



Influence of mechanical anisotropy on shear fracture development

E. GOMEZ-RIVAS^{1*} AND A. GRIERA^{2, 3}

¹*Departament de Geologia. Universitat Autònoma de Barcelona, 08193 Bellaterra, Barcelona, Spain.*

²*Université de Toulouse. UPS (SVT-OMP). LMTG. 14 Av. Edouard Belin, 31400 – Toulouse, France.*

³*CNRS. LPES. 59655 – Villeneuve d'Ascq, France.*

**e-mail: enrique.gomez@uab.es*

Abstract: Analogue models have been used to investigate the influence of the orientation of a planar mechanical anisotropy on the development of shear fractures. Anisotropic plasticine models with the anisotropy planes initially oriented at different angles with respect to the deformation axes have been deformed under pure shear boundary conditions. Two sets of shear fractures are formed in all the experiments. Their asymmetry depends on the initial orientation of anisotropy. In oblique cases the local stress field inferred from fracture sets differs from the stress field applied by the deformation apparatus. The degree of anisotropy can be estimated from the differences between both stress fields using a simple analytical method.

Keywords: shear fracture, anisotropy, stress field, orientations, analogue modelling.

The mechanical development of shear bands and fractures is a major research topic in geology and rock mechanics. There is a large amount of studies analysing the fundamental controls of the development of shear bands and fractures in homogeneous isotropic rocks (e.g. Wolf *et al.*, 2003 and references therein). However, many rocks in nature are anisotropic and heterogeneous (Biot, 1965; Cobbold *et al.*, 1971, Weijermars, 1992) and have a different response to normal and shear stress. It has been historically observed that the presence of a planar anisotropy (i.e. layering, cleavage, pre-existing faults, joints, etc.) can affect the onset and orientation of fractures. The existence of directional heterogeneities may enhance the partition of deformation (Lister and Williams, 1983) and can produce a deviation of the local stress field with respect to the regional deformation conditions (Bradshaw and Zoback, 1988; Peacock and Sanderson, 1992). In this kind of situations inferring the regional

stress field from fracture data of individual outcrops becomes a difficult task.

Since the experimental works of Anderson (1951), Donath (1961, 1963, 1970) and others, it has been assumed that the orientation of fractures in anisotropic rocks is influenced by the orientation of anisotropy or layering with regard to the principal stress axes. These experiments stated that when anisotropy is oriented either parallel or perpendicular with respect to the axis of maximum compression σ_1 , shear fractures are formed at an angle of 30–40° to σ_1 , as expected by the Mohr-Coulomb criterion. However, when the angle between the planar structure and σ_1 varies between 15° and 60°, shear fractures tend to develop subparallel to the orientation of anisotropy. Only for very specific layering orientations fractures tend to describe angles higher than 45° with respect to σ_1 . These observations are in general valid for strongly anisotropic rocks deformed under brittle conditions.

However, other experimental and field studies performed in ductile anisotropic materials (e.g. Harris and Cobbold, 1985) showed that very often the principal direction of shortening bisects the obtuse angle between conjugate fracture sets, meaning that the angles between σ_1 and fractures are higher than 45° , which is the predicted orientation assuming the Von Mises criterion. Additionally, a common observation is that in this kind of rocks, fractures do not tend to develop subparallel to anisotropy (e.g. Cobbold *et al.*, 1971; Harris and Cobbold, 1985; Hanmer *et al.*, 1996; Kidan and Cosgrove, 1996).

It is not yet clear how the presence of mechanical anisotropy affects the development of fractures and how it can influence the orientation of the local stress field with respect to the regional deformation conditions. This work presents an experimental study of the influence of the orientation of anisotropy on the nucleation and evolution of shear fracture sets in a ductile material. Five anisotropic plasticine multilayers have been deformed under pure shear boundary conditions varying the initial orientation of layers with respect to the deformation axes imposed by the deformation apparatus. The orientations of fractures are analysed and used to infer the local stress field using stress inversion methods. After that, a simple analytical model is presented to estimate the degree of anisotropy using the deviation

of the local inferred stress field with respect to the boundary conditions applied by the deformation apparatus.

Materials and methods

The models were made by stacking alternating coloured layers of a mixture composed by plasticine, vaseline and paper flakes (confetti). These flakes were preferentially oriented parallel to layering in order to increase the degree of anisotropy. Layers were initially oriented at an angle φ_0 (from 0° to 40°) with respect to the maximum extension direction (X). The models were deformed at pure shear boundary conditions at a constant strain rate of $2 \times 10^{-5} \text{ s}^{-1}$ and at temperature of 26°C until a bulk strain ratio of $R_{X/Z}=4$ (i.e. 50% shortening). Compression was applied in the Z -direction, Y was constrained to remain constant and the material could freely flow in the X -direction (Fig. 1). Fractures, which were measured from the top surface, were mostly planar in the third dimension. A constant area at the centre of each sample was used to collect fracture data.

The mechanical properties of the analogue materials were analysed carrying out uniaxial compression and relaxation tests. These mixtures behave as a highly non-linear elastoviscous material with stress exponents of $n=8$ and dynamic effective viscosity values of the order of $10^8\text{-}10^9 \text{ Pa s}$.

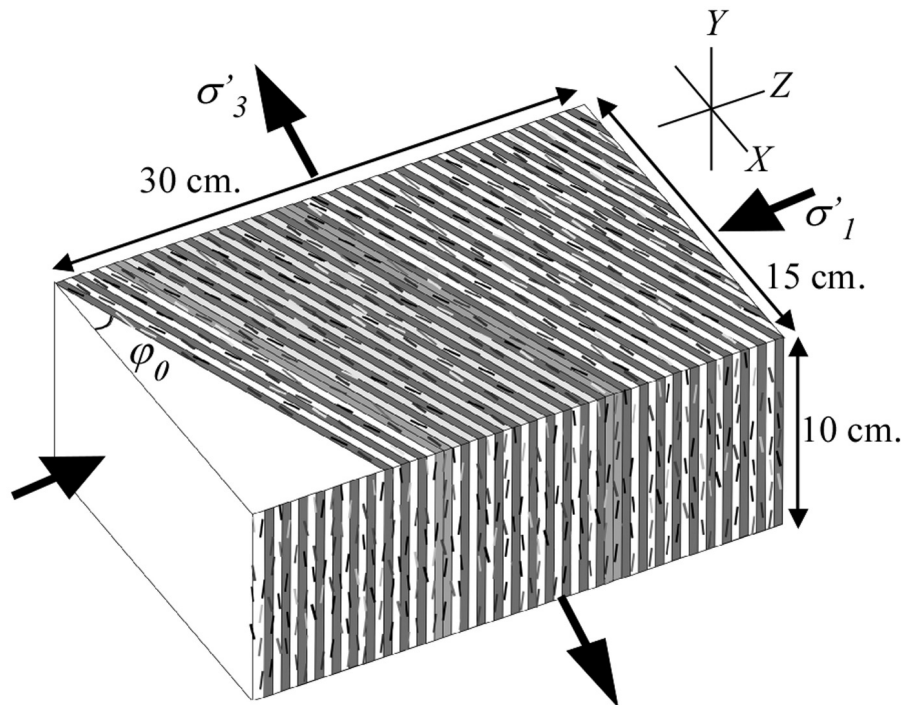


Figure 1. Sketch of a multilayer model. φ_0 is the initial angle between layering and the extensional axis X . Arrows show the direction of the principal stresses (σ'_1 , σ'_3) applied by the deformation apparatus.

Experimental results

During the first stages of the experiments, deformation was accommodated mainly by homogeneous flattening and rotation of layers towards the extension direction X . Not much layer slipping was observed. At about 15-18% of shortening the strain-stress curves registered a yield stress, which occurred simultaneously to the nucleation of the first macroscopic structures (shear fractures, tension cracks and pinch-and-swell instabilities). With the increase of deformation these early structures gave rise to new shear fractures.

Two symmetrical conjugate sets of fractures were formed in models with layers parallel to the maximum extension axis X ($\varphi_0=0^\circ$) (Fig. 2). However, the models with oblique anisotropy ($\varphi_0>0^\circ$) showed an asymmetrical orientation of fracture sets with respect to the Z axis. In this case, the dextral set of fractures nucleated at a considerably higher angle than the

sinistral one. With the increase of deformation layers rotated towards the X direction and the oblique models tended to display a more symmetrical arrangement of the new fractures. There is a clear relationship between the initial obliquity of anisotropy (φ_0) and the number of fractures developed for each case: the increase of obliquity of the initial layering (higher φ_0) produces a more asymmetric arrangement of sets of fractures and a decrease in the number of fractures (Fig. 2).

A classical stress inversion method was used to determine the stress fields expected from the fracture networks orientations. As fractures were mostly planar in the third dimension, a horizontal slip line was assumed. The strong asymmetry of fracture sets observed in figure 2 for models with initial oblique anisotropy ($\varphi_0>0^\circ$) is also evidenced by the misorientation of the inferred local stress fields with regard to the stress field applied by the deformation appa-

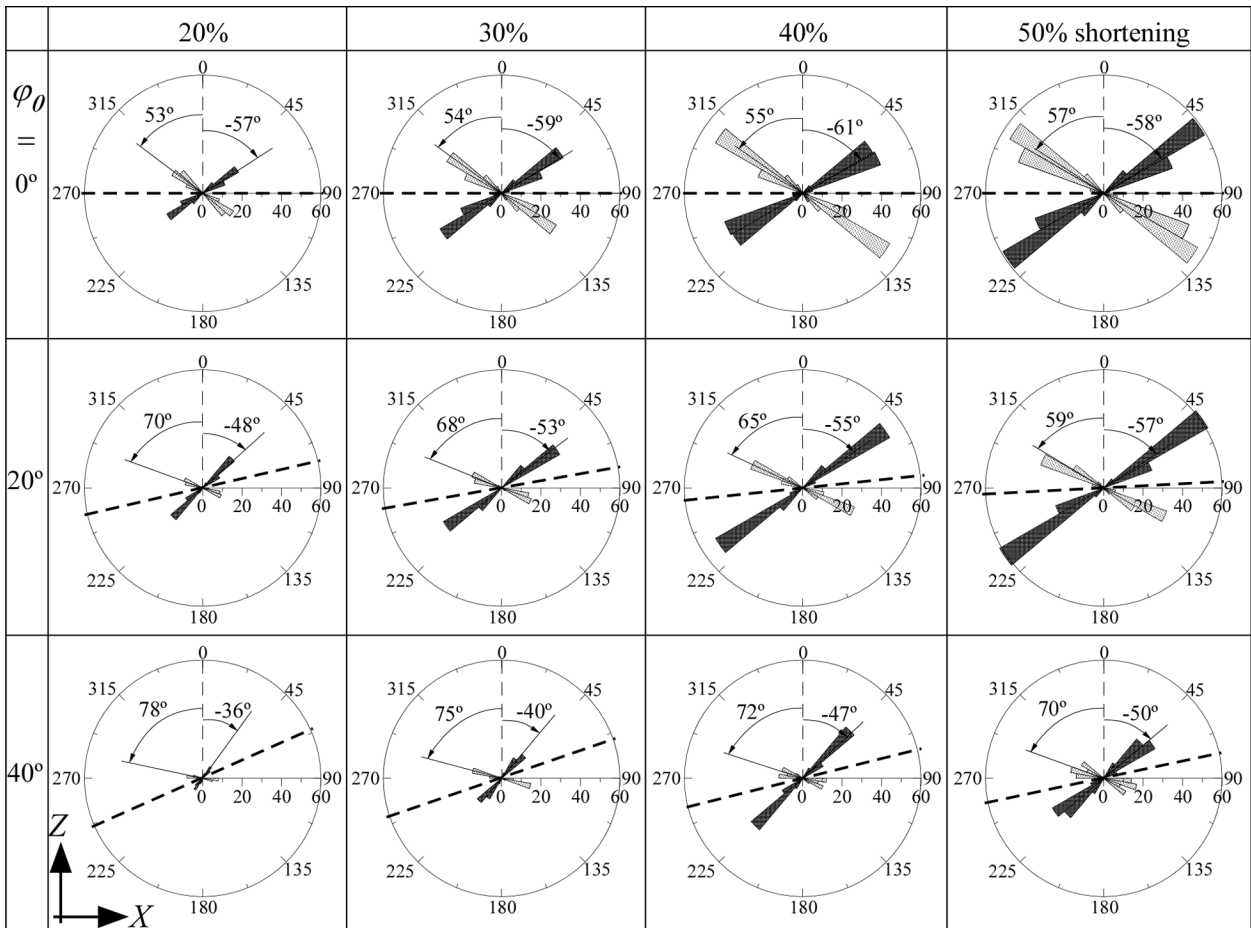


Figure 2. Rose diagrams that show the orientation (δ) and the population of fractures, at orientation intervals of 10° , of three of the analysed models. The average orientation of each set is indicated. Dark grey clusters correspond to the sinistral set of fractures while light grey clusters show data of the dextral set. Dashed lines indicate the orientation of anisotropy.

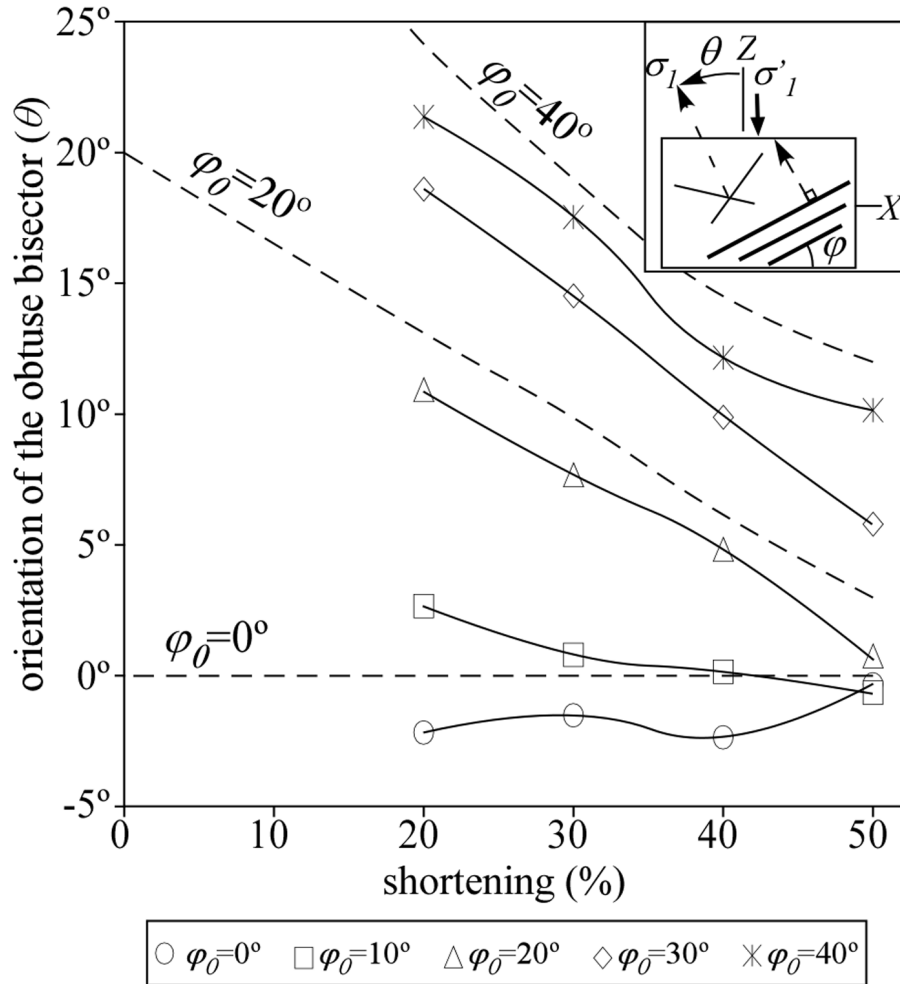


Figure 3. Evolution with the increase of deformation of the angle θ between the obtuse bisector of the two conjugate fracture sets and the maximum compression axis Z . Dashed lines show the orientation ϕ of anisotropy planes with respect to the maximum extension axis X . Data from the five experiments are represented with different symbols.

ratus, which can be considered a regional stress field in our system. On one hand, for models with layers initially parallel to the extension direction X ($\phi_0=0^\circ$), the principal stresses calculated from the conjugate fracture patterns are parallel to the stresses applied by the deformation apparatus. In this case, the local principal compression stress σ_1 lies parallel to the maximum compression deformation axis Z . On the other hand, for ($\phi_0>0^\circ$) models, the estimated stress field for conjugate shear fractures (i.e. local stress field) does not coincide with the applied boundary conditions (i.e. regional stress field). The results show that σ_1 is at all times parallel to the obtuse bisector between both arrays of fractures and nearly perpendicular to the anisotropy planes (Fig. 3). The orientation of this local compression stress (σ_1) is clearly different from the regional compression stress (σ'_1), that is the one applied by the deformation device (Fig. 4a).

Determination of the degree of anisotropy from stress field differences

The misorientation of the inferred local stress field with respect to the one applied by the boundary conditions depends on the degree of anisotropy of the deforming material. If the material is completely isotropic both stress fields will be parallel, whereas the increase of the degree of anisotropy produces a progressive deviation of the local stress field in relation to the regional one. An estimation of this misorientation can be deduced from the mechanics of an incompressible viscous fluid. The degree of anisotropy (m) can be simulated as a dependence of viscosity on tangential stress, and then normal (η_n) and shear (η_s) viscosities can be distinguished (Fletcher, 1977; Johnson and Fletcher, 1994):

$$m = \frac{\eta_n}{\eta_s} \quad (1),$$

where η_n and η_s are the normal and shear viscosities.

For a two dimensional system with axes parallel and perpendicular to the anisotropy planes (n , s), as defined in figure 4b, the relationship between stress and strain rate can be expressed as:

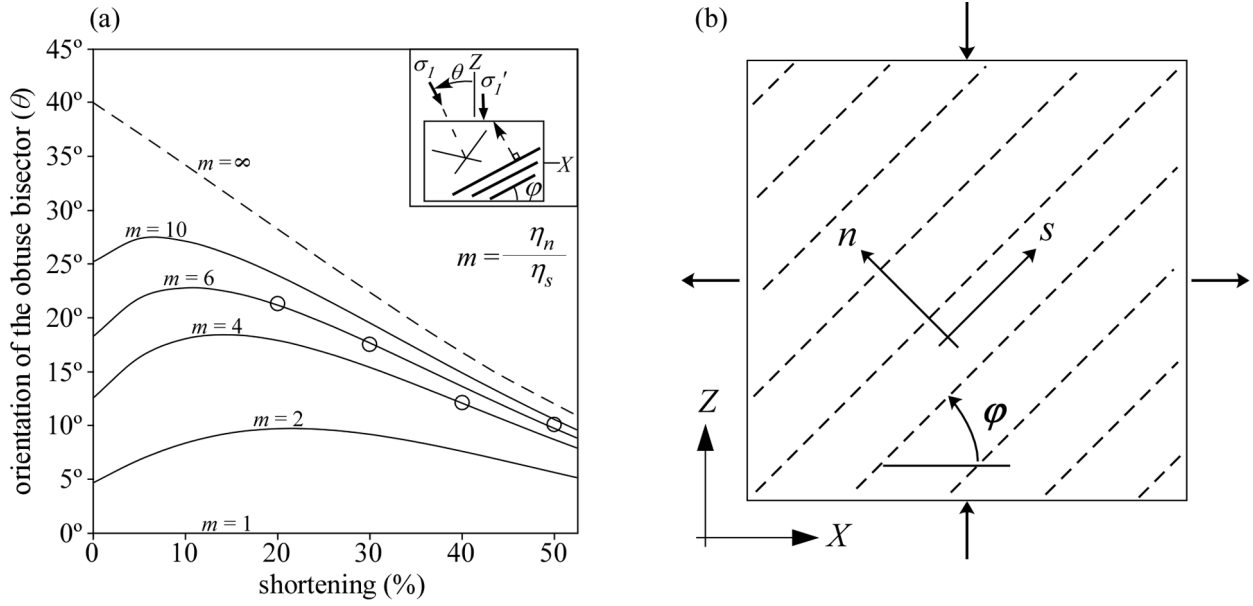


Figure 4. (a) Evolution of the angle θ between the local (σ_1) and the regional (σ_1') principal compression stresses for finite deformation. The curves were calculated for a material with the anisotropy initially oriented at $\varphi_0=40^\circ$ with regard to the extension axis X . Open dots represent data measured from our $\varphi_0=40^\circ$ experiment. The good-fitting of data allows us to estimate a degree of anisotropy of $m=6$ for this case, (b) elemental cube of anisotropic material with two reference frames: internal (n, m, s) and external (X, Y, Z). φ is the angle between anisotropy and the external extension axis X .

$$\begin{aligned}\sigma_{nn} &= 2\eta_n \dot{\epsilon}_{nn} \\ \sigma_{ss} &= 2\eta_n \dot{\epsilon}_{ss} \\ \sigma_{sn} &= 2\eta_n \dot{\epsilon}_{sn}\end{aligned}\quad (2),$$

where σ is stress and $\dot{\epsilon}$ is strain rate. If we choose an external reference frame (X, Z) parallel to the deformation axes of the experimental device, the tensors of $\dot{\epsilon}$ and σ can be calculated using the rotational matrix and the angle between both reference systems. Then, the equations (2) can be transformed to (modified from Johnson and Fletcher, 1994):

$$\begin{aligned}\sigma_{xx} &= 2A' \dot{\epsilon}_{xx} + 2B' \dot{\epsilon}_{xz} \\ \sigma_{zz} &= 2A' \dot{\epsilon}_{zz} + 2B' \dot{\epsilon}_{xz} \\ \sigma_{xz} &= 2A' \dot{\epsilon}_{xz} - B'(\dot{\epsilon}_{xx} - \dot{\epsilon}_{zz})\end{aligned}\quad (3),$$

where A' and B' can be calculated from the normal and shear viscosities and the angle φ between the anisotropy planes and the extensional X axis (Fig. 4b):

$$\begin{aligned}A' &= [\eta_n \cos^2 2\varphi + \eta_s \sin^2 2\varphi] \\ B' &= [(\eta_n - \eta_s) \cos 2\varphi \sin 2\varphi]\end{aligned}\quad (4),$$

If we assume that the models were deformed approximately under pure shear conditions and that the experimental material is incompressible, then $\dot{\epsilon}_{xx} = -\dot{\epsilon}_{zz}$, $\dot{\epsilon}_{xz} = 0$ and the angle θ between the resolved principal stress and the reference frame can be calculated as:

$$\tan 2\theta = \left(\frac{2 \cdot \sigma_{xz}}{\sigma_{xx} - \sigma_{zz}} \right) = \left(\frac{B'}{A'} \right) \quad (5),$$

Using the above equations the dependence of m on the stress misorientation can be calculated. If we assume an incremental deformation where the degree of anisotropy is constant and the layers rotate as passive markers, the evolution of the angle θ with the increase of strain can then be calculated. Figure 4a shows these curves for pure shear conditions in one of the analysed experiments. The angle θ decreases with the increment of shortening, after reaching a maximum. When the θ angle data collected from the experiment are plotted in the graph, the degree of anisotropy of this model can be estimated. In the case of our analogue models the value of m is approximately 6.

Discussion and conclusions

From the experimental data, it comes out that the presence of a strong anisotropy has a significant influence on the angle at which shear fractures nucleate. In models with layering oriented parallel to the extension axis X two symmetrical sets of shear fractures develop, while these arrays are asymmetrical for models with oblique anisotropy.

The local stress field inferred from fracture networks using classical stress inversion methods in models with oblique initial anisotropy ($\phi_0 > 0^\circ$) differs from the stress field applied by the deformation apparatus. This deviation is controlled by the degree of anisotropy and can be quantified using a simple analytical method assuming that the material behaves as an incompressible viscous fluid. Even if the material might have experienced some volume loss, this assumption should not have a significant influence on the final result.

From the data plotted in figure 2 it can be observed that the dihedral angles between conjugate fracture sets are always higher than 105° and the local principal compression stress σ_1 is always parallel to the obtuse bisector between these sets and approximately perpendicular to layers. Therefore the angles between σ_1 and fractures are at all times higher than 45° , which is the failure orientation predicted by the Von Mises criterion. These high fracture angles, which were observed by other authors in ductile anisotropic materials (e.g. Cobbold *et al.*, 1971; Harris and

Cobbold, 1985; Hanmer *et al.*, 1996; Kidan and Cosgrove, 1996), can be explained because of the elastoviscoplastic character of the deforming material, the kinematics of deformation and the presence of a strong planar anisotropy.

The results of the present experimental work strongly differ from the observations of classical contributions that studied the formation of fractures in anisotropic rocks (e.g. Anderson, 1951; Donath, 1961, 1963, 1970). The main parameter influencing the brittle experiments of these authors was the effective interlayer slipping along slaty cleavage. The easy slip and localisation of deformation along these weak discontinuities avoided the concentration of stress needed to nucleate shear fractures. On the contrary, in our analogue models, the presence of paper flakes increases the adhesion between layers and produces a decrease in the slip between layers compared to other experiments without paper flakes. At experimental conditions, viscous flow and slight sliding along layers and papers flakes cannot avoid the increase of stresses up to the material failure and the onset of fractures.

Acknowledgements

This work was financed through the PhD grant BES-2003-0755 to EGR and research project CGL2004-03657, both funded by the Spanish Ministry of Education and Science. The authors are very grateful to the reviewer F. Bastida and to the editor J. Poblet who helped to improve the manuscript.

References

- ANDERSON, E. M. (1951): *The dynamics of faulting*. Oliver and Boyd, Edinburgh, 208 pp.
- BIOT, M. A. (1965): *Mechanics of incremental deformations*. Wiley, New York, 601 pp.
- BRADSHAW, G. A. and ZOBACK, M. D. (1988): Listric normal faulting, stress refraction, and the state of stress in the Gulf Coastal Basin. *Geology*, 16: 271-274.
- COBBOLD, P. R., COSGROVE, J. W. and SUMMERS, J. M. (1971): Development of internal structures in deformed anisotropic rocks. *Tectonophysics*, 12: 23-53.
- DONATH, F. A. (1961): Experimental study of shear failure in anisotropic rocks. *Geol. Soc. Am. Bull.*, 72: 985-990.
- DONATH, F. A. (1963): Fundamental problems in dynamic structural geology. In: T. W. DONNELLY (ed): *The Earth Sciences*. University of Chicago Press, Chicago: 83-103.
- DONATH, F. A. (1970): Some information squeezed out of rock. *Am. Sci.*, 58: 54-72.
- FLETCHER, R. C. (1977): Folding of a single viscous layer: exact infinitesimal-amplitude solution. *Tectonophysics*, 39: 593-606.
- HANMER, S., CORRIGAN, D. and GANAS, A. (1996): Orientation of nucleating faults in anisotropic media: insights from three-dimensional deformation experiments. *Tectonophysics*, 267: 275-290.
- HARRIS, L. B. and COBBOLD, P. R. (1985): Development of conjugate shear bands during bulk simple shearing. *J. Struc. Geol.*, 7: 37-44.
- JOHNSON, A. M. and FLETCHER, R. C. (1994): *Folding of viscous layers. Mechanical analysis and interpretation of structures in deformed rock*. Columbia University Press, New York, 461 pp.
- KIDAN, T. W. and COSGROVE, J. W. (1996): The deformation of multilayers by layer normal compression; an experimental investigation. *J. Struc. Geol.*, 18: 461-474.

LISTER, G. S. and WILLIAMS, P. F. (1983): The partitioning of deformation in flowing rock masses. *Tectonophysics*, 92: 1-33.

PEACOCK, D. C. P. and SANDERSON, D. J. (1992): Effects of layering and anisotropy on fault geometry. *J. Geol. Soc. London*, 149: 793-802.

WEIJERMARS, R. (1992): Progressive deformation in anisotropic rocks. *J. Struc. Geol.*, 14: 723-742.

WOLF, H., KÖNIG, D. and TRIANTAFYLIDIS, T. (2003): Experimental investigation of shear band patterns in granular material. *J. Struc. Geol.*, 25: 1229-1240.