2007). These studies have shown that it is theoretically possible to determine strain, flow conditions such as the kinematic vorticity number (Means *et al.* 1980), and some other parameters from flanking folds. In practice, the ideal circumstances needed to carry out such quantitative analyses will be rarely found in field examples. However, even if detailed quantitative analysis is not possible or needed, flanking folds can be very useful for two purposes; 1) they can be used as shear sense indicators; 2) they can indicate the presence of open voids and active brittle faults in otherwise ductilely flowing rocks, even if the faults and voids have only been present transiently and have been subsequently sealed and overprinted. This is obviously useful, since open voids or faults can be indicative of enhanced fluid pressure or excessive strain rates.

In most cases, flanking folds are isolated asymmetric structures in strongly deformed terrains and geologists will be tempted to use them as indicators for the sense of shear. This is possible, but not in all cases, and before one attempts to use these structures as shear sense indicators, it is important to consider why and how they form. We have carried out a number of simple analogue experiments, which we present here to illustrate the concept. In addition, the experimental results are used to interpret natural flanking folds in Namibia.

Terminology

Flanking folds can occur wherever a host element (HE), a planar or linear marker structure such as a foliation, bedding, or a lineation, is transected by a disc shaped object or fault, known as the crosscutting element (CE). Flanking folds are deviations in the orientation of the HE close to the CE (Fig. 1). Several suggestions have been made for terminology to allow a quantitative description of flanking folds (Passchier, 2001; Grasemann and Stüwe, 2001; Grasemann *et al.*, 2003; Exner *et al.*, 2004; Grasemann *et al.*, 2005; Wiesmayr and Grasemann, 2005; Coelho *et al.*, 2005; Kocher and Mancktelow, 2006; Gomez *et al.* 2007), but no consensus presently exists. Here, we restrict ourselves to simple terminology to distinguish different geometries of flanking structures (Fig. 1). Wherever the HE bends into the CE to become more parallel, the geometry will be similar to that of shear bands and we refer to this shape as "shear band type" (Fig. 1); where the HE becomes less parallel when approaching the CE, the shape is that of a fish-hook, and we refer to it as "hook-type", after Hudleston (1989). Shear band type and hook-type flanking folds correspond to positive and negative lift of the HE above the intersection point of the HE and the CE as defined by Coelho *et al.* (2005). Both categories are separated by "neutral" lift, when no flanking folds exist (Fig. 1).

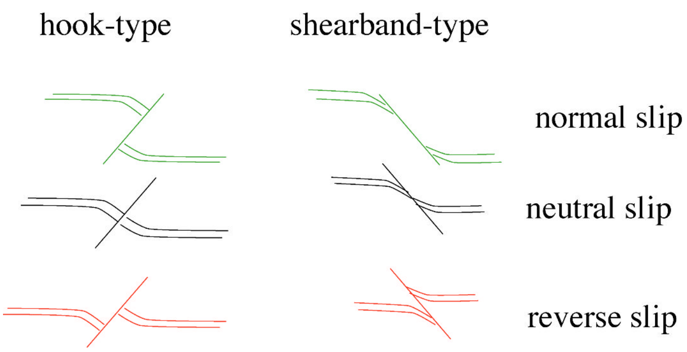
Figure 1. Different types of flanking folds



Different types of flanking folds

Besides the two possible geometries of flanking folds, the magnitude and sense of slip on the CE is important. Most of us are used to an intuitive concept where slip on faults will have a "drag" effect on the HE that will tend to decrease the amount of separation of the cut-off points as compared to a neutral situation, where the HE runs up to the CE without distortion (Fig. 2); we call this "normal slip". However, counterintuitive "reverse slip", where the amount of separation is increased (Fig. 2), is commonly observed in flanking folds. Reches and Eidelman (1995) recognized that drag occurs along a CE with reduced or non-existing friction, resulting in reverse drag at the CE centre and normal drag at the CE tips. The drag is a result of perturbations of the strain or flow field at the vicinity of the CE (Passchier *et al.*, 2005) which causes the flanking structure to form.

Figure 2. Definition of the geometry and slip of flanking folds as used in this paper



Definition of the geometry and slip of flanking folds as used in this paper

Two mechanisms – one result

Flanking folds form in response to local inhomogeneous deformation in the rock. Two groups of mechanisms of formation have been proposed, which are of different nature, but which can produce very similar geometries:

1 – Object-related flanking folds

These are structures that form in a continuum where a planar object or CE of different rheology is present oblique to the HE. If a CE of lithology B is embedded in lithology A, flow in both units will be different because of different responses to the imposed external stress field. Refraction of foliation through layers, and the deflection of foliations around rigid porphyroclasts in metamorphic rocks are examples of this kind of behaviour. Flanking folds can form at the contact to a CE with a different rheology, even if the rheology is uniform in A. A CE with different lithology will produce "strain shadows" on both sides where the stress field will be affected by the presence of the CE; as a result, folds will develop there. This kind of flanking fold is least predictable in the types of geometries that will form; fold shape depends on the shape, rheology and orientation of the CE. In the case of dykes or fractures, the wall rock may have been altered adjacent to these, which effectively gives a CE composed of three parallel rheological zones; flanking folds commonly develop in such alteration zones.

2 – Andersonian flanking folds

As first recognised by Anderson (1905,1905a), principal axes of stress must be parallel and normal to "free surfaces", external surfaces of a solid body where these are in contact with a medium that cannot support a shear stress, such as air, water or magma. The Earth´s surface is such a free surface, and the orientation of brittle structures that interrupt it or form close to it is therefore affected as a boundary effect. This is visible in faults that have preferential orientations at the Earth´s surface, and in secondary mudcracks, which usually impinge on primary ones at right angles. What is not often explicitly said or realised, however, is that the "Anderson principle" also applies to free surfaces that occur deep within the Earth's crust or upper mantle. Fluid-filled cavities or faults can form if fluid pressure equals lithostatic pressure, and they can form at any depth. If such a fluid-filled inclusion transects a marker such as a foliation or bedding, deformation close to the inclusion is governed by the Anderson principle and stress axes will rotate to be parallel and normal to the contact. As a result, fluid inclusions will strongly deflect the orientation of the stress field and the far field deformation will be different from the deformation close to the inclusion. However, in this case the Anderson principle governs the orientation of ductile deformation structures rather than brittle faults. In many cases, this leads to the development of flanking folds (Arslan *et al.* 2008). In fact, in the absence of a clear lithology contrast, the presence of flanking faults along a planar surface in the rock implies that it acted as an open and probably fluid-filled fracture during ductile deformation in the wall rock. An extreme example of such faults are foliation boudins, where flanking folds develop in opposite geometry on both sides of a lozenge-shaped cavity that can reach a fluid-filled volume of several cubic metres, even in the middle crust (Arslan *et al.* 2008).

Experiments

In order to illustrate how flanking folds develop by the two main mechanisms mentioned we present a series of analogue experiments, using a transparent putty in a simple shear box. Experiments were carried out with either a rigid piece of cardboard or open fractures at various initial positions.

EXPERIMENTAL SETUP - APPARATUS

The apparatus used for the analogue experiments consists of the four-sided deformation box (fig. 3) described by Piazolo *et al.* (2001). Plexiglas segments are connected with flexible plastic to form a wall of chevron-folded pistons (Fig. 3). Metal springs on the outside allow for homogeneous contraction and extension of the walls. The corners of the springs are connected to aluminium plates (P in figure 3). Each plate is attached to a sliding carriage (C1 in figure 3) operated by a motor (M1, M2, M3 and M4) to control the movement in the x-direction. The motors are attached to two PVC boards (B1). Two additional motors (M5) control the movement of the PVC boards along sliding carriages (C2) in the y-direction. The entire assembly is attached to a basal plate (B2). The maximum extension of the walls is approximately 35 cm in the x-direction and 25 cm in the y-direction. Towards the edges of the box, deformation becomes increasingly less homogeneous. The top of the box is open.

The six motors are controlled by the PC-program LabView and allow five different transpression regimes ranging from simple shear to plane strain conditions by defining the kinematic vorticity number and the stain rate along a specific axis. The maximum shear strain that can be reached is around two, depending on the original geometry of the box. During the experiment, pictures of the top of the box are taken by a stationary digital camera. The shear box was lighted from below through the transparent basal plate. Pictures were taken every 300 seconds and later combined to generate Canvas movies.

Materials

The matrix material used in the deformation box is polydimethyl-siloxane (PDMS, trade name SMG 36), a polymer manufactured by Dow Corning, Great Britain. PDMS is a transparent non-toxic polymer with a density of 0.965 g/cm^3 and a viscosity (at room temperature) of 5.0*10^4 Pa s. The material shows Newtonian viscous flow behaviour for strain rates <5*10^{-1} s^{-1} (Weijermars, 1986). Glycerin was used at the bottom of the box as a lubricant to reduce basal shear, but this is non-reactive with the PDMS and has a lower viscosity (1.55*10^{-2} Pa s) and a higher density (1.17 g/cm^3).

To represent a rigid CE oblique to HE during deformation, a 1 mm thick and ~4 cm long piece of cardboard was placed in the centre of the box (movie 1). To represent fluid filled fractures or veins that do allow slip during deformation, we used two methods; (1) two pieces of overhead-projector plastic with Silicone gel (200/12.500 CS Fluid, manufactured by Dow Corning, Great Britain) in between, which were allowed to slip past each other (Movie 2, 4). The viscosity of the Silicone gel (1.25*10^4 Pa s) is about 40 times lower than that of the PDMS; (2) an open fault, created by making a vertical knife cut in the putty which was filled with a drop of lubricating kitchen soap to keep the fault from healing (Movies 3 and 5).

Experimental procedure

The basal plate was lubricated with a thin film of glycerin after which the PDMS was set into the deformation box. We let the PDMS settle for three hours to eliminate most of the trapped air bubbles until the upper surface smoothened. A cut of ~ 4 cm long was made in the centre of the box at angle α, where α is the angle between the CE and the HE. A piece of cardboard, overhead-projector paper with glycerine, or lubricating kitchen soap was placed inside the cut, after which we let the PDMS settle for another hour. A 0.5 x 0.5 cm carbon powder grid was set on the top of the PDMS using a non-fixated plastic sheet photocopy of a regular grid, which was pressed onto the PDMS to transfer the line pattern from the plastic to the putty. Again, we let the PDMS settle for another hour before the experiment was started.

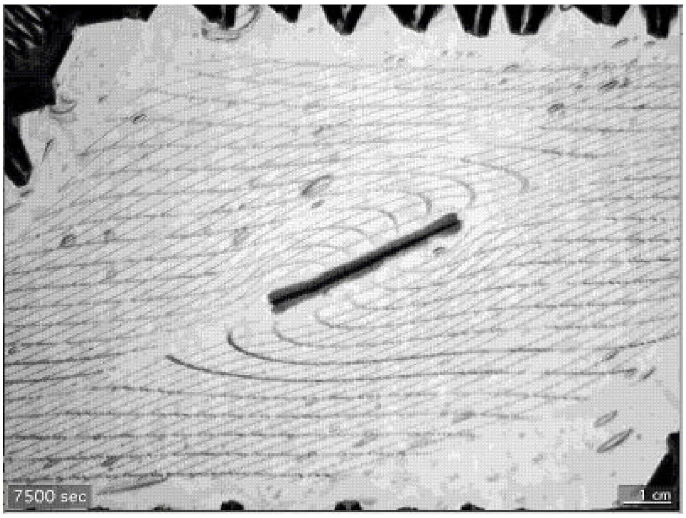
The experiments were conducted under simple shear conditions with initial box dimensions of 210 mm x 180 mm. The displacement applied by motors M1, M2, and M3 was set at 150 mm with a velocity of 0.02 mm/s. Each experiment took 7500 second, resulting in a shear strain of 1.65 and a shear strain rate of 2.2*10^{-4} s^{-1}. All experiments were carried out at room temperature.

Experiments

The first experiment used a 1 mm thick piece of cardboard at an initial position α = 90°. The second through fifth experiments represent fractures / veins that allow slip during deformation, oriented at initial positions of α = 90°, 135° and 160° respectively.

RESULTS

Figure Movie 1. Flanking folds along a rigid object, α = 90°

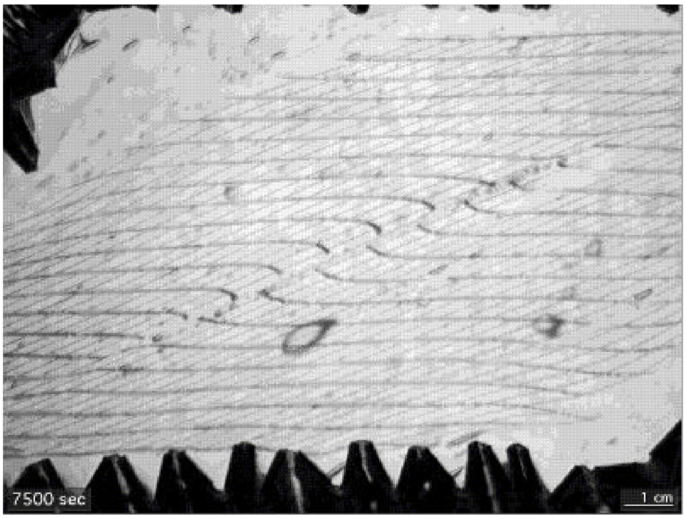


During rotation of the cardboard model-CE, an anticlinal and synclinal hook-type flanking fold train develops in the hanging- and footwall respectively, with axial surfaces parallel to the CE. Most intense folding occurs at the upper tip of the CE in the hanging wall and in the lower tip of the CE in the footwall. The HE shows significant extension parallel to the axial surfaces within both fold hinges. Note that the horizontal markers above and below the CE display synforms and antiforms respectively, formed due to the fact that the CE does not stretch; as a result, the material over and below the CE undergoes extra stretch, resulting in the opposite fold geometry on both sides and a "necking structure" of the HE at the tips of the CE. Progressive deformation results in amplification of the fold trains. The final structure generated is a hook-type flanking fold without slip and with over-roll according to the classification of Coelho *et al.* (2005). A natural equivalent of this experiment could be a short competent vein within a less competent matrix.

Figure Movie 2. Andersonian flanking folds - rigid fault walls - α = 90°

In the early stages of the experiment, increasing antithetic slip is observed along the CE with increasing rotation of the CE. Anticlinal and synclinal fold trains develop in the hanging- and footwall respectively, with axial surfaces parallel to the CE. Most intense folding occurs at the centre of the CE and decreases towards the tips. Only minor extension in the fold hinges is observed. Note the reverse steps in the HE at the tips of the CE, with up-stepping markers the upper tip and down-stepping markers at the lower tip. With progressive deformation, the reverse slip gradually changes into normal slip along the CE at the end of the experiment. The final structure generated in the horizontal marker lines is a hook-type flanking fold with normal slip (negative slip, negative lift and over-roll according to the classification of Coelho *et al.*, 2005). The folds in the horizontal marker lines have their maximum interlayer separation at some distance from the CE because the inserted plastic sheets cannot stretch. Away from the centre of the CE, the fold shape is clearly different on both sides of the CE, resulting in asymmetric, lobate- cuspate pairs, the cusps being located on the CE; tight on one side, more open on the other. A natural equivalent of this experimental result could be alteration rims along an open slipping fracture.

Figure Movie 3. Andersonian flanking folds -deformable fault walls - $\alpha = 90°$

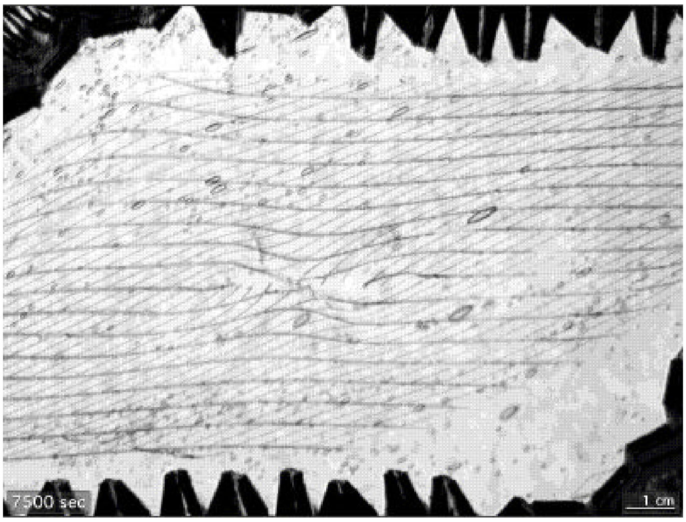


This experiment is very similar to the previous one, but illustrates what happens if a stretching fault or free-slipping fault exists in a ductilely flowing material (Means 1990; Barr and Housemann 1996). There is a clear transition during the deformation process from reverse to normal slip along the fault. Also, the fold shape is different from the previous experiment; the maximum separation of layers in now directly along the fault plane, not away from it. The hook shape of folds is less pronounced, and there is a more symmetrically distribution of the fold shape on both sides of the CE. A natural equivalent of this experimental result could an open, slipping fracture during ductile flow.

Figure Movie 4. Andersonian flanking folds - rigid fault walls - $\alpha = 135°$

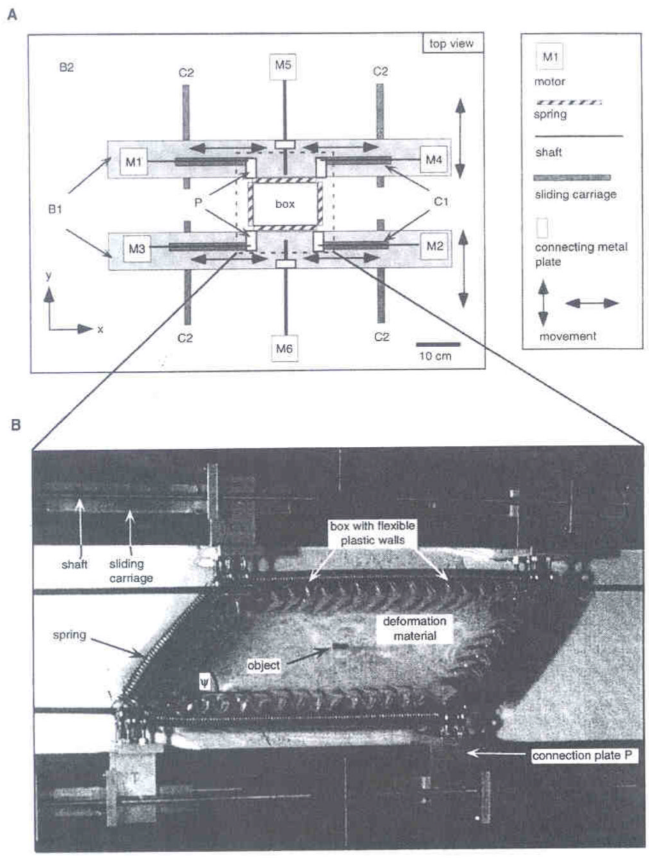
During the entire experiment, reverse slip is observed along the CE with increasing rotation of the CE, although the slip halts and is about to change to normal at the end of the experiment. Anticlinal and synclinal fold trains develops in the hanging- and footwall respectively, with axial surfaces parallel to the CE. Most intense folding occurs at the center of the CE and decreases towards the tips. Only minor extension in the fold hinges is observed. Reverse steps in the HE occur at the tips of the CE, with up-stepping markers at the upper tip and down-stepping markers at the lower tip. Initially, the flanking folds in the horizontal marker lines are shear band type, but after the CE rotates through an angle of $\alpha = 90°$, they change to hook-type. The final structure generated in the horizontal marker lines are hook type flanking folds with reverse slip (negative lift and over-roll according to the classification of Coelho *et al.*, 2005). Away from the centre of the CE, the fold shape is clearly different on both sides of the CE, resulting in asymmetric, lobate-cuspate pairs, the cusps being located on the CE; tight on one side, more open on the other. A natural equivalent of this experimental result could be alteration rims along an open slipping fracture.

Figure Movie 5. Andersonian shear bands -deformable fault walls - $\alpha = 160°$



This experiment shows an open fault, filled with lubricating kitchen soap, at a small angle to the horizontal marker lines. In this orientation, a fault is strongly shortened but rotates little during progressive deformation; as a result, shear band type flanking folds develop. In addition, the horizontal marker lines bends towards the CE on both sides, creating an opposite antiform-synform pair. This is due to the enhanced shearing rate along the lubricated fault with respect to the far field flow.

Figure 3. Deformation apparatus



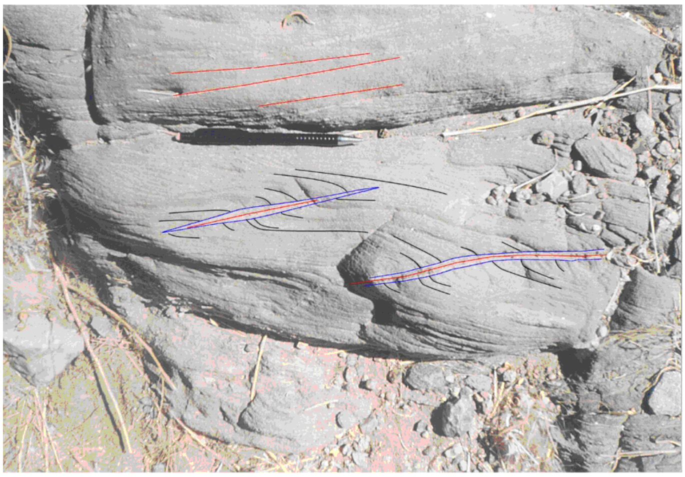
A. Schematic drawing of deformation apparatus (view from the top) where x and y are along symmetric axes of apparatus. B1 are PVC boards, B2 is the base plate, C1 is the set of 4 sliding carriages parallel to x-direction, C2 is a set of 4 sliding carriages parallel to the y-direction, P are connecting aluminium plates, and M1-M6 are motors. B. Close up of deformation box with flexible walls (view from top). Angle ψ is the angle between the sides of deformation box. (Piazolo *et al.*, 2001).

Examples from Namibia

1 – object-related flanking folds

The structures in Fig. 4 are developed in metaturbidites of Neoproterozoic age on the Lower Ugab Domain, Namibia, which were invaded by syenite plutons during ductile deformation at greenschist facies conditions in the Cambrian (Passchier *et al.* 2002, 2007). Close to the plutons, the metaturbidites were invaded by aplitic and pegmatite veins. Fig. 4 shows an outcrop where the tips of such veins fractured the layered metaturbidites and locally developed 1-2 cm wide zones of alteration in the wall rock (in blue in fig 4). The metaturbidite is locally enriched in albite. On the photograph it is clear that wherever alteration zones are present, hook-shaped flanking folds with neutral slip have formed such that the angle between CE and HE at the intersection points is nearly 90°. Where no alteration zones formed around the fractures, in the top of the outcrop, no flanking folds formed. We interpret this to indicate that the original angle between the fractures and HE was steep, possibly close to 90°. Ductile flow in the metaturbidites reduced this angle to ~30°, except where alteration zones were present; there, flow was deviant from the far field conditions, and preserved the original steep angle between CE and HE to some extent. We interpret the development of this structure to be similar to that shown in Movie 1.

Figure 4. Flanking folds in metaturbidites from Namibia



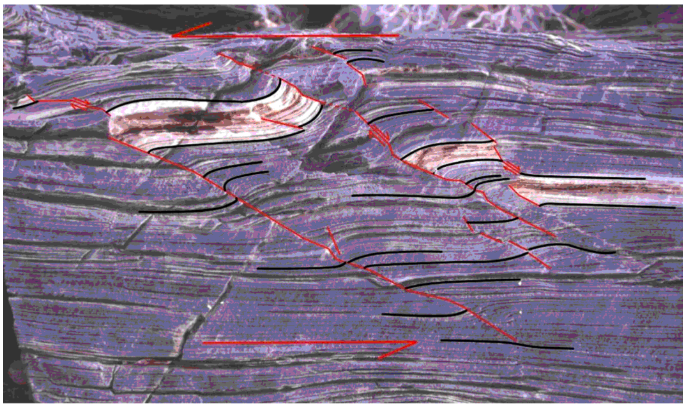
Explanation in text. Location 14,2947 E, -20,7236 S.

2 – Andersonian flanking folds

We show two types of Andersonian flanking folds from Namibia, hook-shaped and shear band shaped, but both with reverse slip.

(a) The first example in Fig. 5 shows layering in turbiditic marbles from the lower Ugab domain, which was interrupted by minor faults, along which hook-shaped flanking folds developed with reverse slip. The white layer in the photograph was originally one continuous bed in the stratigraphy. The amount of slip along the faults decreases downward as can be seen in Fig. 5, and the faults terminate in the marble before reaching the lowest beds visible. No alteration zones are visible, and the faults do not show any deposition of vein material or alteration rims. We interpret this type of flanking fault to have formed by slip on the fault planes during ductile flow in the marble away from the faults; faults either formed by enhanced fluid pressure or relatively high strain rate. Since the marbles have statically recrystallised, it is impossible to estimate differential stresses during ductile flow. Faults may have generated as fractures nearly oblique to layering, after which the rocks underwent sinistral shear while the fractures remained open and acted as dextral faults. Sinistral shear sense can be determined independent of the flanking folds from the shape of quartz sigmoids (Passchier and Trouw 2005) in the same outcrop. The Anderson principle caused the marble close to the faults to flow by a different flow type than that in the far field, creating the flanking folds. We imagine that the evolution of this structure was very similar to that shown in movie 3. Hook-type flanking folds with reverse slip are amongst the most common types of flanking folds.

Figure 5. Hook-type flanking folds in marble formed along fractures.



Explanation in text. Location 14.3858E, -20.7484S

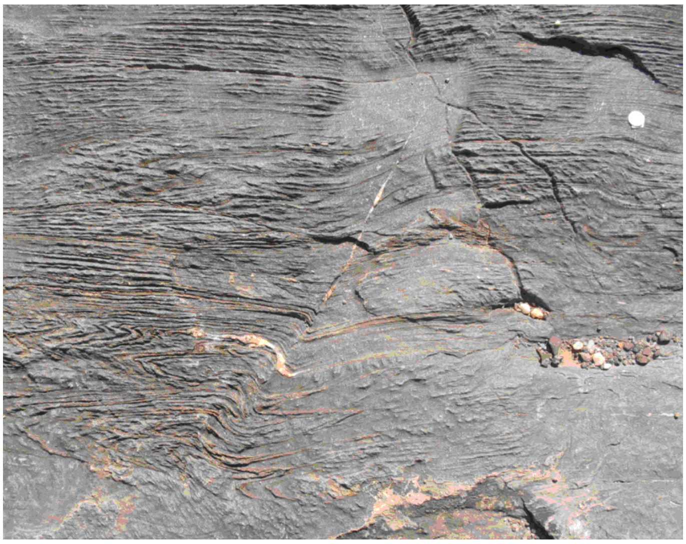
(b) Spectacular hook- and shear band type flanking folds develop along thin quartz veins in marbles near the "House of the German" (HOG) in the central Goantagab domain, Namibia (Passchier *et al.* 2002; Coelho *et al.* 2005). We refer to these features as HOG-structures after the location. Here, two sets of older quartz and carbonate veins have been boudinaged to asymmetric shear band boudins and sigmoids, indicating sinistral shear sense. This shear sense also fits shear sense on a regional scale determined during our mapping project (Passchier *et al.* 2002). Slip along the faults was dextral, opposite to the ductile bulk shear sense: This slip sense is indicated by layer offset along the faults, and the shape of quartz-filled jogs within the fault (Fig. 6). More than 60 faults, with lengths varying from 10-300cm were investigated, and all show the same geometry of flanking folds along the length of the faults. Figs. 6 and 7 show typical examples; in the centre of the faults, shear band geometry flanking folds with reverse slip dominate; these grade laterally into neutral and then hook-shaped flanking folds with normal slip. All flanking folds show dextral displacement of the layering with a gradation of tight folds to open folds as the amount of slip decreases from the tips of the faults into the wall rocks.

How can these enigmatic structures be explained? At first sight, the shear-band flanking folds suggest a two-phase evolution of sinistral slip and shear band formation, followed by dextral offset. However, the development of these structures can be explained by a single stage of tectonic evolution. The shear band shaped flanking folds with reverse slip can be explained if the angle between faults and bedding was originally small; a sinistral bulk shear sense in this case will steepen the faults with respect to the foliation, while inducing a dextral slip sense along them. Due to the Anderson principle, the layering close to the fault retains a relatively small angle to the fault and therefore develops a shear band shape, which is not due to shear band drag on the fault since the slip is reverse. At the tips of the fault, slip induces S-shaped folds that transform into hook-shaped flanking folds when the faults propagate outwards through them. (Fig. 7) This type of flanking folds seems to be rare in nature, but we compare its development with that shown in movie 4.

Figure 6. Shear band type folds

Shear band type folds along a fault with reverse slip formed by bulk sinistral shear sense. A quartz filled jog in the vein indicates slip sense is dextral on the fault. Location 14.4299E, -20. 6756S

Figure 7. Shear band type folds



Shear band type folds along a fault with reverse slip formed by bulk sinistral shear sense, overprinting isoclinal folds in marble. Location 14.4299E, -20. 6756S

How to distinguish object-related and Andersonian flanking folds

Object related flanking folds will normally show no slip, unless they intruded as veins along older faults (Movie 1, Fig. 4). Also, a certain volume of material of a rheology different from that of the wall rock must be present. If flanking folds are induced by alteration rims, they can normally be spotted since the alteration rims will vary in thickness or be locally absent; flanking folds will then be bound to the sites with alteration only (Fig. 4).

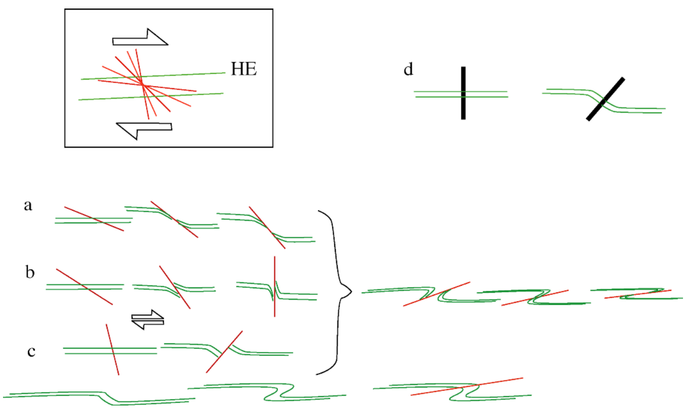
Andersonian flanking folds are normally associated with slip, and reverse slip is quite typical (Movies 2-4; figs 5-7). Faults may be sealed with vein material (Fig. 6, 7), but can also remain free of deposits. Typically, gradients in the geometry of flanking folds are smooth and flanking folds are present along the entire length of the CE. Where faults open in extension, foliation boudins can form with larger veins filled with blocky and idiomorphic crystalline vein material (Arslan *et al.* 2008).

How to determine shear sense from flanking folds

Flanking folds can form by the two main groups of mechanisms mentioned above, and by polyphase deformation. Andersonian flanking folds are most useful as shear sense indicators, since they are better understood and more predictable in their development. Basically, the geometry of the folds that form depend on initial orientation of the faults with respect to the HE (the angle α), and the flow conditions. Even these two basic parameters can give rise to a bewildering array of flanking fold types (Passchier, 2001; Grasemann and Stüwe, 2001; Grasemann *et al.*, 2003; Exner *et al.*, 2004; Grasemann *et al.*, 2005; Wiesmayr and Grasemann, 2005; Coelho *et al.*, 2005; Kocher and Mancktelow, 2006; Gomez *et al.* 2007). Grasemann *et al.* (2005) even lamented that flanking folds are useless as shear sense indicators since they occur in mirror pairs for opposite shear sense. Gomez *et al.* (2007) suggested to use groups of flanking folds in different stages of development, but the obvious problem is to decide whether flanking folds of different shape really belong together.

The situation may not be as desperate as suggested by the literature, though. First of all, most shear zones with undeformed wall rocks must form in a flow regime close to simple shear. Secondly, the range of possible initial orientation of fractures may be limited. From the orientation of the stress field, fractures will most likely develop in tension, parallel to σ_1 of stress or at a small angle to σ_1: in simple shear, this implies fractures between 20°-80° inclined to the flow plane (Fig. 8, inset). Gently dipping fractures will lie parallel to HE, or develop into normal shear bands in this case, but the steep fractures will develop a reversed shear sense and rotate in the shear direction; these are the ones that can develop shear band-shaped flanking folds for shallow angles, and hook shapes for steep angles. The possible range of development of such structures is illustrated in Fig. 8.

Figure 8. Possible range of flanking folds and their evolution within sinistral shear.



a) Shear bands with normal slip. b) Shear band with reverse slip that evolves into hook shaped flanking fold with reverse slip along shallow CE. c) Hooked shape flanking fold with reverse slip along steep CE, could evolve into normal slip with progressive deformation. d) Flanking folds along a rigid CE.

Shear bands with normal slip on shallow fractures may not rotate enough to develop into hook-shaped flanking folds (Movie 5; Fig. 8a). However, those on faults with reverse slip will develop into a shear band geometry and gradually rotate to form tight hook shaped flanking folds (Movie 4; Fig 8b, c). Only originally steep faults will develop hook-shaped flanking with reverse slip from a start (Fig. 8c). Since these are much more common than shear band shapes with reverse slip, most active fractures in shear zones probably start a at steep angles to the foliation.

If flanking folds form early during the development of a ductile shear zone, they may gradually develop into closed hook shaped folds, while the shear sense on the fault may reverse during deformation (movie 3; Fig. 8b, c). This was first shown by Exner *et al.* (2002) and is confirmed by our experimental results presented above (movie 3). As a result, the reverse slip of hook-type flanking folds can transform to normal slip, after which the flanking folds cannot be distinguished from those that would form by a fold train that is cut by a late fault. Fortunately, the vergence of the folds is similar for all these different scenarios. Object related flanking folds formed from original steep orientations of the CE will also develop the same vergence as Andersonian ones. As a result, flanking folds can usually be used as shear sense indicators.

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