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Patterns of folding and strain influenced by linearly anisotropic bands

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Abstract—Are there characteristic patterns of deformation in rocks dominated by linear fabrics? Detailed examination of deformed calcite fibres shows strain partitioning into shortening normal to the fibres achieved by pressure solution, by buckling of inclusion bands within the fibres, and shear parallel to the fibre long axes. Folding of rocks with opposed directions of anisotropy may lead to discontinuities due to the incompatibility of the folding directions.

INTRODUCTION

THE FACT that certain geological structures, such as shear zones (Ramsay & Graham 1970) and kink bands (Paterson & Weiss 1965), occur with specific, reproducible and recognizable geometries in a variety of rock types and metamorphic grades suggests that certain constraints have been operative during the formation of the structure. These 'characteristic' patterns do not necessarily specify unique conditions because we know, for example, from model work, how chevron folds may evolve from either sinusoidal folds or from kink bands (Cobbold *et al.* 1971). The fold geometries may be very similar although presumably the finite strain or the incremental strain paths may well be different.

The constraints are likely to be of several types: the maintenance of strain compatibility, stress equilibrium, a minimum energy condition and the rheological condition of the rocks. If material continuity is maintained across the boundary of the characteristic structure, then a condition of strain compatibility at the boundary is required. Also the system must be statically admissable; that is, the conditions of deformation must satisfy stress equilibrium [the material scientists call such a deformation a 'controllable deformation' (Spencer 1972)]. Finally, if the rock has a distinctive rheological state, such as being strongly anisotropic, there may well be a characteristic pattern of deformation which reflects the strong anisotropic response of the rock.

This approach to understanding patterns of deformation has been elegantly used in the analyses of chevron folds by Cobbold (1976) and Casey (1976), and of kink bands by Summers (1979). It complements the field-oriented geometric approach of tracking incremental strains (for instance, from fibre growths) to see how a structure may have evolved and built up over time.

We are aware of many examples of deformation of rocks governed by a strong planar anisotropy. In well-layered rocks, a characteristic response to deformation is that the strain is concentrated as bedding-plane shear in incompetent layers between more competent layers, or as discrete bedding-plane slip. Kink and chevron folds are characteristic patterns of deformation in rocks with a strong, planar anisotropic fabric (Cobbold 1976).

This paper addresses the question of whether there are any characteristic patterns of deformation in rocks which have linear fabric components. It examines the relationship between linear anisotropy and structures which post-date, and therefore may be controlled in their development by, the linear features. To this end a detailed examination is made of a small-scale example of crenulated calcite fibres from the Arra Mountains, Ireland (Watkinson & Cobbold 1981). The fibres are one example of linear features; others such as rods, boudins, folds and linear tectonite fabrics may constitute a control on a regional scale. One possible regional-scale example will be discussed.

FIELD OBSERVATIONS OF CRENULATED FIBRES

Detailed examination of crenulated calcite fibres from slates in the Arra Mountains, SW Ireland reveals the following features.

(1) The crenulation folds and associated cleavage frequently switch parallel to the fibre direction wherever the fibres are strongly developed. This leads to local directions of transposed cleavage with respect to the major folds.

(2) The calcite fibres frequently occur in bands on the bedding planes (Fig. 1a).

(3) There is material continuity between the crenulation folds in the bands and those outside; that is, no obvious fault discontinuities exist.

(4) Profile thin-sections show the calcite occurring as sheeted, thin plates made up of the fibres and constituting a multilayer unit in a slate matrix (Fig. 2a).

(5) The crenulation folds show curved calcite deformation lamellae in hinge areas, interpreted as evidence of bending (Fig. 2a).

(6) Thin sections reveal deformation features in the calcite fibres. Sutured contacts with clay 'residues' are

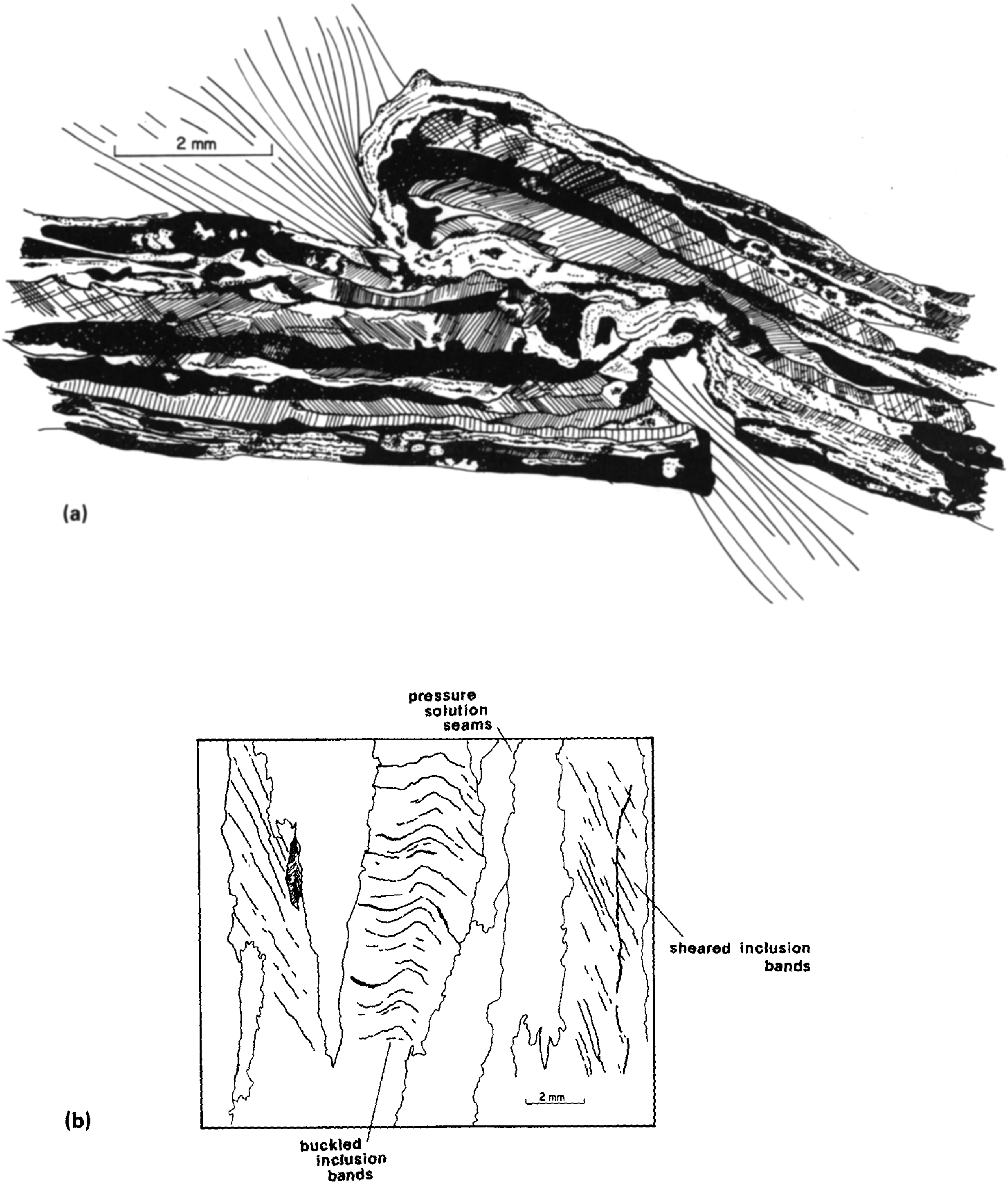

Fig. 2. (a) Profile cross-section of the crenulated fibres, showing pressure-solution cleavage seams through the fold limb and the curved deformation calcite lamellae in the fold hinge zone. (b) Annotated line drawing of a segment of Fig. 1(b), with scale.

frequent along the edges of the fibres. This is evidence of solution transfer (pressure solution) along the contacts between the fibres. Profile thin-sections also show pressure-solution style cleavage cutting through the calcite layers at fold limbs.

Ramsay has described examples of undeformed inclusion bands in calcite fibre growths (Ramsay 1980). The bands are parallel to calcite vein walls and normal to the long axis of the fibres (Fig. 3a). The fibres in these Arra Mountain examples are clearly deformed in that they have deformation lamellae, and show deformed inclusion bands. The inclusion bands show either a consistent sense of shear displacement (assuming them to have been near-perpendicular to the fibre axis in an undeformed state) with respect to the long axis of the fibre and/or are buckled (Figs 1b and 2b).

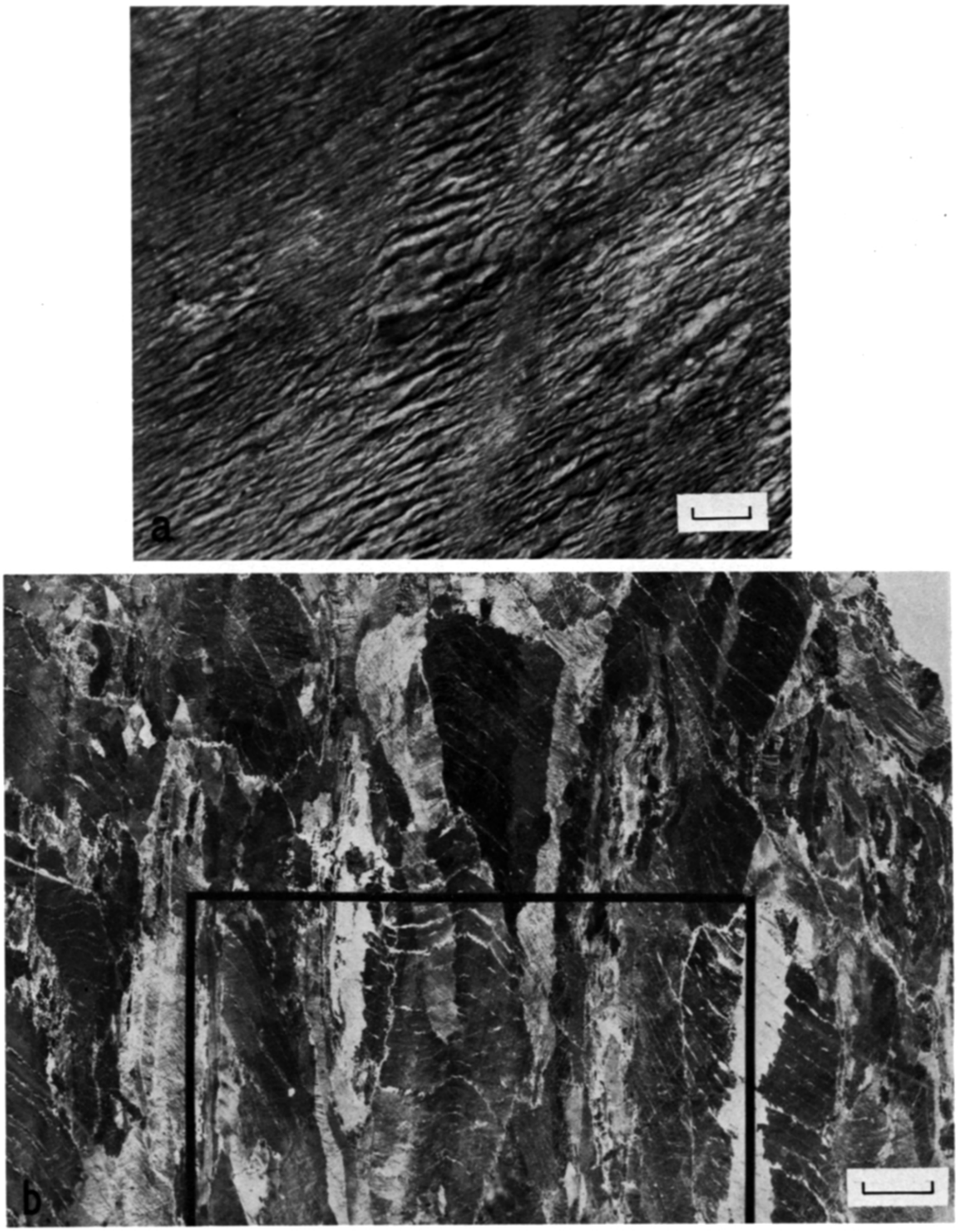

Fig. 1. (a) Banded nature of the crenulations on the bedding planes, Arra Mountains, Ireland. The bands contain the crenulated calcite fibres. Bar scale: 2 cm. (b) Thin section of the fibres, cut parallel to the bedding plane, (So) containing the fibres. Pressure solution seams between the fibres and the buckled and sheared inclusion bands are shown. Cross-nicols. Bar scale: 2 mm.

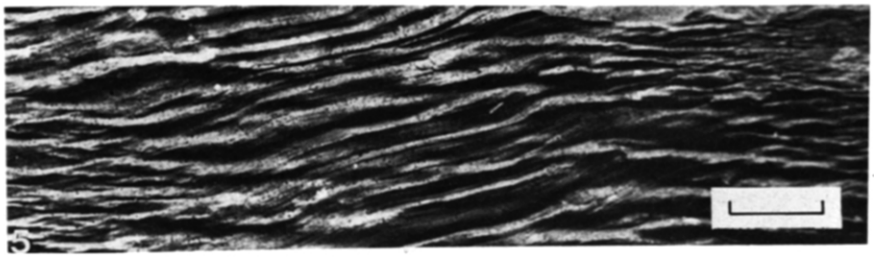

Fig. 5. Example of a crenulated fibre band showing material continuity between the crenulations within and outside the band. Notice the change in angle of the lineation as it comes into the fibre-band. Bar scale: 2 cm.

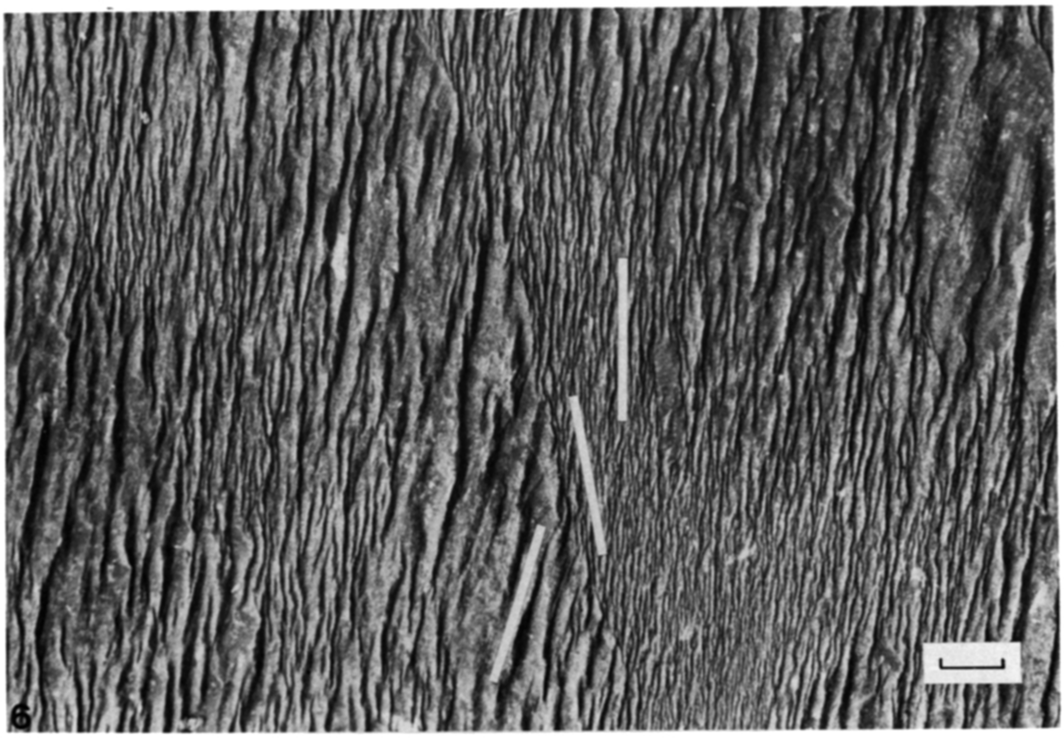

Fig. 6. A mixed zone showing three directions of folding (parallel to the white bars). One direction is parallel to the boundary between the fibres and a fibre-free zone, another direction is parallel to the fibres and the last is parallel to the major fold axes. Bar scale: 2 cm.

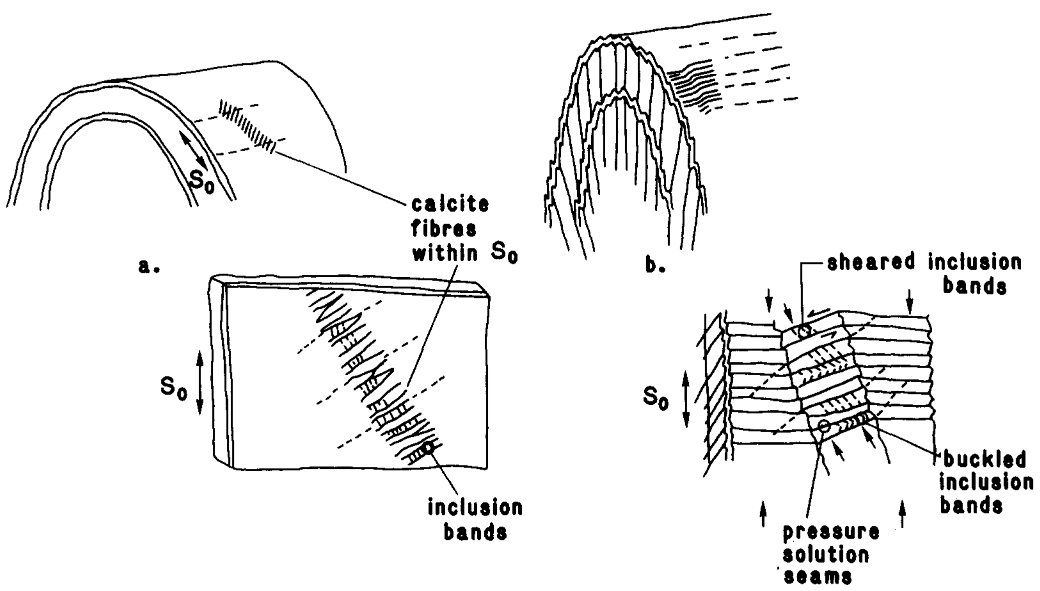

Fig. 3. (a) Possible original or undeformed configuration of the fibre bands. Notice that in the undeformed state, the inclusion bands are near-perpendicular to the long axes of the fibres (cf. Ramsay 1980, fig. 3). (b) Final configuration with potential strain components.

INTERPRETATION

The interpretation of the fibrous calcite is that early growth of the Arra Mountain folds involved a component of bedding-plane slip, with the fibres growing in the slip direction and recording some increment of the bedding-plane slip. In these examples, the fibres record a component of slip which was oblique to the fold axis direction; others show some component of slip perpendicular to the fold axes. As the amplification of the folds increased, the bedding-plane slip locked up and further shortening occurred, resulting in the cleavage and in the crenulation of the early-formed fibres (Fig. 3b).

Banded fibres

The observations strongly suggest that the strain in the folded fibres is partitioned into several components. The fibrous sheets have buckled with the fold axes parallel to the fibre long axes. Pressure solution has occurred along the long edge of the fibres, and shearing parallel to the fibres. Shortening has occurred of the inclusion bands within the fibres by buckling.

Since the calcite fibres occur in bands and since material continuity and the folds are maintained across the bands into the non-fibrous bedding plane, strain compatibility requirements place some constraints on the boundary strains. Shear parallel to the band boundaries, volume loss and pure shear components have been recognized as viable options whereby continuity can be maintained across banded structures (Ramsay & Graham 1970, Cobbold 1977, Summers 1979). These options appear to be compatible with the observations made on the Arra Mountain fibres (Figs. 3b and 4).

Within the bands, the crenulations are parallel to the fibres whereas in the external zones, the crenulations are parallel to the major fold axes and do not seem to be affected by the fibre growth (Fig. 5). For this reason, it is assumed that in the exterior zones the bedding surfaces were crenulated and have behaved in an effectively isotropic fashion *within* the plane of the bedding; that is,

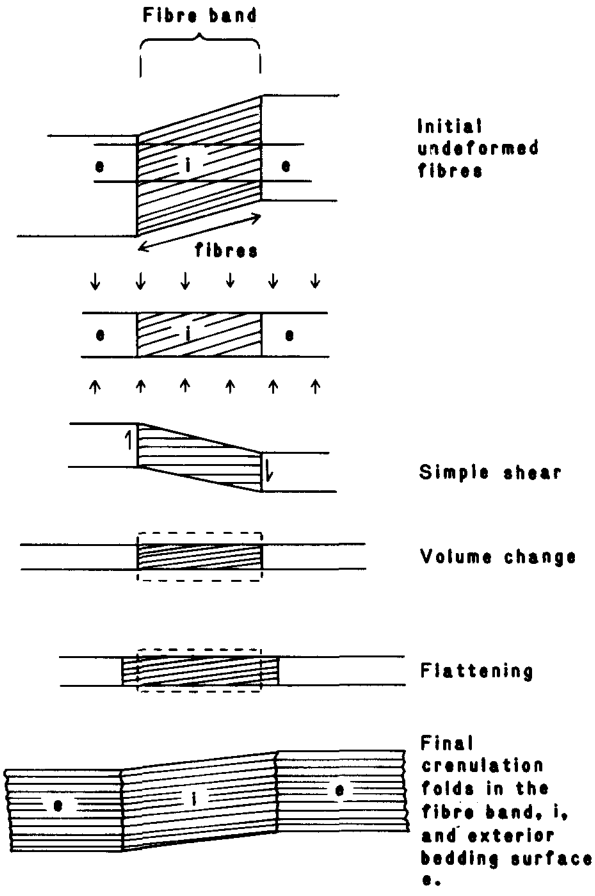

Fig. 4. Possible compatible strain components to maintain continuity between the bands, i, and the external bedding planes, e (cf. Summers 1979, figs. 3.2a and c).

unaffected by the fibre directions. The linearly anisotropic band of strong fibre growth is thus connected to an effectively isotropic external zone where the fibres are weakly developed, or not developed at all. The compatibility requirements are thus similar to those proposed by Summers (1979) for his analyses of kink band compatibility.

It is further assumed that the fabric symmetry of the calcite fibres in the sheets (orthorhombic) reflects the symmetry of their rheological properties (i.e. orthotropic) (Paterson & Weiss 1961). The fact that the crenulation folds switch parallel to the fibre long axes suggests a strong anisotropic control of the fibres on the fold axis orientation. Cobbold & Watkinson (1981) have suggested that if an orthotropic material is strongly reinforced by fibres, the material tends to deform by shearing parallel to the fibres and/or by shortening normal to them. That predicted rheological response seems compatible with this field example.

Non-banded fibre zones

The calcite fibres also occur in more diffuse zones rather than in discrete bands and the folding patterns are then usually more complex. Zones of two directions of folding are observed, one parallel to the fibres and the other parallel to the major fold axes, with the latter arranged en-echelon fashion between the fibre-parallel folds. Another observed fold geometry is the formation of folds parallel to the boundaries of the fibre zones (Fig. 6), which presumably reflects a condition of maintenance of compatibility with the exterior zones. In this case it appears that folds have formed in at least three orientations in a single deformation event. One direction is parallel to the fibres, another parallel to the major fold axes and the third parallel to the boundaries of the fibre zone.

DISCUSSION

In these small-scale examples it seems clear that the fibres markedly affect the orientation of later deformation features and as such constitute an anisotropic control. It appears that the deformation has maintained material continuity by components of shortening, expressed as buckling and by volume loss by pressure solution parallel to the fibre axes, and finally by possible shear parallel to fibre axes within the banded structures.

Are there any examples of these components of deformation operating on a larger or regional scale in areas with other forms of strong linear fabrics? In the Baronnies region in the Provencal alps, Goguel (1947) and Flandrin (1966) have documented how early east–west folds are reactivated by later, oblique (north-westerly) Alpine-phase folds. The renewed folding is evidence of components of shortening across the early fold axis direction. There is also evidence of shearing along the limbs forming en-echelon fault patterns on the limbs and shear displacement along the axial surface of the folds (Goguel 1962).

It would be instructive to look in other areas of strong linear fabrics affected by later deformation events. From these discussed examples, it appears that when early fabrics with linear components are deformed by later events, in directions oblique to the early fabrics, the response of the rocks is to shorten normal to the early linear fabric and shear parallel to the linear fabric. It would be interesting to know if this was a characteristic response.

Finally, the discussion so far has been about situations where material continuity exists across the boundary of the structure and the external zone. However, rock associations might occur with opposed anisotropic directions. Such an example might be found in overlapping nappe sequences with penetrative linear/planar fabrics. In these situations, further deformation may lead to décollement due to incompatibilities developed across the boundaries of the opposed anisotropic directions. As an illustration of this idea, the author's recent model experiments of deforming layers containing fibres have resulted in zones of décollement developing across layers with fibres in orientations with as little as 10–20° difference between the layers. Folds have formed parallel to the fibres and zones of local to pervasive décollement occur in order to accommodate the opposed fold directions. This constitutes another form of a mechanical impetus to décollement rather than a control due to incompetent layers. Such a situation could well occur in nature.

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