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From XY tracking to buckling: axial plane cleavage fanning and folding during progressive deformation

Giulio Viola[a,*], Neil S. Mancktelow[b]

[a]Department of Geological Sciences, University of Cape Town, 7701 Rondebosch, South Africa
[b]Geologisches Institut, ETH-Zentrum, CH-8092 Zürich, Switzerland

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Abstract

Folding of axial plane cleavage can occur during progressive deformation without a change in the overall background flow. Two field examples of upright (Lachlan Fold Belt, SE Australia) and recumbent (Naukluft Nappe Complex, central Namibia) folds are presented, in which strongly refracted pressure solution cleavage in competent layers on the fold limbs is buckled as a result of ongoing fold amplification. Finite element modelling confirms that cleavage refraction on limbs can be sufficient for cleavage planes to be subsequently shortened and therefore folded. Cleavage refraction is unequally developed on opposite limbs of asymmetric folds formed by oblique shortening of a layer in coaxial flow or by folding in a more general shear environment. The differences in finite strain on opposite limbs can be quite marked even when the fold shapes themselves are not obviously asymmetric. For folding in simple shear flow, as specifically modelled here, refraction is only strong on the fold limb that rotates against the imposed sense of shear. In known shear environments, this provides a potential kinematic indicator in folded units at relatively low strain (e.g. in simple shear, γ of around one), where other higher-strain indicators, typical of mylonites, are not yet sufficiently developed or are equivocal.

Keywords: Cleavage refraction; Folds; Shear criteria; Finite element modelling

1. Introduction

Since the earliest classic studies of Sharpe (1847) and Sorby (1853), one of the principles applied to studying deformed rocks is that the cleavage or schistosity developed during a single phase of deformation is approximately parallel to the XY plane of the finite strain ellipsoid (Cloos, 1947; Badoux, 1970; Siddans, 1972; Wood, 1973, 1974; Tullis and Wood, 1975). It has been recognized for even longer that folds and cleavage have a genetic relationship, and that cleavage is approximately axial planar to coeval folds (Sedgwick, 1835; Darwin, 1846; Rogers, 1856). In fact, most field structural geologists rely on the orientation of axial plane cleavage to infer and reconstruct the geometry and orientation of large-scale folds. If the cleavage itself is folded, this is taken as evidence of a second distinct deformation phase. In general, this is well-founded in theory, analogue (e.g. Roberts and Strömgård, 1972) and numerical modelling (e.g. Dieterich, 1969), and natural observation (e.g. Wood, 1973). However, it is not universally correct, as has been recognized for some time (e.g. see discussion in Hobbs et al. (1976)). Cleavage defined by compositional differences (e.g. pressure solution or crenulation cleavage) is fixed to material points in the rock. In a non-coaxial deformation, the XY plane rotates through material points and a material plane cannot therefore track the XY plane (e.g. Murphy, 1990). It is also well known that in progressive shearing the XY plane (and foliation) rotates toward near parallelism with the shear plane and even small perturbations (e.g. due to stronger grains or particles) will locally take the foliation orientation through the shear plane, leading to folding (and refolding) of the foliation in a single high shear strain deformation (e.g. van den Driessche and Brun, 1987). For very high shear strains, fold hinges themselves will rotate towards

* Corresponding author. Now at: Geological Survey of Norway, N 7491 Trondheim, Norway. Tel.: +47-73-904000; fax: +47-73-921620
E-mail addresses: gviola@geology.uct.ac.za; giulioviola@operamail.com (G. Viola).

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parallelism with the shear direction (Sanderson, 1973) and sheath fold geometries can develop (Cobbold and Quinquis, 1980).

We present here another example where folding of an axial plane cleavage can occur during progressive deformation without a change in the overall background flow, but at much lower strain magnitude. This occurs as the result of cleavage refraction in the more competent layers of folded rocks and cleavage fanning. Examples are discussed from very disparate geographic areas and tectonic environments, suggesting that the process may be quite general and widespread. The unequal development of folded cleavage on alternate fold limbs may also provide a sense-of-shear indicator for folds developed during shear.

2. Field examples

Two examples are presented, one from a region of upright folding (Lachlan Fold Belt, SE Australia), and one from a region of recumbent folding developed during low-angle thrusting and nappe emplacement (Damara Belt, Naukluft Nappe Complex, central Namibia).

The example from the Lachlan Fold Belt is shown in Fig. 1. The outcrop represents one limb of an upright anticline–syncline pair (anticline to the left looking north as in Fig. 1) with a wavelength on the order of 50–100 m. In outcrop, cleavage is a penetrative slaty cleavage in the marly shales and a spaced pressure solution cleavage in the more limestone-rich beds (the lighter and less obviously cleaved beds of Fig. 1). There is very marked cleavage refraction, with the cleavage nearly perpendicular to bedding in the limestones. Closer examination of the cleavage in the limestones reveals that the cleavage is actually weakly folded with a wavelength on the scale of a few centimetres and an axial plane approximately parallel to the bedding (Fig. 1b).

The second example is from the Naukluft Nappe Complex (NNC), central Namibia (Korn and Martin, 1959; Hartnady, 1978). The NNC forms a far-travelled klippe whose source is still uncertain. As the frontal zone of the Damara Orogenic Belt, the NNC is characterized by the occurrence of thrust sheets comprised of sediments detached from their substrata.

The small fold discussed here is parasitic to a larger-scale train of recumbent folds. Fig. 2 shows the fold and a corresponding sketch. The fold is developed in carbonate (dominantly dolomite) beds with thin, darker, marly intercalations and shows a quite spectacular convergent cleavage fan. The fold axis plunges 5° towards 042°.

Locally the bedding is modified and accentuated by pressure solution during deformation, as discussed below,

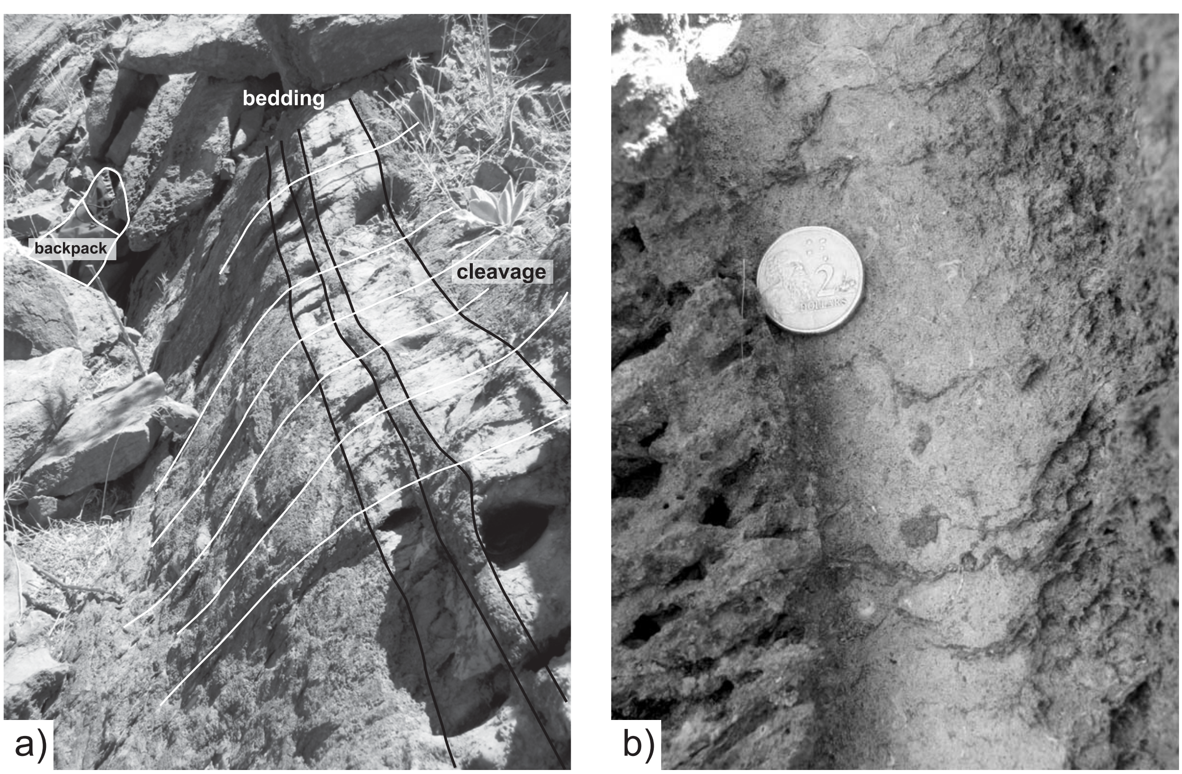


Fig. 1. Cleavage refraction on the limb of upright folds in alternating marly shales and limestones from the Lower Devonian Cavan Bluff Formation, Lachlan Fold Belt, SE Australia. The location is Tait's Straight, on the Murrumbidgee River, ca. 10 km SW of Yass. A description of the deformation history in a region 8–10 km SE of this location, but in the same stratigraphy, is given by Hood and Durney (2002). (a) Overview looking north showing the marked cleavage refraction on the limb of an anticline (to the left)—syncline pair. (b) Close-up, looking north, of a single limestone bed showing cleavage refraction into an orientation approximately perpendicular to bedding and the development of small scale folds in cleavage with an axial plane parallel to bedding.

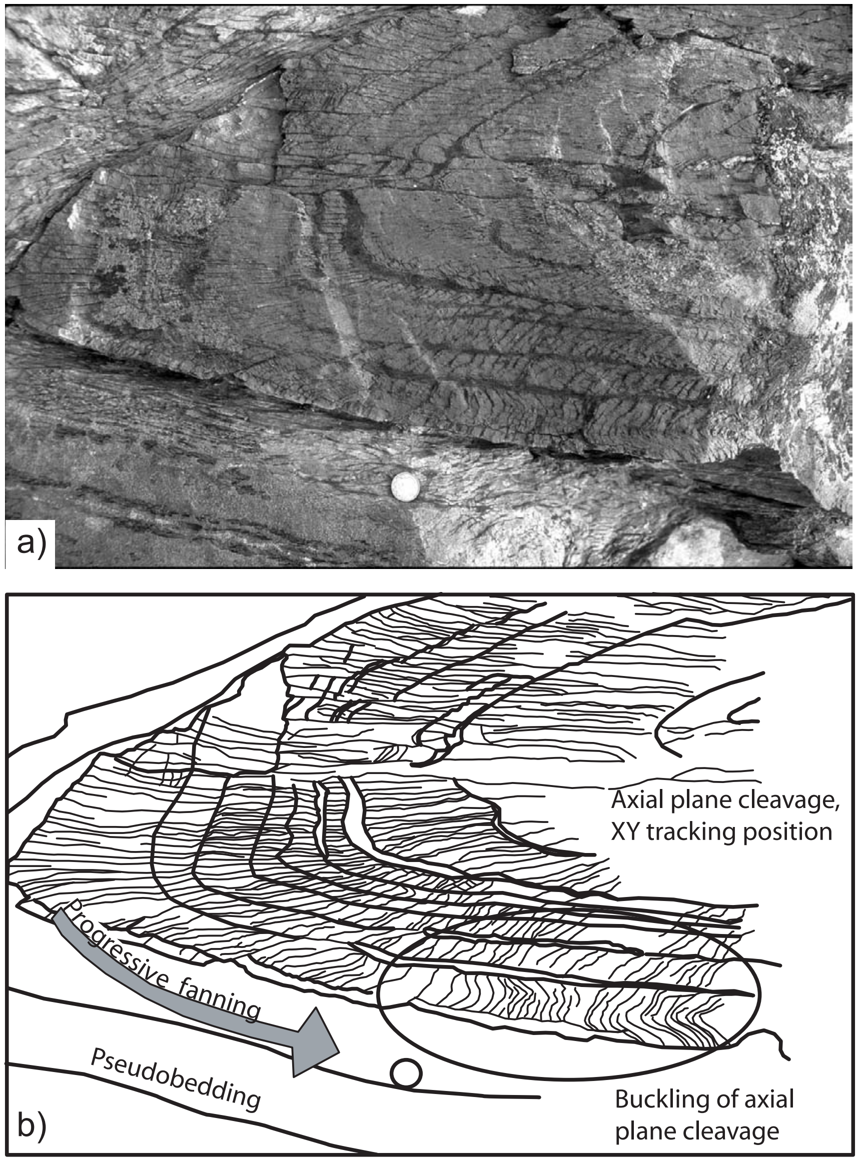


Fig. 2. Recumbent fold in alternating more dolomitic and marly layers from the Naukluft Nappe Complex (NNC) of central Namibia. Photo looking northeast, on the Remhoogte Pass road, GPS coordinates 23° 58.3555′, 16° 16.739′ relative to WGS84.

and is therefore referred to here as pseudobedding. Pressure solution in the cleavage domains is clearly an important process, as evidenced by the concentration of insoluble residual material and by the marked offset of dark marly layers defining the pseudobedding across individual cleavage surfaces.

Within the region of the hinge and upper limb, the axial planar cleavage is formed by disjunctive, equally spaced surfaces that are approximately planar and parallel. Significant fanning of this spaced pressure solution cleavage is only observed on the lower fold limb. The fanning is already noticeable immediately below the fold hinge and becomes progressively stronger moving from the hinge into the lower limb. Near the hinge, the approximately planar form and domainal spacing is similar to that on the upper limb, the only difference being the slight convergent fanning away from the axial plane orientation. However, further toward the inflection point on the lower limb, the average cleavage orientation gradually approaches a near perpendicular orientation with respect to pseudobedding and becomes progressively more folded, with an axial plane approximately parallel to the pseudobedding itself. The small-scale folds have amplitudes of 10–20 mm and wavelengths of 40–60 mm. In this region of cleavage folding, the spacing between the cleavage domains also increases. Individual cleavage domains are offset across pseudobedding surfaces. The pseudobedding surfaces across which offset occurs show an increased thickness of darker insoluble material when compared with the same continuous surfaces closer toward the hinge where no folding or offset is observed. All these observations are consistent with layer perpendicular shortening (i.e. layer parallel stretching and thinning) overprinting cleavage domains bound to material surfaces of different and more competent composition, which were near perpendicular to bedding prior to this overprint. Because both the competence contrast and the amplitude of initial irregularities in the cleavage surfaces were probably not very large, a significant component of more homogeneous cleavage-parallel shortening would have occurred during folding of the cleavage domains, particularly in the initial stages (e.g. Ramberg, 1970; Hudleston, 1973; Hudleston and Stephansson, 1973; Abbassi and Mancktelow, 1992; Mancktelow, 2001). This is reflected in the increased spacing between cleavage domains in the folded region. Part of the shortening was also clearly accommodated by pressure solution in the marly intercalations of the pseudobedding, producing the apparent offset of the folded cleavage domains across pseudobedding surfaces.

3. Analytical analysis of stress and strain refraction

In an isotropic material, the instantaneous stretching axes (ISA) are parallel to the principal stress axes. An analysis of stress refraction across an interface is therefore a good basis for considering the progressive development of cleavage refraction during folding (Treagus, 1973, 1983). The result for two viscous incompressible materials A and B with viscosities μ_A and μ_B was derived independently by Strömgård (1973) and Treagus (1973) and is given by:

$$\frac{\tan 2\phi_A}{\tan 2\phi_B} = \frac{\mu_B}{\mu_A} \quad (1)$$

where ϕ_A and ϕ_B are the angles made by the principle compressive stress axis σ_1 with the interface in materials A and B, respectively. The equation is graphed in Fig. 3 for values of the viscosity ratio μ_A/μ_B from 1 (no difference and no refraction) to 100 (very strong refraction). From Fig. 3 it is immediately obvious that for values of the viscosity ratio exceeding ca. 20, σ_1 is either nearly parallel (for layer shortening) or perpendicular (for layer extension) to bedding in the more competent (i.e. higher viscosity) layer. The changeover between these two situations occurs over a very small range in layer orientation to either side of 45° relative to the orientation of σ_1 in the weak matrix, i.e. the orientation where the layer is neither shortened nor extended. As discussed by Lister and Williams (1983), buckle folding with a high viscosity ratio between layer and matrix is thus an excellent example of coaxial deformation coupled with spin (i.e. rigid body rotation of the fold limbs). Until the limb reaches an orientation of 45° to the imposed shortening direction, the almost coaxial strain history will produce a cleavage nearly perpendicular to bedding in the limb. From 45° onward, the strain still remains approximately coaxial but there is a switch in principal axes resulting in shortening parallel to the existing cleavage

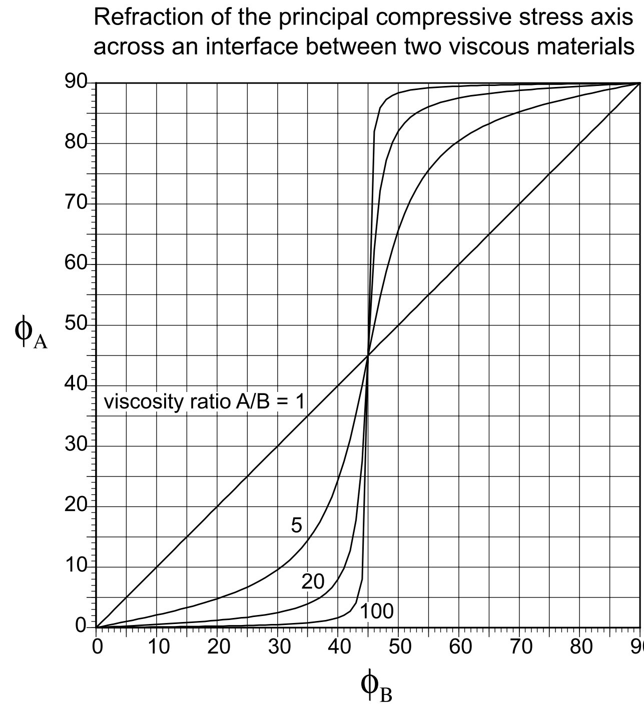


Fig. 3. Refraction in orientation of the principal compressive stress axis across an interface between two incompressible viscous materials for different viscosity ratios of A to B. ϕ_A and ϕ_B are the angles made by the principal compressive stress axis σ_1 with the interface in materials A and B, respectively.

planes. If the cleavage has already developed a sufficiently strong anisotropy or if it has developed a domainal compositional banding, as in the case of pressure solution, the switch to shortening parallel to cleavage can produce folding of the cleavage planes themselves with an axial plane parallel to the layer boundary.

For symmetric folding in pure shear, where the layer is initially parallel to the shortening direction, both limbs should have a similar history and be mirror symmetric about the axial plane. However, if the layer is initially oblique to the shortening direction the two limbs will have distinctly different histories, because one limb initially rotates toward and one away from the bulk shortening direction. As discussed above, the XY plane (and therefore cleavage) forms at a high angle to layering, with the result that refraction relative to the cleavage in the adjacent matrix is stronger on the limb that rotates away from the shortening direction.

The same will be true in simple shear (or any general shear between pure and simple), because one limb rotates with and one against the background rotational component. Because the XY plane, and therefore the cleavage, in the matrix rotates with the sense of shear, asymptotically approaching the shear plane with increasing shear, there will be a more strongly developed refraction of cleavage from matrix to layer in the counter-rotating than in the co-rotating limb. The tendency to later shorten parallel to the cleavage in the layer, and therefore to develop a folded cleavage, is consequently also greater in the counter-rotating limb.

4. Numerical modelling

To test this theoretically expected behaviour, finite element numerical models were run for pure shear shortening parallel to a single layer and simple shear of a single layer initially inclined at 20° to the shear direction (Figs. 4 and 5). Comparable models for pure shear shortening of an oblique layer have already been published by Anthony and Wickham (1978). In all our models, the viscosity ratio between layer and matrix was 50, the wavelength to layer thickness ratio of the initial introduced sinusoidal perturbation was approximately equal to the theoretical 'domidominant' or fastest growing wavelength (cf. Biot, 1961; Smith, 1975; Fletcher, 1977), and the initial amplitude was 1/20th of the layer thickness. The finite element models assume an isochoric linear viscous rheology for both layer and matrix. Local or global volume change, as is clearly involved in the development of pressure solution cleavage domains in the natural examples of Figs. 1 and 2, cannot be reproduced. However, the incremental and finite strain pattern developed in these simplified numerical models fits well with the natural observations on cleavage development.

In particular, convergent cleavage refraction is strongly developed in the limb regions of the competent layer, as expected from Fig. 3 for a viscosity ratio of 50. It is not possible to introduce a mechanical anisotropy or layering parallel to cleavage in the current numerical models. However, to get an idea of the effects that could develop, fold development in Fig. 4 was split artificially into two stages. In Fig. 4a, the long axis of the finite strain ellipse (corresponding to the trace of the XY plane in 3D) is plotted at 60% bulk shortening, when the limbs have already rotated through the 45° orientation. This highlights the strong refraction of cleavage expected in the limbs. In Fig. 4b, the long axis of the incremental strain ellipse for subsequent folding from 60 to 70% bulk shortening is shown. It is clear

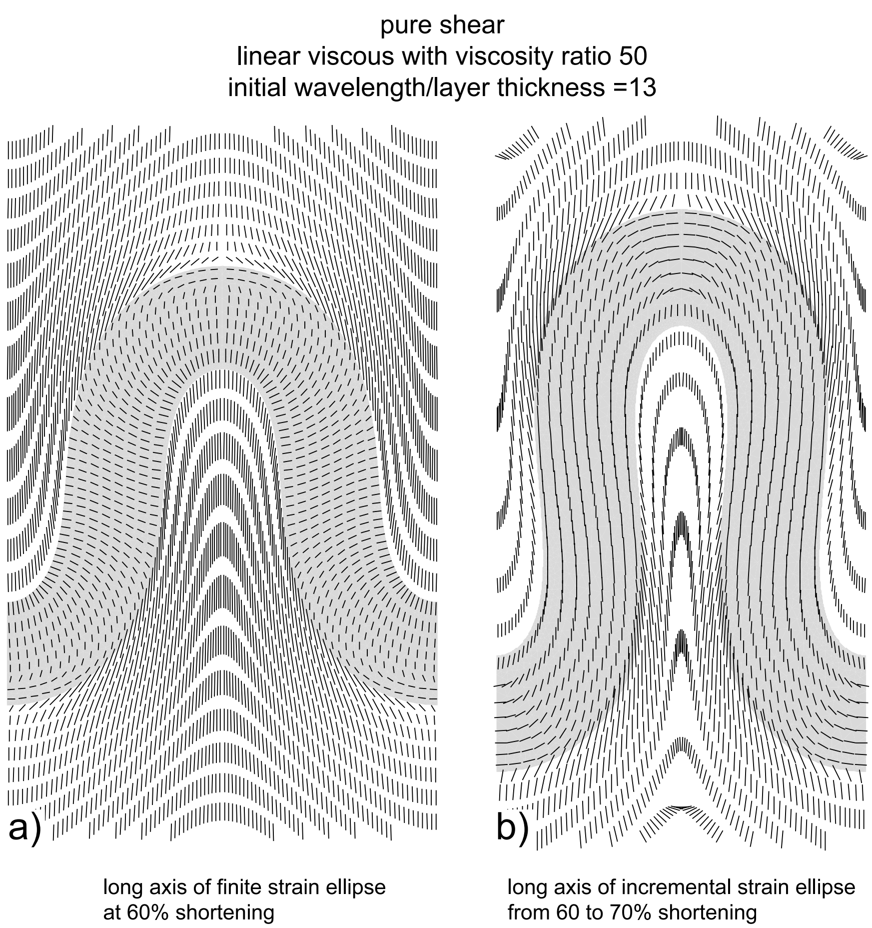
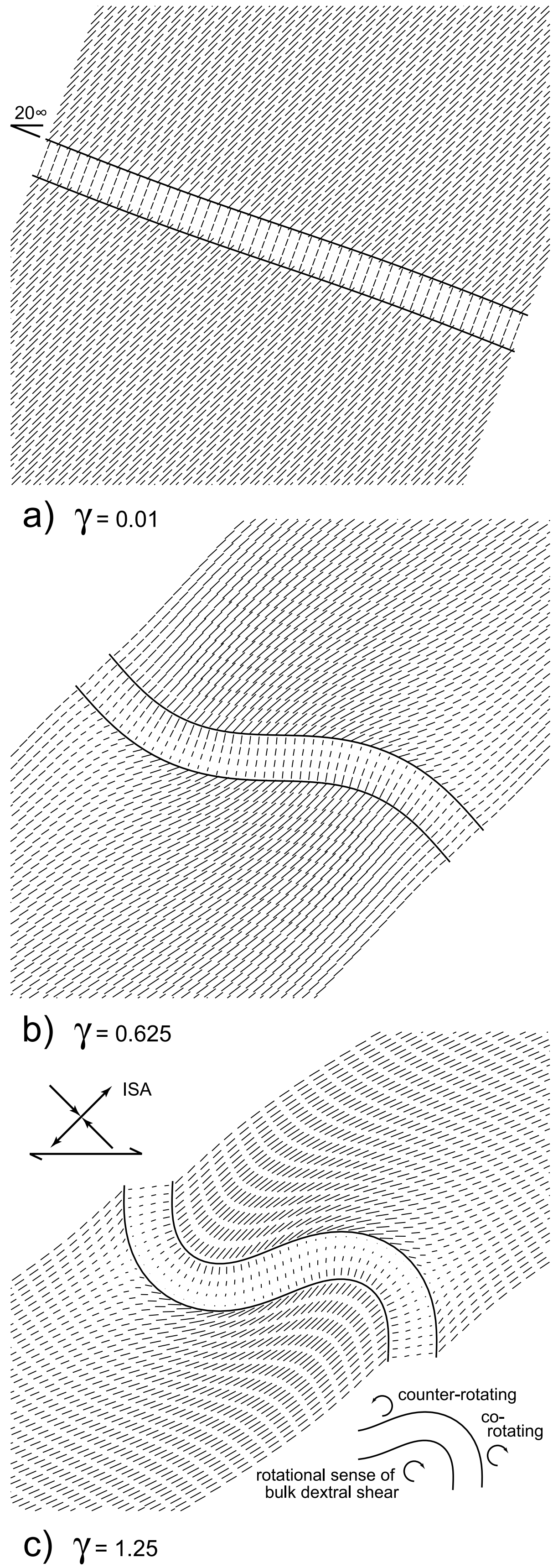


Fig. 4. Finite element numerical model of single-layer folding for incompressible viscous materials in pure shear, with bulk shortening initially parallel to the layer. Lines are the direction of the major principal axis of finite strain in (a) and of incremental strain in (b). Modelling was done with a personally developed code (N. Mancktelow) including Uzawa iterations to maintain incompressibility, 7-node triangular elements with seven internal integration points, linear (3-node) interpolation of pressure, elimination of pressure at the element level, and automatic remeshing when triangle quality degenerated (e.g. Hughes, 2000; Zienkiewicz and Taylor, 2000). The viscosity ratio was 50, the wavelength to thickness ratio of the initial sinusoidal perturbation was 13, and the initial amplitude was 1/20th of the layer thickness.


20∞
a) γ = 0.01
b) γ = 0.625
ISA
counter-rotating
co-
rotating
rotational sense of
bulk dextral shear
c) γ = 1.25

that this subsequent deformation will result in a shortening near parallel to the previously developed cleavage surfaces close to the inflection points on the limbs, which could produce the folding observed in nature. Moving toward the hinge zone, there is a transition region where the angle between the previous cleavage orientation (developed as a result of the initial stage of 60% bulk shortening) and the subsequent incremental extension direction (representing a further 10% shortening) is much smaller than in the case of the inflection points on the limbs. In this region, the existing cleavage would not be folded but instead a cleavage orientation should develop that more accurately reflects the total finite strain.

In pure shear with the layer initially parallel to the shortening direction, the two limbs of the fold have a mirror symmetric relationship to each other (Fig. 4), reflecting the overall system symmetry. This is not the case for pure shear with a layer initially inclined to the shortening direction, nor for single layer folding in simple shear. Anthony and Wickham (1978) have already published the results of finite element models for folding of an oblique layer in pure shear. As can be seen from their fig. 5, refraction of the XY plane of finite strain (and therefore cleavage) is much stronger on the longer limb that initially rotated away from the shortening direction than on the shorter limb that initially rotated toward the shortening direction. Anthony and Wickham (1978) note that "extension structures, such as boudinage, may occur in the long limb in the latter stages of folding". Extension of the long limb would be accompanied by shortening of the refracted cleavage planes and therefore potentially folding of this existing cleavage, as observed in our natural examples.

Here we present finite element model results for folding in simple shear, which we believe are more appropriate to the Naukluft Nappe Complex example. As can be seen in Fig. 5, the overall asymmetry in fold shape is not very marked but there is a clear difference in the refraction of XY (and therefore cleavage) for opposite limbs of the fold. Cleavage refraction in the limb that counter-rotates relative to the imposed shear is very marked in comparison to the adjacent matrix, whereas the refraction on the co-rotating limb is much more subdued. In Fig. 5b ($\gamma = 0.625$), both fold limbs are still being shortened and the XY cleavage plane is therefore still being progressively extended on both limbs. In going from Fig. 5b to Fig. 5c (i.e. from $\gamma = 0.625$ to 1.25), the co-rotating limb continues to be shortened and the XY cleavage on this limb is continuously extended. However, the counter-rotating limb has rotated into the field of incremental extension, with the result that the XY cleavage planes on this limb are incrementally shortened. Folding of already developed anisotropic cleavage or pressure solution cleavage domains could occur, as observed in Fig. 2.

5. Discussion

Folding of layered rocks is generally accompanied by strong cleavage refraction on the fold limbs, because the viscosity ratio necessary for buckling instability also produces important stress refraction across layer boundaries (Strömgård, 1973; Treagus, 1973, 1981; Cobbold, 1983; Treagus, 1983, 1988; Treagus and Sokoutis, 1992). The shear stress that can be sustained at the layer interface is determined by the viscosity of the weaker matrix and the shear strain rate parallel to the interface in the strong layer will therefore be low. As a result, buckle folding of competent layers in a weak matrix is a good example of spinning coaxial strain (Lister and Williams, 1983), with the ISA in the competent layers always nearly parallel or perpendicular to the layer boundary. A switch between the shortening and stretching ISA occurs as the layer in the limb position rotates from an orientation producing layer shortening to one of layer extension. Cleavage planes developed up until this stage are subsequently shortened, with both parts of the deformation history being nearly coaxial. Cleavage in rocks is not generally a simple passive marker surface but represents a mechanically active element (e.g. solution cleavage domains that have a different composition or mechanical anisotropy related to a more pervasive cleavage). Shortening of such mechanically active cleavage planes can therefore lead to buckling of the existing cleavage, with axial planes parallel to the layer boundary. Strong cleavage refraction and subsequent folding should be restricted to the fold limbs close to the inflection point, as is actually observed in the natural examples of Figs. 1 and 2.

The structures developed should be mirror symmetric for symmetric folds developed in overall pure shear. Folding of an oblique layer in pure shear will result in asymmetric folds with strong refraction preferentially developed on the long limb (Anthony and Wickham, 1978, fig. 5). Single layer folds developed in more general shear (including the

Fig. 5. Finite element numerical model of single-layer folding with viscoelastic materials in dextral simple shear. Initial layer inclination was 20° to the shear direction, the viscosity ratio was 50, the wavelength to thickness ratio of the initial sinusoidal perturbation was 13.4, and the initial amplitude was 1/20th of the layer thickness. Elastic properties were set such that the viscous behaviour was very dominant ($R \ll 1$; see Schmalholz and Podladchikov, 1999), and results are therefore directly comparable with that for purely viscous materials. Modelling was performed with the commercial program MARC-Mentat. (a) Major axis of finite strain, X, at very low shear strain, $\gamma = 0.01$. Note that, as expected from Fig. 3, the refracted trace of the XY plane (here in fact X) is effectively perpendicular to layering in the more viscous layer. (b) An intermediate stage for $\gamma = 0.625$, already showing the marked difference in refraction on opposite limbs. (c) At $\gamma = 1.25$, the co-rotating limb has already been in the field of incremental shortening for some time, whereas the counter-rotating limb has just reached the transitional (vertical) orientation of no instantaneous stretch. The infinitesimal stretching axes (ISA) of the bulk simple shear flow are indicated, as well as the definition of co- and counter-rotating fold limbs. The local ISA in the stiff layer are always approximately parallel or perpendicular to the layer boundary (see Fig. 3).

end-member of simple shear) may still be quite symmetric in fold shape (Fig. 5), but the strain pattern on opposite limbs will be markedly different. This is because one limb rotates with and one against the rotational component of the background flow. Strong refraction and thus the potential for cleavage folding only occur on the limb that rotates against the imposed sense of rotation.

The marked asymmetry of the cleavage fan and the potential for folding of earlier cleavage planes, restricted to the counter-rotating limb, provides a potentially reliable sense-of-shear criterion in folds developed in a flow field with a consistent shear component. However, similar asymmetric cleavage patterns can also be produced in pure shear with an initially inclined stiff layer (Anthony and Wickham, 1978, fig. 5). It follows that refracted and folded cleavage occurring only on alternate fold limbs, as in Fig. 2, cannot be used in isolation as evidence for a regional shear sense in folded rocks. The reliability of this potential kinematic indicator should always be tested against other kinematic criteria and, in particular, its application should be restricted to rocks deformed in flow conditions dominated by simple shear (as established from other, independent field observations). Nonetheless, the principle involved is quite general and the observed asymmetry should develop in any general shear, with the effect becoming stronger and more obvious with increasing simple shear component.

The fold with the strongly asymmetric cleavage pattern shown in Fig. 2 in fact comes from a shear-dominated fold-and-thrust belt, the Naukluft Nappe Complex of Namibia. The regional sense of shear in this region is top-to-the-SE or -SSE and the asymmetric pattern shown in Fig. 2 is consistent with this regional sense of shear.

6. Conclusions

Cleavage and folding of cleavage can develop during a single continuous folding event. This is due to the strong refraction of cleavage within competent layers in limb positions and the switch from layer-parallel shortening to stretching as limbs rotate with increasing fold amplification. Folded cleavage is therefore not always an unequivocal indicator of polyphase deformation. Cleavage refraction (and potentially cleavage folding) is unequally developed on opposite limbs of folds developed in a shear environment. Refraction is only strong on the limb that rotates against the imposed sense of shear. If used with caution, asymmetric cleavage refraction provides a potential kinematic indicator in sheared and folded units at relatively low strain (e.g. in simple shear, $\gamma >$ ca. 1), where other higher-strain indicators, typical of mylonites, are not yet sufficiently developed or are equivocal.

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