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Development of conjugate shear bands during bulk simple shearing

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Abstract—In rocks possessing a strong planar fabric, shear bands of constant shear sense and oriented at an oblique angle to the foliation are considered by many authors to be characteristic of a non-coaxial bulk deformation history, whereas conjugate shear bands are considered to indicate coaxial shortening. However, in two areas where bulk deformation history appears to be non-coaxial (Cap Corse, Corsica and Ile de Groix, Brittany), conjugate shear bands are observed. In order to investigate this problem, experiments were performed by bulk simple shearing using Plasticine as a rock analogue. When slip between layers of the model is permitted, shear bands of normal-fault geometry form with both the same and opposite shear sense as the bulk simple shearing at approximately the same angle with the layering (40°) irrespective of layer orientation in the undeformed state (for initial orientations of 50, 30 and 15°). Shear bands are initially formed within individual layers and may propagate across layer interfaces when further movement along these is inhibited. The existence of conjugate shear bands in Corsica and Ile de Groi:: is therefore not incompatible with a model of bulk simple shearing for these two regions. In field studies, one should perhaps exercise care in using shear bands to determine the kind of motion or the sense of bulk shearing.

INTRODUCTION

In rocks possessing a strong planar fabric, shear bands of constant shear sense, oriented at an oblique angle to the foliation, are considered by many authors to be characteristic of a non-coaxial deformation history (e.g. Berthé *et al.* 1979, Platt & Vissers 1980). The bulk shear sense is deduced from the sense of shear and orientation of the minor shear bands and is often seen to be in agreement with other microstructural criteria such as the obliquity of quartz *c*-axes and the asymmetry of pressure shadows and sigmoidal micas. Similar distributions of shear bands are observed during experimental bulk simple shearing of clays and granular materials (Tchalenko 1968, Mandl *et al.* 1977). Conjugate shear bands of 'normal fault' geometry, on the other hand, are often taken as evidence for coaxial shortening (see for example Hobbs *et al.* 1976, Platt & Vissers 1980). Conjugate sets of shear bands have been observed in areas having a non-coaxial deformation history, however, in many examples a later phase of coaxial shortening superposed on a primary shearing has been invoked to explain their formation (e.g. the Betic Movement Zone, Platt & Vissers 1980). We may therefore ask the following questions: (a) Can conjugate shear bands be formed during a non-coaxial deformation history? (b) Does the sense of displacement on shear bands always agree with the overall shear sense? (c) What effect does rheological anisotropy have on shear band environment and orientation? (d) Can shear bands alone be used as field criteria for establishing the deformation history of a given area, or as indicators of bulk shear sense where a non-coaxial history is established?

To answer these questions, we have studied two areas with non-coaxial deformation histories and containing conjugate shear bands. Also, various models made from a rock analogue (Plasticine) have been experimentally subjected to bulk simple shearing and attention given to the nature and distribution of resulting shear bands.

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SHEAR BAND ORIENTATIONS

There have been many experimental studies of the formation of shear bands during bulk simple shearing of granular materials and clays; that is, materials with initial structural isotropy (e.g. Tchalenko 1968, Mandl *et al.* 1977). The studies have shown that shearing may occur simultaneously along primary shear bands, D, parallel to the bulk shearing plane and along secondary Riedel shears, R, (Fig. 1b; Riedel 1929). The shear senses in the bands are the same as the bulk shear sense. If a passive plastic state is achieved (requiring build up of a high normal stress after peak shear stress has been passed), a further set of secondary shear bands, referred to as thrust or P shears, may develop (Tchalenko 1968, Mandl *et al.* 1977). The interconnection of R, P and D

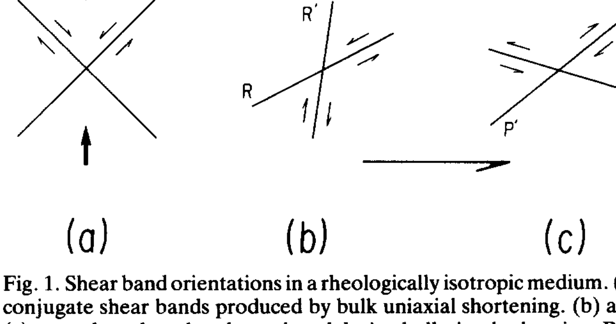


Fig. 1. Shear band orientations in a rheologically isotropic medium. (a) conjugate shear bands produced by bulk uniaxial shortening. (b) and (c) secondary shear bands produced during bulk simple shearing. R & R': Reidel shears (only R shears are generally active). P & P': Thrust shears (only P shears are generally active.).

shears isolates shear lenses, their orientation being influenced by the predominant type of secondary shear processes operating (Tchalenko 1968).

Many rocks are foliated, however, (that is, they have a layering, a cleavage or a schistosity) and we cannot therefore assume that the sets of shear bands described above would develop if these foliated rocks underwent a bulk simple shearing. We have also found that a strong anisotropy may inhibit the development of shear bands (Cobbold *et al.* in prep.).

FIELD EXAMPLES OF CONJUGATE SHEAR BANDS

Cap Corse, Corsica

Highly deformed gabbros (euphotides) outcropping north of Erbalunga on the east coast of Cap Corse, Corsica form part of an Alpine obducted ophiolite complex (Durand-Delga 1974, Mattauer & Proust 1976). These rocks possess a strongly developed, generally subhorizontal foliation (where unaffected by subsequent phases of folding) which contains a mineral-stretching lineation trending 110°. Glaucophane-rich metagabbros alternate with gabbros containing little or no glaucophane. Lithological layering is parallel to the foliation. Emplacement of Corsican ophiolites may have been dominantly by bulk simple shearing (Faure & Malavieille 1980, 1981, Mattauer *et al.* 1981), the shear sense being generally from E to W in this part of Cap Corse (Harris, in prep.).

Centimetric to decametric shear bands making an angle of 30 ± 15° with the foliation and dipping either to the E or W occur individually (Figs. 2a & b) or form arrays of conjugate sets (Fig. 2c) defining a type of foliation boudinage. Conjugate shear bands are symmetrically disposed about the foliation. The sense of shear in the bands is the same as that of 'normal faults' developed in horizontally bedded rocks, and indicates extension parallel to the foliation. Other conjugate shear bands are seen in rocks of similar lithology along the west coast of Cap Corse where the bulk sense of shear is towards the SSW (Harris, in prep.) and in the Centuri orthogneiss, NW Cap Corse (Malavieille & Harris, in press). In mica–quartzite beds throughout Cap Corse, however, there is a single family of shear bands that agrees with the local sense of shear.

Ile de Groix, Southern Brittany

Intercalated metapelitic and metabasic rocks of the Ile de Groix have undergone intense Hercynian deformation and metamorphism. The resulting foliation is generally subhorizontal, parallel to lithological layering, and contains a strongly developed mineral-intersection lineation, trending between 120 and 140°. The foliation is locally folded into complex, sometimes sheath-like folds (Quinquis *et al.* 1978). Observed structures were interpreted by Quinquis (1980) as being the result of a simple shearing associated with northward obduction of oceanic sediments and basalts onto the Armorican continent.

Shear bands occur frequently in most lithologies and at various scales (thin-section to metric). Up to three families of shear bands making various angles with the foliation can occur (Fig. 2d). Most of these have the same shear sense as that proposed by Quinquis (1980) for the bulk motion. The foliation has been folded into open folds of complex geometry between shear bands and there is large-scale foliation boudinage, resembling that described on a smaller scale by Platt & Vissers (1980). Metric-scale shear bands have been developed between boudins of metabasic rocks (glaucophanites) in mica schists or prasinites. The asymmetry of these structures and the rotation of boudins is also generally consistent with a N-directed overthrusting. Smaller shear bands within a variety of rock types are often seen to be approximately conjugate about the foliation, however, at an angle of between 20 and 30° (Figs. 2e & f). As in Corsica, these shear bands always have normal-fault geometries.

EXPERIMENTAL STUDY

Introduction

Plasticine (a proprietary mixture of mineral particles in a wax and mineral oil matrix) has been used as a rock analogue in the following experiments. The physical properties of Plasticine have been studied by McClay (1976) and Peltzer (1983). In layered Plasticine models, deformed by bulk uniaxial shortening perpendicular to the layering, conjugate shear bands formed at approximately 40° to the layering. The stress-strain curve for such an experiment is shown in Fig. 3(a). Shear bands appeared, accompanied by a stress drop, between 7 and 15% shortening. Their development is attributed to strain softening (Peltzer 1983). Shear bands were not formed during compression parallel to the layering (Fig. 3b), and no stress drop occurred. Peltzer interpreted this as being due to the alignment of the small mineral particles in the Plasticine brought about by rolling of the layers during model preparation.

Simple shearing of an isotropic Plasticine model produced secondary shear bands, with the same sense as the bulk shear sense, but inclined at 14° to the shear direction. Models with 'I-shaped' cross-sections (a shape used to concentrate shear band formation within the model and not along its boundaries; see template, Fig. 10b) were prepared using the method described in the appendix and deformed in a simple shear apparatus (Cobbold & Quinquis 1980) until the displacement was about equal to the height of the model. Glass walls of the apparatus permitted observation and filming during deformation.

Model 1

In the first model, layers were inclined at 50° to the shear direction and marker lines scratched on one outer

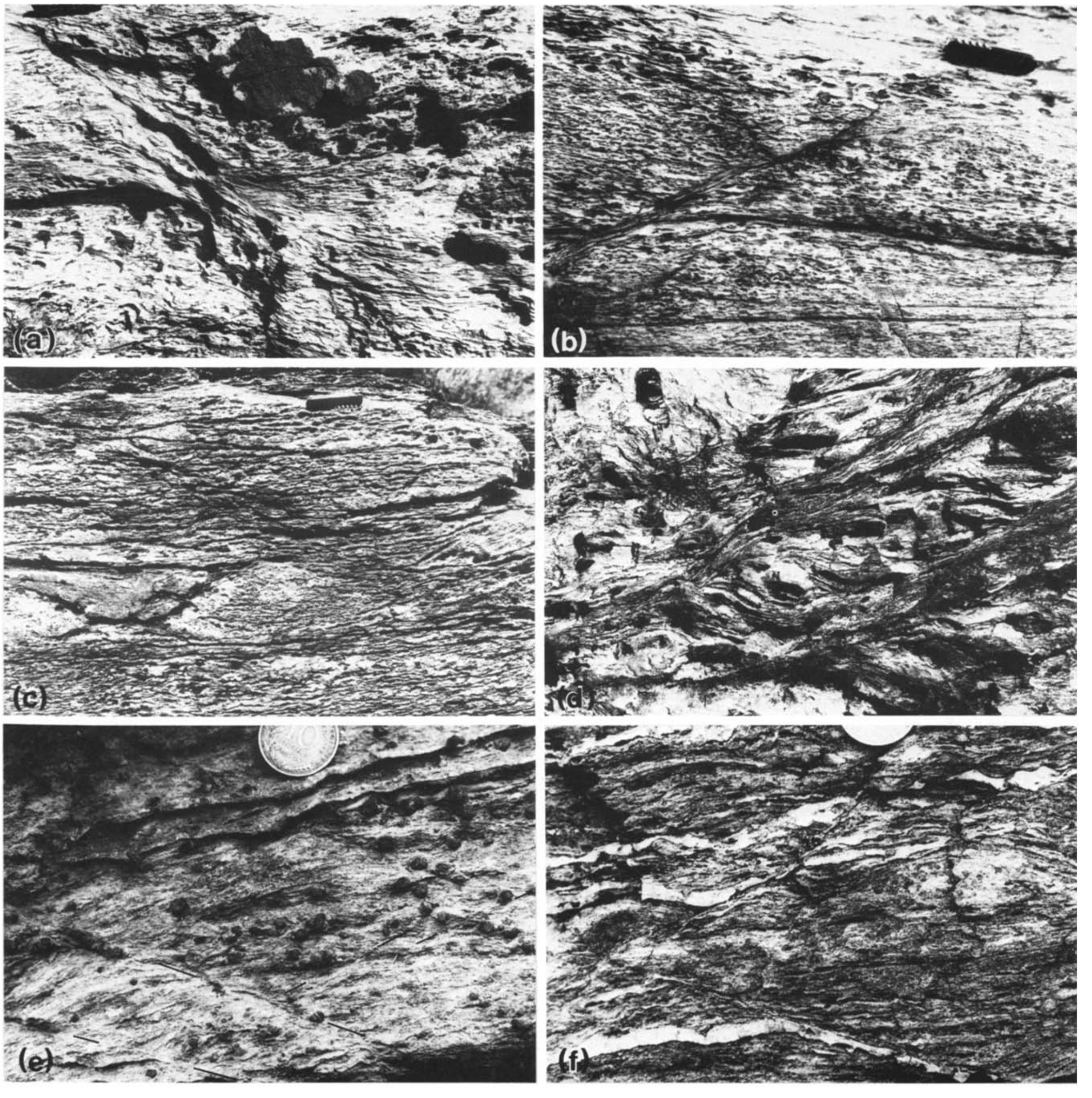
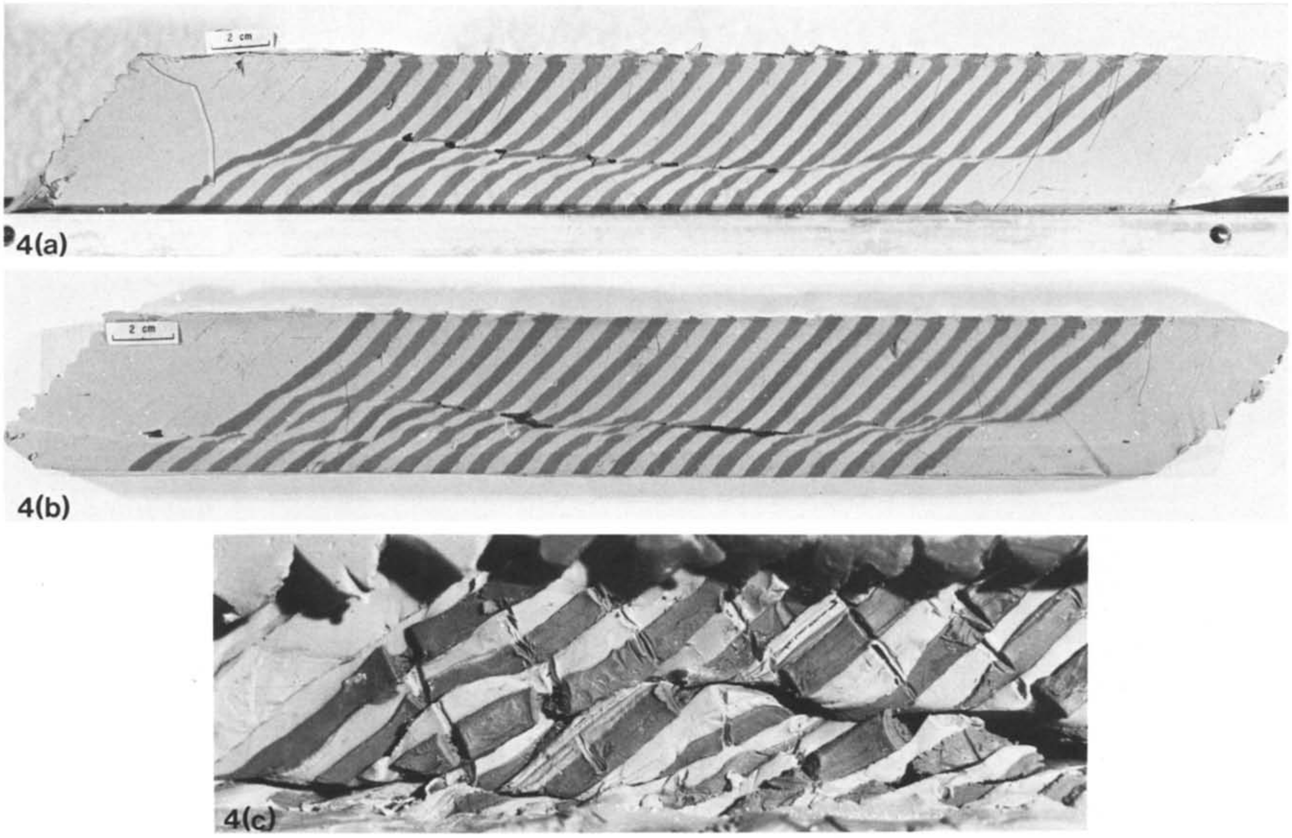


Fig. 2.(a), (b) and (c) Shear bands formed in highly deformed gabbro, Cap Corse. Photos looking N. Length of knife = 8.5 cm. (d) Metric shear bands in metapelitic rocks (looking E), Ile de Groix. (e) and (f): Conjugate shear bands (looking W), Ile de Groix.



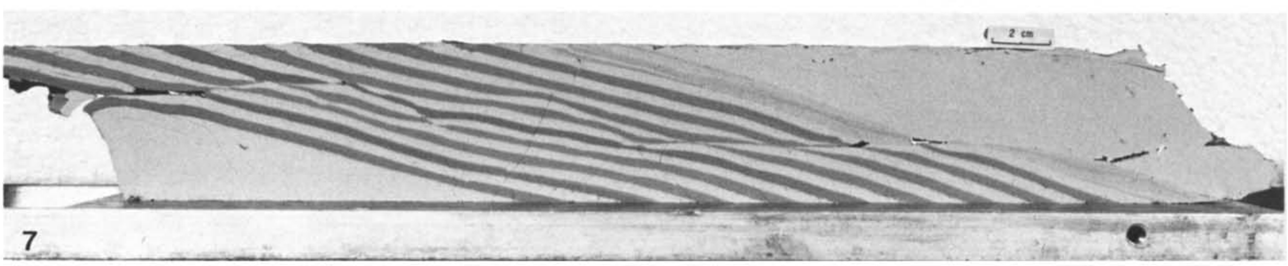


Fig. 4. Model after dextral bulk simple shearing. Layers (made up of two halves of different colour) were initially inclined at 50° to shearing planes. (a) and (b) Two parallel cuts of the model. (c) Detail of outer surface showing displacement of lines scratched on the surface perpendicular to layering. Slip along layering is sinistral between second and third layers from left, dextral on right-hand side of model.

Fig. 6. Model 2 after sinistral bulk simple shear. Layers were initially inclined at 30°.

Fig. 7. Model 3 after sinistral bulk simple shearing. Layers were initially inclined at 15°.

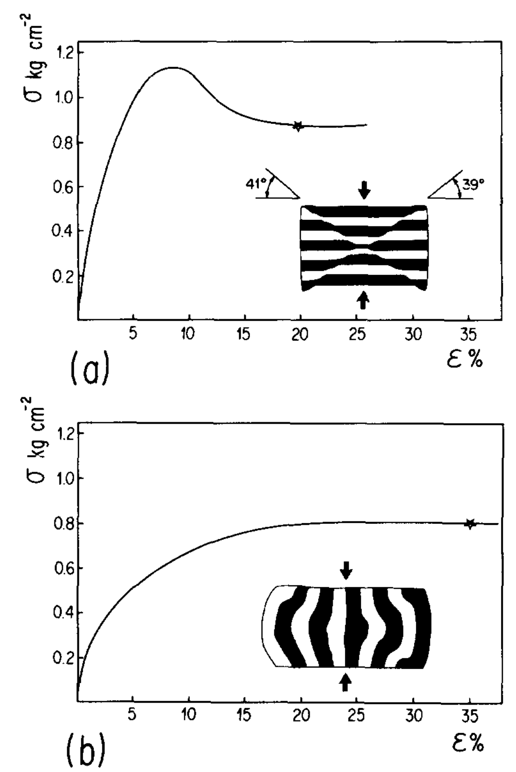


Fig. 3. Experimental deformation of plasticine by bulk uniaxial shortening (after Peltzer 1983). (a) Compression perpendicular to layering has produced conjugate shear bands during the stress drop between 7 and 15% shortening. (b) Compression parallel to layering: no shear bands were formed. σ, applied stress; ϵ, resulting strain and *, position corresponding to illustrated model.

surface in the undeformed state. Two parallel cuts of the model after dextral bulk simple shearing are shown in Fig. 4. The first cut (Fig. 4a) shows a major undulating dextral shear band in the central region of the model. The band is slightly oblique to the bulk shearing plane. In the second cut (Fig. 4b), the left hand side of the model shows two major shear bands, '*en relais*', with left-stepping overlap. These two shear bands can also be observed on the outer surface of the model (Fig. 4c) where displacement of marker lines reveals slip between layers. Slip is sinistral between the second and third layers from the left, dextral on the right-hand side of the photograph. Portions of these two slices (Figs. 5a & b) show the complexities of the major shear zones. Both sinistral and dextral displacements have occurred along secondary shear bands which have a normal fault geometry. Near the major (dextral) shear zone, secondary dextral shear bands oblique to D are predominant and displace more layers than sinistral shear bands. Sinistral shear bands initiate within individual layers (e.g. layers 3, 5 and 6 in Fig. 5a): the colour banding within those layers has been offset although there are no displacements at incoherent layer interfaces. Other sinistral shear bands (e.g. in layer 1, Fig. 5a and in the majority of cases in Fig. 5b) have cut across the layering. In some layers (e.g. layers 9 and 10, Fig. 5a and layers 8 and 9, Fig. 5b), sinistral and dextral shear bands form intersecting conjugate pairs. Some layers (e.g. layer 3, Fig. 5a) appear to be extremely attenuated in the shear zone without the development of discrete shear bands. Sinistral shear bands generally occur at an angle of between 70 and 80° with respect to the shear direction and at an average angle of 36° with the layering. Dextral shear bands occur at angles ranging from 0 to 23° with D and at an average value of 45° with the layering.

Model 2

This model is similar to the first except that the layer thickness has been reduced to 0.7 cm and that the layers were initially inclined at 30°. A central cut of this model after deformation by bulk sinistral simple shear is shown in Fig. 6. Two major shear zones with a slight, right-stepping overlap can be seen in the upper left and lower right

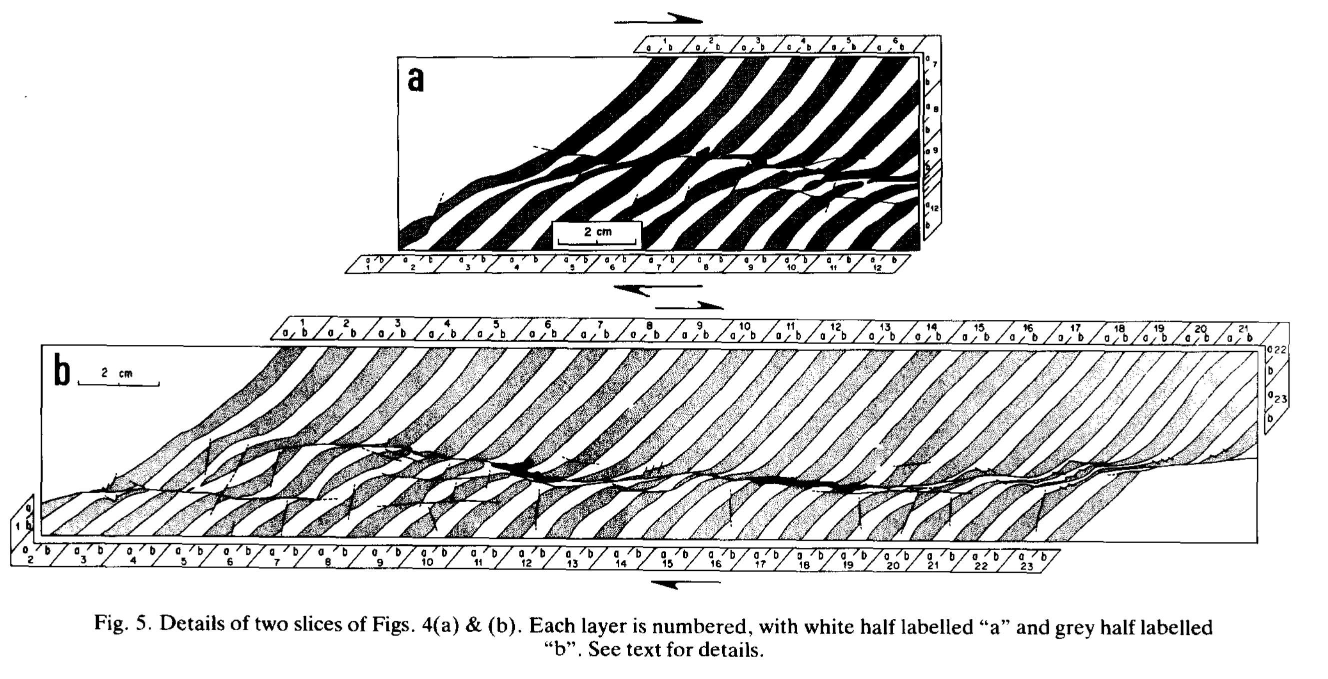


Fig. 5. Details of two slices of Figs. 4(a) & (b). Each layer is numbered, with white half labelled "a" and grey half labelled "b". See text for details.

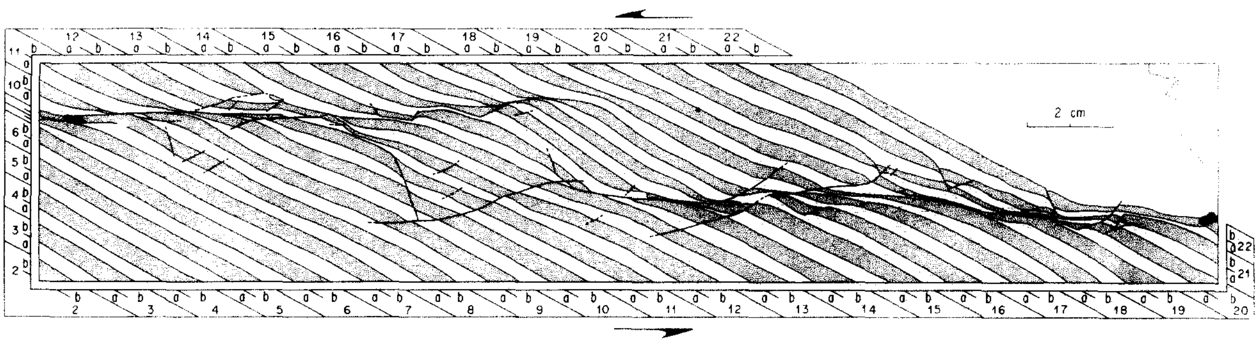


Fig. 8. Detail of model 2. See text for details.

portions of the model. Detailed examination of this region (Fig. 8) shows extensive development of oblique sinistral shear bands, which displace several layers and dip at angles of between 0 and 40°, along with a second set of dextral shear bands dipping generally between 65 and 75° in the opposite direction. Sinistral, secondary shear bands make an average angle of 45° with the layering. For dextral shear bands, this angle is 40°. Several intersecting conjugate shear bands occur (e.g. in layers 11 and 12, 21 and 22; Fig. 8). The block between the two major shear zones rotated clockwise (i.e 'backwards') during deformation (observed on a video replay of the experiment). Layers outside this region of the model are now inclined at about 26° whereas layers 16 and 17 are at a steeper 38°.

Model 3

This model is similar to model 2 except that the layers were initially inclined at 15° and that layer 10 does not contain a colour banding. After bulk simple shearing, a geometry of structures similar to that of the second model is observed (Fig. 7), though in this case, no overlap exists between the two right-stepping major zones that have been developed. Details of the central region (Fig. 9) show that there has been a lesser development of secondary shear bands. Minor sinistral, dextral and conjugate pairs of shear bands are especially developed near the termination of, and between, the two major shear zones. Most sinistral secondary shear bands make an angle of between 50 and 60° with respect to D and an average angle of 36° with the layering. Dextral shear bands were formed at angles between 18 and 32° to D and make an average angle of 40° with the layering.

DISCUSSION

In the experiments, movement along primary shear zones takes place along a combination of closely spaced shear bands whose geometry is equivalent to that of D- and R-type shears (Fig. 1b). In model 1, minor shear bands equivalent to P-type shears were also developed in regions of local dip reversal. In all experiments, we have seen that secondary shear bands of normal fault geometry may develop with the same shear sense as the bulk simple shearing, as well as shear bands of the opposite sense that make an angle of approximately 40° with the layering, irrespective of the initial orientation of the layering. We therefore suggest that the presence of a layering along which slip may occur favours the development of shear bands of opposite sense to the bulk simple shearing, as well as shear bands of the same shear sense, and that the orientation of this layering governs the orientation of secondary shear bands. As decoupling between layers takes place, tensile stresses parallel to the layering may exist within the layers during bulk simple shearing (see also Lister & Williams 1979) thus producing conjugate shear bands within the layers. Once initiated, these shear bands may propagate across a layer interface where further movement along the interface is inhibited.

The experiments resulted in domainal patterns of structures, including (a) domains of clearly defined primary shears along with oblique, secondary shear bands of the same shear sense, (b) domains of clearly defined primary shears along with oblique secondary shear bands of opposite sense, (c) domains of clearly defined primary shears with conjugate secondary shear bands of normal fault geometry, (d) conjugate secondary shear bands of normal fault geometry with no primary shears

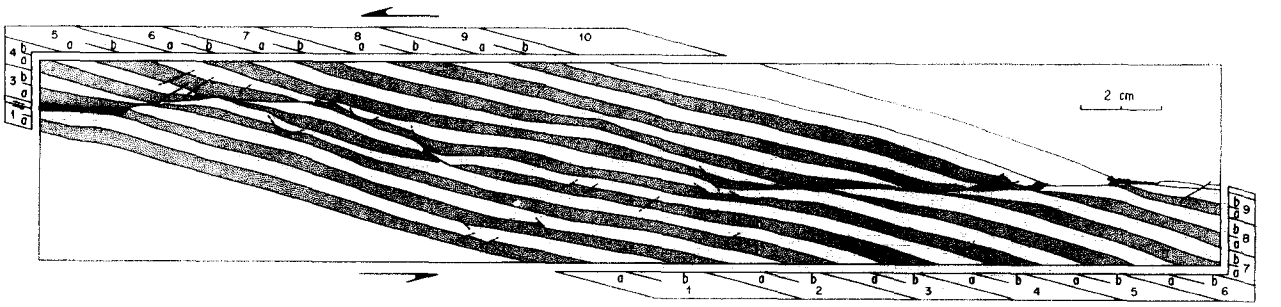


Fig. 9. Detail of model 3. See text for details.

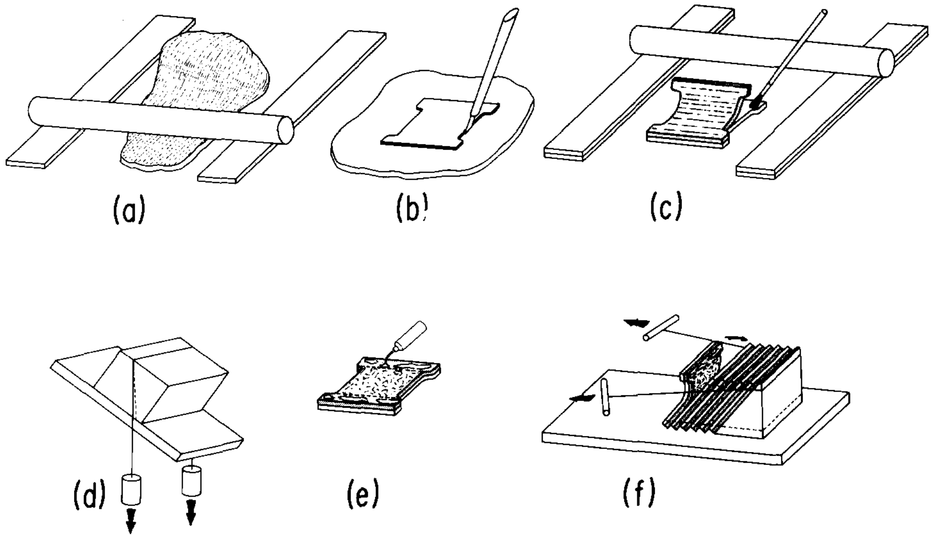


Fig. 10. Method used for model construction. See Appendix for explanations.

(between overlapping, primary shear bands) and (e) entire blocks which have undergone a backwards rotation (between overlapping, '*en relais*' shear zones).

If layers were initially at an angle greater than 45°, sliding along these layers would first have been in a sense opposite to that of the bulk shear sense (Etchecopar 1977). After layers pass 45°, the sense of sliding will change. We may therefore find domains of different senses of total displacement along the layering, as observed in model 1.

Recognition of the coexistence of the structures described above is extremely important for the structural interpretation of a given area by the field geologist. The structures created in these models may be encountered in the field on the scale of a hand specimen, an outcrop or a region. At the scale of a thin section, domains in which a fabric study gives an opposite sense of shear to that deduced from other field evidence may be found along with domains in which the fabric is in agreement with the regional sense of shear (Celma 1982).

In natural examples, voids which have been seen to be formed along major shear zones in these experiments may be sites for neomineralization (e.g. quartz or calcite veining).

In hand specimens of sheared granites, shear bands nearly always have an '*en relais*' geometry, especially where the foliation makes a small angle with the shear band (Gapais, pers. comm.) and sliding along the foliation must occur to accommodate movement along them. On a slightly larger scale, we see that the conjugate geometry described above for shear bands in gabbros from Cap Corse and in metamorphic rocks from Ile de Groix may be produced within an overall regime of bulk simple shear if sliding along the foliation or between beds of slightly different competence has taken place, for example between glaucophane-rich and glaucophane-poor layers of gabbros. We may also postulate the existence of normal faulting on a large scale within terrains having undergone bulk non-coaxial deformation.

CONCLUSION

Conjugate shear bands are not diagnostic of a regional bulk coaxial deformation history but may be formed locally during bulk simple shearing if sliding along a foliation (such as a layering, cleavage or schistosity) takes place. The orientation of secondary shear bands is then controlled, not so much by the orientation of the bulk shear direction or the principal directions of total strain, but by the attitude of the layering.

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APPENDIX

Preparation of multilayered Plasticine models

Multilayered Plasticine models (Fig. 10) are prepared using the following steps. (a) Soft Plasticine is rolled, using guide plates, to half the thickness required for layers in the model. (b) A half-layer is cut out using a template (allowing an excess length for final trimming). (c) A second half-layer is cut from Plasticine mixed with a small quantity of haematite powder to provide a colour contrast. The two half-layers are bonded using a solvent (carbon tetrachloride) and left for at least 24 hours for the solvent to be diluted by diffusion into adjacent layers. (d) End blocks of the model are cut to the required angle from a block of soft Plasticine using a thin metal wire (guitar string). For an even cut, the base plate is inclined and a vertical force applied to the wire. (e) Vaseline is applied to the narrow part of each bi-coloured layer. The two wider ends are coated with cyanoacrylate glue. (f) Layers are glued to the end block and to each other, a second end block is placed and the model is cut to slightly more than the required height using the metal wire. Final shaving with a large knife provides a regular, horizontal surface to the model. Acetate film longer than the model and of the same width is glued to the upper and lower surfaces. The model is then placed in the simple shear machine and attached, via the acetate sheets, to the upper and lower metal plates of the machine. The sides of the model in contact with the glass plates of the machine are 'lubricated' with talc powder.

After deformation, the model is cut lengthwise into slices using the metal wire.