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Transected folds: a re-evaluation, with examples from the 'type area' at Sulphur Creek, Tasmania

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Abstract—The term 'transected fold' was introduced to describe cleavage which cuts both limbs of a contemporaneous fold with the same asymmetry in the profile plane. If transected folds can form in a single deformation then the reliability of cleavage-bedding or cleavage/cleavage asymmetry for the identification of fold closures becomes suspect for some deformation regimes.

Re-examination of the 'type area' for transected folds (Sulphur Creek, Tasmania, Australia) revealed that these folds were produced by a polyphase deformation history. The 'transected folds' are D_1 structures with a weak axial-plane slaty cleavage (S_1) overprinted by D_2/D_3 cleavages and composite folds. There is also evidence of a weak D_4 event which crenulates the earlier cleavages.

Several examples of 'transected folds' have been published but as yet there has been no rigorous demonstration that these folds are not simply the result of a polyphase deformation. The mechanism proposed for producing transected folds, where the cleavage and fold are synchronous, was based on the hypothesis that the fold axis will develop parallel to the long axis of the ellipse generated by the intersection of a plane with the strain ellipsoid. If this plane is oblique to the X, Y and Z axes then the long axis of the elliptical section generated through the strain ellipsoid will not necessarily lie in the XY plane. It is suggested that this mechanism is invalid for a plane (layer) with finite thickness and for heterogeneous deformations, because the strain in any layer being folded should be controlled directly by the three-dimensional strain within the layer and its immediate environment, rather than by a two-dimensional section through the bulk strain ellipsoid.

INTRODUCTION

CLEAVAGE commonly lies approximately parallel to the axial planes of folds produced by the same deformation event, particularly in areas of high strain (Turner & Weiss 1963, Ramsay 1967, Wood 1974, Hobbs *et al.* 1976). However, cleavage that does not contain the fold axes of apparently coeval folds has been recorded in low-grade metamorphic terrains (cf. Stringer 1975, Bell 1978, Borradaile 1978, Stringer & Treagus 1980, Gray 1981, Treagus & Treagus 1981).

A special form of non-axial plane cleavage which cuts both limbs of the folds with the same asymmetry in the profile plane (Fig. 1) was proposed by Powell (1967, 1974). He suggested the term 'transected fold core' for these structures and suggested that the folds and cleavage were of the same age. Borradaile (1978) and Gray (1981) extended the definition of transected folds to include any form of non-axial plane cleavage. However the term 'transected fold' will be used here only in the original sense of Powell (1974) for cleavage generated at the time of folding which cuts both limbs of the fold with the same asymmetry in the profile plane (Fig. 1).

The implication of Powell's interpretation of fold transection is that the normally accepted overprinting criteria can break down in certain circumstances (cf. Borradaile 1978). Since these overprinting criteria are used as a fundamental mapping technique in terrains of polydeformed rocks, it was considered essential to re-investigate the phenomenon of transected folds. This paper describes the results of a re-examination of (1) the area for which transected folds were proposed at Sulphur Creek, Tasmania, Australia and (2) the assumptions on which a theory was developed to explain the phenomenon (Borradaile 1978) and fold axis oblique cleavage (e.g. Ramberg 1959, Flinn 1962, Ghosh 1966, Treagus 1972, 1973, 1981, Treagus & Treagus 1981).

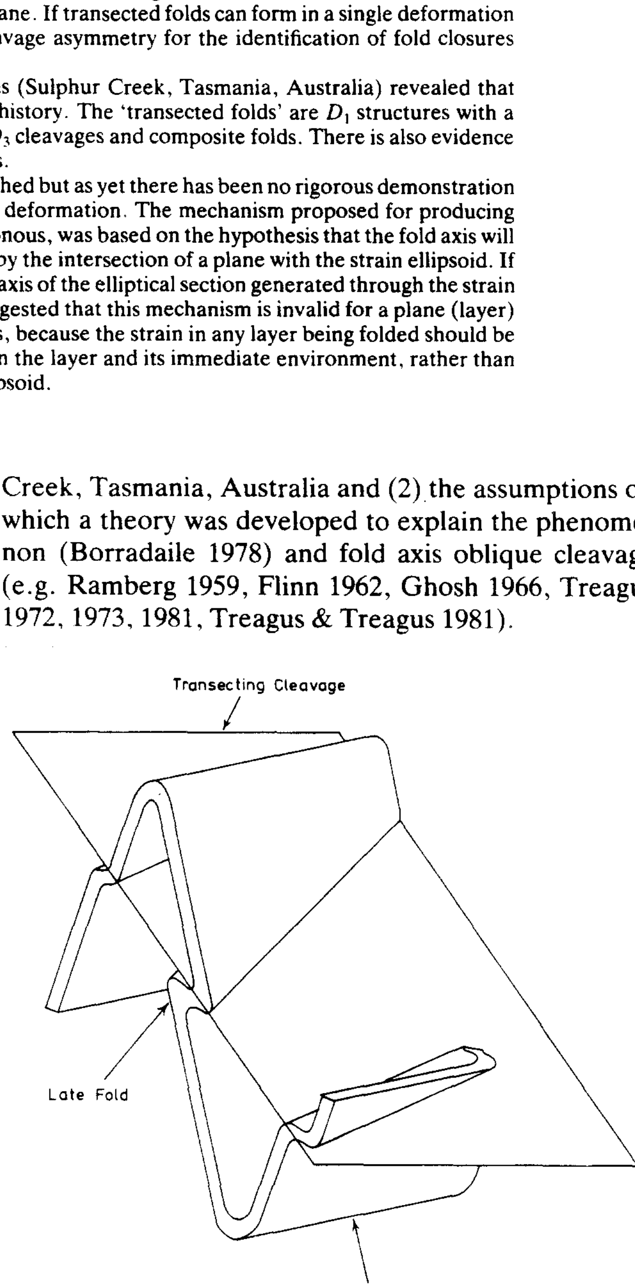

Fig. 1. Diagramatic example of a transected fold as described by Powell (1974). The transecting cleavage, that he interpreted, was produced by the same deformation that generated the early fold. This cuts both limbs of the early fold, with the same asymmetry in the profile plane. The cleavage/bedding and fold asymmetry, and the vergence are not useful for identifying transected fold closures; only younging and structural facing data identify such structures. Note that the illustrated structure is identical to a refolded fold produced during polyphase deformation.

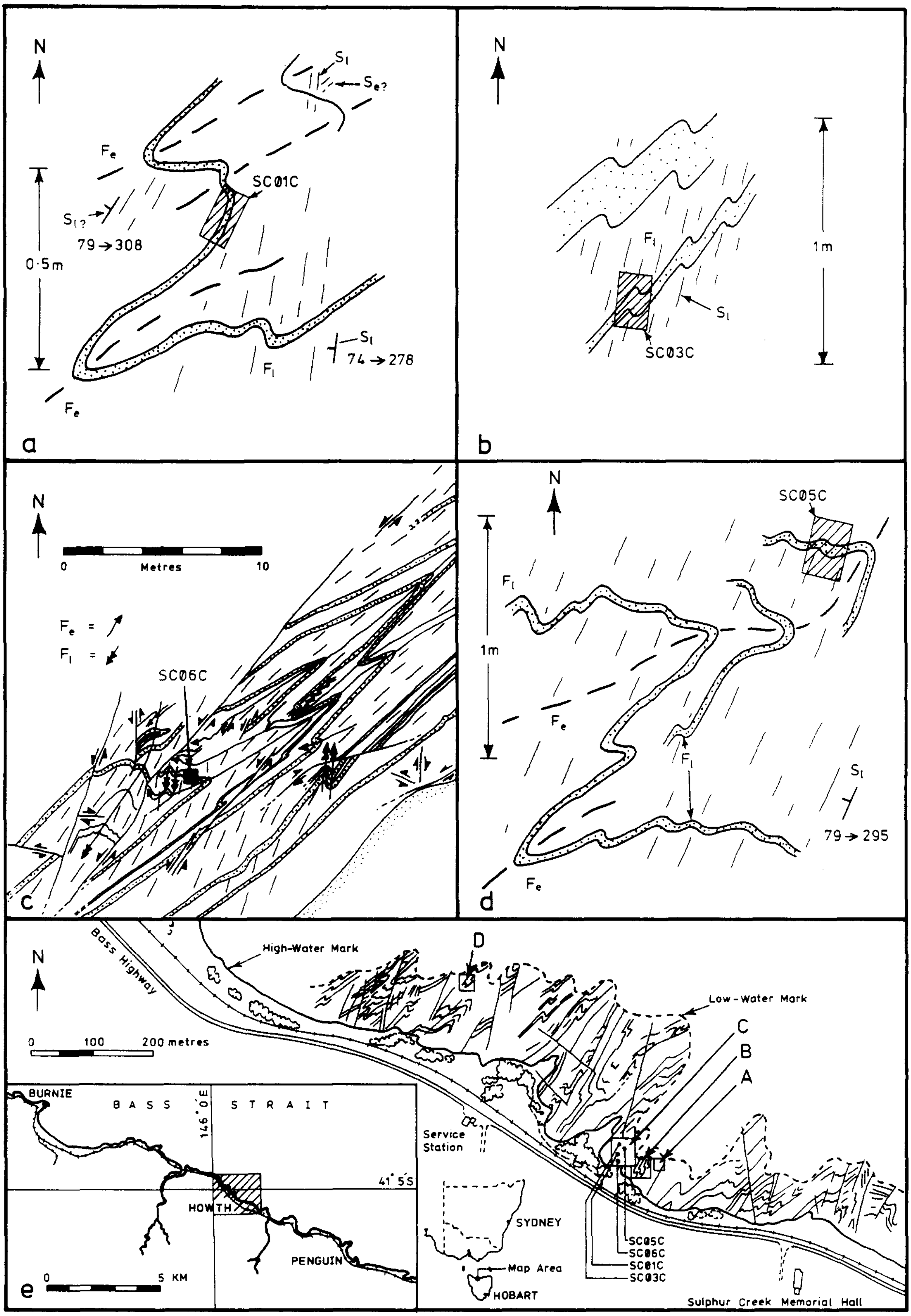

Fig. 2. Sample localities and location map of Sulphur Creek, northern Tasmania, Australia. All specimens were taken from area C (Powell 1974). All cleavage readings given as dip and dip azimuth. (a) Sketch map of early fold (F_e) cut by a cleavage axial plane to the late folds (F_l). Location of sample SC01C. (b) Sketch map of F_l folds. Location of sample SC03C. (c) Map after Powell (1974), part of Powell's area C showing location of specimen SC06C. F_e and F_l folds identified. (d) Sketch map of refolded (transected) early fold (F_e) cut by the cleavage S_l. Location of specimen SC05C. (e) Location map (after Powell 1974) of sample locations. Areas A, B, C and D are locations of areas mapped by Powell (1974). Powell's area E is 900 m NW of area D (off the map). Note, only specimen SC06C can be shown located on Powell's detailed map C which covers a narrow band of the area depicted as C on Powell's original location map as shown.

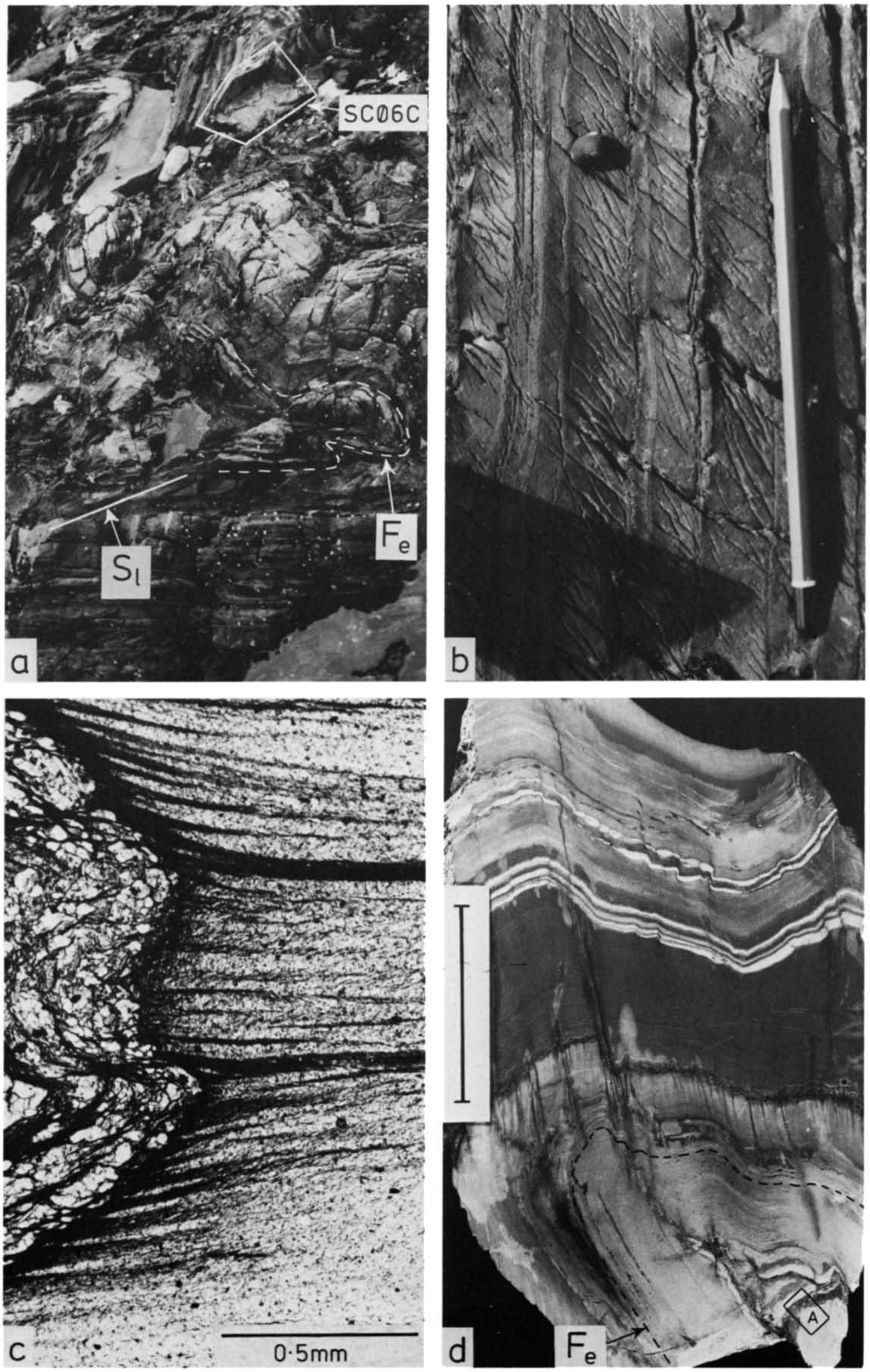

Fig. 3. (a) 'Transected fold' from Sulphur Creek, Tasmania (area C, Powell 1974) (also see Fig. 2c). The dominant cleavage (S_l) cuts both limbs of the early fold (F_e) with the same asymmetry. Note the development of the late folds with S_l axial plane to them on the right-hand or northwestern limb of the fold. Location of specimen SC06C shown. Photograph looking south (south = left margin). The height of the image is approximately 2 m. (b) Field evidence for two spaced solution-seam type cleavages from Sulphur Creek, Tasmania. The cleavage cutting S_0 at about 55° is associated with the late folding event and is axial planar to the late folds. The cleavage at about 30° to S_0 is approximately parallel to the axial plane of the early folds. (c) Thin section of a late fold from Sulphur Creek (SC03C, Fig. 2b) showing a well-developed slaty cleavage subparallel to S_0 and a distinct and well-formed crenulation cleavage axial plane to the late fold (F_l). Plane polarized light. (d) 'Transected fold' (specimen SC06C, Figs. 2c and 3a) from Sulphur Creek. Specimen cut parallel to the profile plane of the early fold (F_e). Lower portion of the specimen shows a tight, early fold with no obvious axial-plane cleavage. The fold is 'transected' by a spaced crenulation cleavage at about 40° to the early fold axial plane. The transecting or late cleavage is parallel to the axial planes of the smaller-scale late folds which refold the early fold. Detail of area A can be seen in Fig. 4(a). Bar scale is 5 cm.

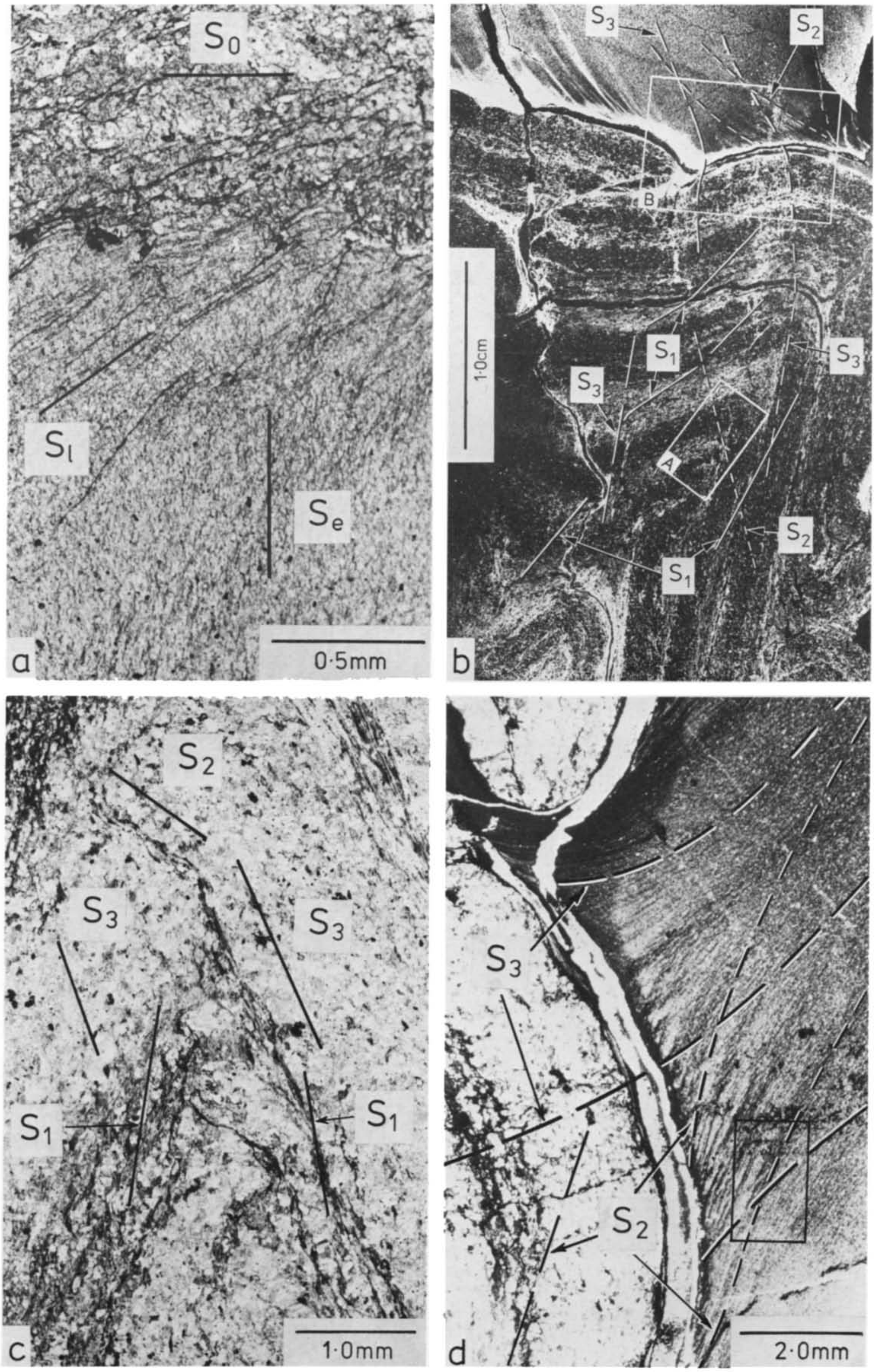

Fig. 4. (a) Plane polarized thin section view of area A in Fig. 3(d). S_e is a penetrative slaty cleavage axial planar to the early fold (F_e or F_1^0). S_l is the transecting crenulation cleavage axial planar to the late folds. (b) Negative print of a thin section of an early fold ($F_1^0 = F_e$, specimen SC01C, Fig. 2a) with a related axial plane S_1 slaty cleavage. There is evidence of several overprinting events, the most intense of which is nearly parallel to the right-hand limb of the F_1^0 fold. This cleavage is interpreted as the third event to affect these rocks and is termed S_3. S_3 overprints a previous crenulation cleavage in the fine-grained micaceous lithology shown in the upper portion of the figure. Areas A and B are shown in Figs. 4(c) & (d), respectively. (c) Enlargement of area A in Fig. 4(b). Area of early fold closure (F_1^0) with associated S_1 slaty cleavage reverse fanned in the micaceous lithologies. S_2 is weakly developed as solution and/or mica seams which appear to be crenulated by S_3. This is supported by evidence seen in Figs. 4(d) and 5(a). S_3 is a crenulation/crenulation cleavage nearly parallel to the right-hand limb of the early fold, transecting the early fold which consistently cuts S_1 with a Z-shaped asymmetry. Plane polarized light. (d) Enlargement of area B in Fig. 4(b). Contact zone between coarser quartzite layer and fine-grained micaceous slate. S_1 in the slate is strongly crenulated by two well-defined but refracted crenulation cleavages. The later event corresponds to the cleavage subparallel to the right-hand limb of the early fold shown in Fig. 4(c) and is the third tectonic foliation (S_3). S_2 is considerably stronger in the slate as compared with the quartzite. Plane polarized light. Rectangular zone marked is the area covered by Fig. 5(a).

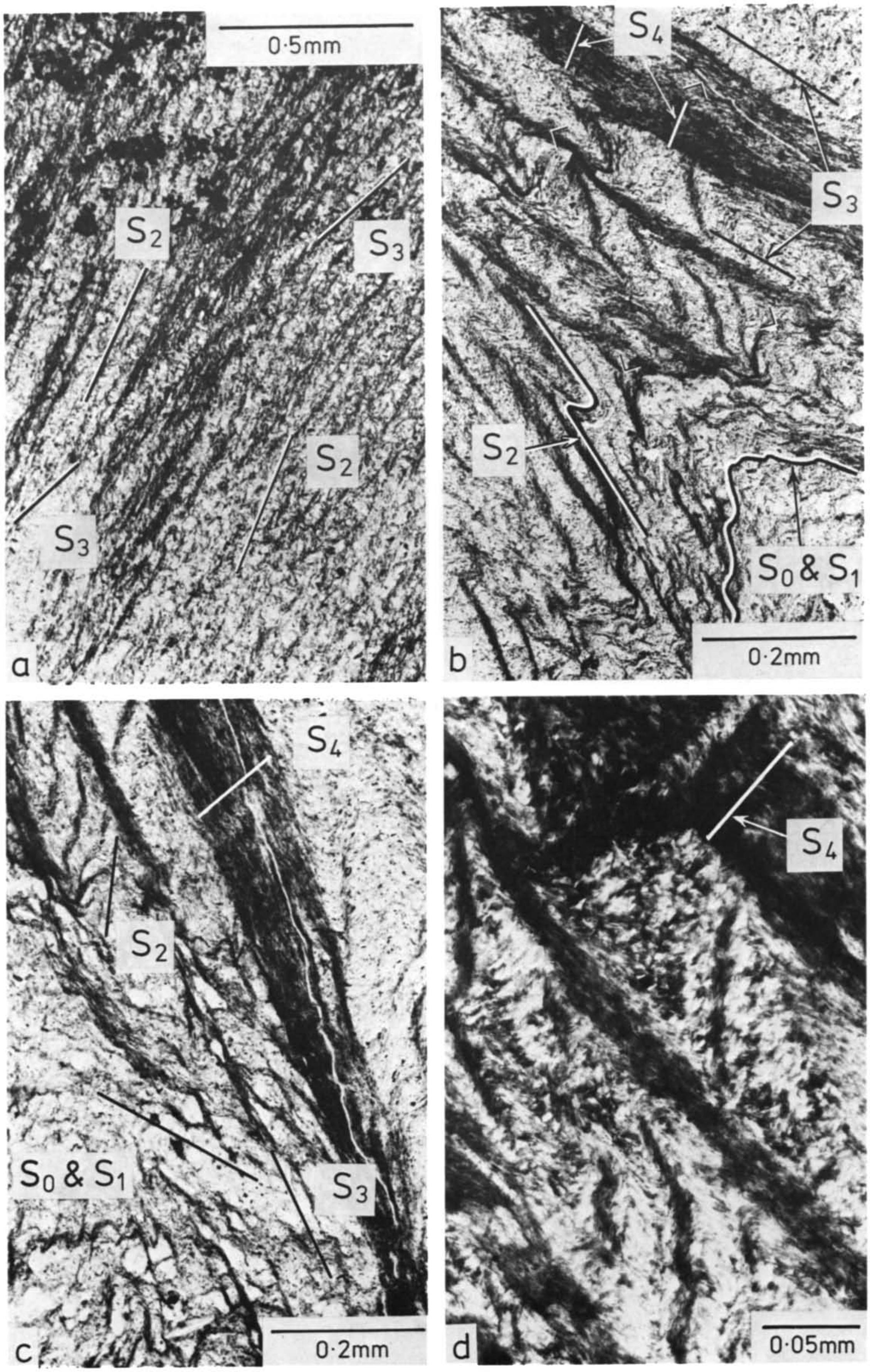

Fig. 5. (a) Enlargement of the area marked in Fig. 4(d). S_1 is overprinted and crenulated by two crenulation cleavages, S_2 and S_3, respectively. Plane polarized light. (b) Thin-section example of a late fold (specimen SC05C, for location see Fig. 2d. Figs 5b–d refer to the same specimen). S_1 is subparallel to S_0 and crenulated by S_2. Axial planar to the late fold is a well-developed S_3 crenulation cleavage. Weakly developed on the limbs of the S_3 crenulations is evidence of a later S_4 crenulation event. Plane polarized light. Rectangular region marked is the area covered by Fig. 5(d). (c) As in Fig. 5(b). Good example of S_1 slaty cleavage nearly parallel to S_0 with elongate quartz grains and mica beards. S_1 is crenulated by S_2, S_3 and S_4. Plane polarized light. (d) Enlargment of the rectangular area marked in Fig. 5(b). Note the S_2 and S_3 crenulation cleavages, also the development of the S_4 crenulation on the limb of the S_3 crenulation cleavage. Cross-polarized light.

STRUCTURE OF SULPHUR CREEK, TASMANIA

Previous study of Sulphur Creek

The interlayered quartzites and slates at Sulphur Creek were originally mapped and described by Gee (1967a, 1967b) and Powell (1967, 1974). Powell (1967, 1974) studied five small areas within the Sulphur Creek region and proposed that there have been at least two folding episodes, F_e and F_l (early and late), but only one cleavage episode (S_l).

Powell found in areas A, B and C in particular (Fig. 2e) (Powell 1974), that F_e folds were the major folds and had no associated cleavage development. The folds are tight to isoclinal and generally have a Z-shaped asymmetry (down plunge) with the succession younging to the southeast. The areas contain a good penetrative cleavage that cuts both limbs of the folds with the same asymmetry in the profile plane (transected folds) and in places it is associated with late Z-shaped asymmetric folds (F_l). S_l appears to be geometrically related to the F_l folds because it is axial planar to them and also fans in their hinge regions. Locally a crenulation cleavage is developed which is part of the late fold generation (i.e. S_l). In the western part of Powell's study area (E, Powell 1974, fig. 1), his early folds have an axial-plane cleavage and there is no evidence of refolding or fold transection.

Powell suggested that these fold and cleavage relationships could be interpreted to indicate that the cleavage developed over a short interval of time during a protracted folding event. Consequently, if the cleavage developed early in the deformation history it would lie parallel to the axial planes of the folds. If however, it developed late, and the fold axial planes had previously rotated out of the plane of cleavage formation, then transected folds could be formed. Powell argued that later folds were produced by a continuation of folding as the cleavage developed and that therefore they formed with normal geometry with respect to cleavage in the profile plane.

Re-examination and interpretation

The main areas of fold transection are areas A, B and C (Fig. 2e) (also see Powell 1974, figs. 1, 2, 3, and 5). After a close study of these outcrops, area C (Fig. 2) was selected as the most suitable for sampling because it contained a high proportion of pelitic rocks (most likely to show an expression of any weak foliation producing events) and a large angular difference between the early fold (F_e) axial planes, and the slaty cleavage (S_l) which is axial plane to the late folds (F_l) (Figs. 2 and 3a).

The S_l cleavage varies from spaced solution seams to an intense and penetrative foliation. In a few places large crenulations or micro-folds of bedding were observed. In a few rare locations, S_l appeared to crosscut and overprint another cleavage as shown in Fig. 3(b). This earlier cleavage is in the correct orientation to be axial planar to the early folds (F_e) suggesting that there may be an early cleavage associated with the early folding event.

In thin section the pelites or slates show a well-developed foliation subparallel to bedding and the dominant cleavage seen in all thin sections is a well-developed crenulation cleavage (S_l) which appears to be geometrically related to the late folds (F_l) as demonstrated by Powell (1974) (Fig. 3c).

Transected folds, or F_e folds (e.g. Fig. 3d, specimen SC06C, for location see Figs. 2c and 3a) are crosscut and refolded by a crenulation cleavage that corresponds to the late folding event. From a thin section study of area A shown in Fig. 3(d) it can be seen (Fig. 4a) that there is a distinct and well-developed cleavage approximately parallel to the axial plane of F_e folds and at a high angle to S_0 (bedding) in the closure of the early fold. This cleavage (S_e) is folded and overprinted by the transecting cleavage S_l. This is evidence of the occurrence of a cleavage associated with the early folding event (S_e).

From close study in thin section of the more micaceous layers in the quartz-rich lithologies (Fig. 4b, specimen SC01C, Fig. 2a), there is evidence of at least two cleavages and a crenulation. In the closure region of the early fold (Fig. 4c, area A in Fig. 4b) a reasonably well-developed slaty cleavage ($S_1 = S_e$) appears to be geometrically related to the early fold ($F_1^0 = F_e$, for F_m^n terminology see Bell & Duncan 1978). This cleavage is best developed in the micaceous layers, and shows convergent fanning with the average orientation approximately parallel to the axial plane. Parallel to the right-hand limb (Fig. 4c) of the early fold (F_1^0) is a well-developed set of crenulations or a crenulation cleavage that consistently cuts S_1 with Z-shaped asymmetry and is termed S_3 for reasons explained later. Also in Fig. 4(c) there is evidence of another weak cleavage (S_2) which produces crenulations of S_1 and some solution seams and mica trails which appear to be crenulated by S_3 (more convincing evidence is shown in Figs. 4d and 5a).

Detailed examination (Figs. 4d and 5a) of area D in Fig. 4(b) shows that two distinct crenulation cleavages are developed in the fine-grained micaceous lithology, and it can be seen that the crenulation cleavage called S_3 overprints the crenulation cleavage S_2. Both these cleavages are strongly refracted in the micaceous lithology (Fig. 4d) but can be traced into the coarser quartz-rich lithology and correspond to the S surfaces named S_2 and S_3 in area A previously discussed (Fig. 4b).

The above observations show that the first or early folds (F_e or F_1^0) developed at the time of generation of the S_1 slaty cleavage. The cleavage was later overprinted by the S_2 crenulation producing event (D_2) which is best expressed in the micaceous lithologies and cross-cuts S_1 with Z-shaped asymmetry. Post D_2, a more intense event, D_3, produced a crenulation cleavage that cuts S_2 at about 30° with an S-shaped asymmetry and is approximately parallel to the right-hand limbs of the F_1^0 folds (Fig. 4b). Later, a weak crenulation event overprinted the S_3 crenulations. This interpretation is substantiated by observations from specimen SC05C (Fig. 2d) discussed below.

Observation of a late fold (F_l, specimen SC05C, Fig. 5b) which occurs on the northwestern limb of an early or transected synformal fold (F_e, Fig. 2d), demonstrates that bedding (S_0) is cut by a slaty cleavage (S_1) which is subparallel to S_0. The slaty cleavage (S_1), as seen in Fig. 5(c), is defined by alignment of micas, elongation of quartz grains and well-developed mica beards, and therefore cannot be a sedimentary foliation. The slaty cleavage is crenulated by S_2, which itself is crenulated by the S_3 cleavage, axial planar to the late fold (cf. Figs. 5b–d). Weakly developed on the limbs of the S_3 crenulations is an overprinted S_4 crenulation (Fig. 5d). The S_4 crenulation only occurs where the axis of maximum shortening for the D_4 event is at a low angle to the mica {001} plane.

Thus the early folds (F_1^0) possess a weak but distinct slaty cleavage (S_1) which does not transect the F_1^0 folds but is approximately axial planar to them and, with some minor exceptions, is generally detectable only in thin section. These D_1 structures are then overprinted by two sets of crenulations or crenulation–cleavages (S_2 and S_3) with fairly similar orientations to each other, and thus making it difficult to distinguish the late folds as either F_2^0 or F_3^0 structures. These late folds are likely to be composite structures derived from both the D_2 and the D_3 deformation events, but appear to be dominated by the S_3 crenulation cleavage, suggesting that the D_3 event made the greater contribution to their development. In areas E, D and parts of A and B (Powell 1974, areas A, B and D also shown in Fig. 2e) the late folding events were subparallel to the D_1 structures and produced no transected fold effects. Only in areas where the D_1 structures have not been rotated into parallelism with the later deformation events, do the F_1^0 folds become refolded and cross-cut by the later deformation structures. Alternate limbs of D_3 crenulations are then overprinted by later minor D_4 crenulations where there is a small angular difference between the axis of maximum shortening and the mica {001} plane (Fig. 5d). Consequently, Powell's 'transected fold' hypothesis (Powell 1974) for the rocks at Sulphur Creek does not appear to fit the evidence seen in thin section, and an alternative hypothesis that the structures could have been developed by a polyphase deformation history appears to be more consistent with the data.

CONSIDERATION OF THE MODEL FOR SYNCHRONOUS FOLD AND CLEAVAGE DEVELOPMENT WITH RESPECT TO TRANSECTED FOLDS

Several authors have discussed the synchronous development of folds and non-axial plane or axially oblique cleavage (e.g. Ramberg 1959, Flinn 1962, Ghosh 1966, Treagus 1972, 1981, Borradaile 1978, Treagus & Treagus 1981), and hence transected fold formation (Borradaile 1978). The model applied by these authors to define the nucleation direction of the fold axis, is that it develops parallel to the long axis (X', Fig. 6) of the elliptical section that any plane makes with the strain ellipsoid (which has principal axes X, Y, Z). If this plane is oblique to all three axes, then the long axis of this elliptical section (X', Fig. 6) may be oblique to the XY plane of the strain ellipsoid (cf. Fig. 6). Therefore, if this plane is assumed to represent a geological layer, and the cleavage develops in the XY plane of the strain ellipsoid, the cleavage will have developed oblique to synchronously with the fold axis (this will be referred to as the 'cut-effect model'). Can the above model be applied with validity to geological environments?

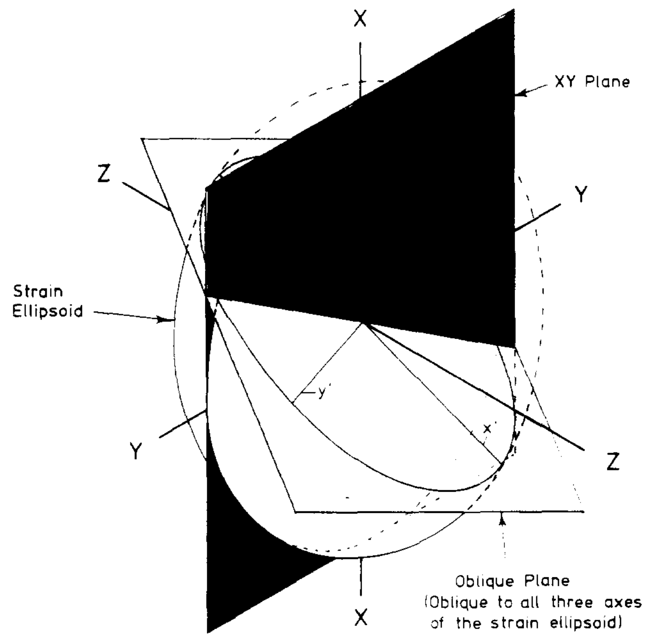

Fig. 6. Example of the 'cut-effect model'. A strain ellipsoid cut by a plane passing through its centre, and oblique to all three principal axes, may generate an elliptical section through the ellipsoid (dependent on the form of the ellipsoid). The longest axis of this elliptical section (X') will not necessarily lie in the XY plane of the strain ellipsoid. If the X' axis is assumed to be the direction of fold axis formation, and the cleavage is assumed to form parallel to the XY plane, then the cleavage will not be axial planar to the folds. See text for additional discussion.

The cut-effect model involves several assumptions. (1) A geological layer can be represented by a layer with no finite thickness, that is, a plane. (2) The layer has identical mechanical properties to its neighbours, otherwise the strain would not be homogeneous and could not be represented by an ellipsoid, except at such a scale that the heterogeneities become insignificant. (3) Cleavage forms parallel to the XY plane of the strain ellipsoid. (4) Prediction of a fold-axis orientation via the strain-ellipsoid concept assumes that the latter accurately models the strain field at the moment of fold nucleation, and that the strain is homogeneous at the scale of interest.

From our understanding of geological materials and environments, fulfilment of all the above assumptions would appear to be unlikely in zones of fold hinge nucleation. For folds to nucleate, the instantaneous strain field must be heterogeneous due to inhomogeneous stress and/or material properties. A geological layer cannot be realistically defined as a plane. If the layer has finite thickness and possesses different physical properties to its neighbours, the strain-ellipsoid concept can be used to give an indication of the average bulk-strain, or it may be reduced in scale so that the local strain field can be considered homogeneous. If the strain ellipsoid is used on a bulk scale to define the strain across a region with heterogeneous physical properties, where the strains will be anything but homogeneous, the above assumptions appear to break down and the cut effect described above may have no significance with regard to the nucleation direction of the fold axis. If the argument is restricted to the interface between two layers, and it is this surface which controls fold nucleation sites such that the cut effect does apply, then the assumptions would still appear to break down. Only an interface between layers with identical physical properties can be regarded as meeting some of the assumptions inherent in this treatment, and such an interface would appear to have little influence on fold development. It is possibly more realistic to consider that folds will not necessarily nucleate on a layer interface, but rather develop within a layer at some site of physical heterogeneity. Interface zones between material layers with different physical properties will be regions of high material heterogeneity and may well be important zones of fold nucleation, but I argue that the three-dimensional stress and strain relationships in the adjacent layers, and the difference between them, control the fold geometry not a two-dimensional cut-effect model. A possible method of demonstrating whether the cut-effect model occurs in naturally deformed rocks is discussed below.

DISCUSSION

If transected folds arise from a single deformation, then severe problems in mapping deformed terrains arise, as demonstrated by Borradaile (1978). The major structural mapping tools of the field geologist are foliation/foliation asymmetry (i.e. the symmetry relationships of cleavage with respect to bedding or cleavage with respect to another cleavage), parasitic fold asymmetry, and vergence (Bell 1981). If there is evidence of younging present, then structural facing (Borradaile 1976) combined with vergence and fold and foliation asymmetry allows ready analysis of a complexly deformed terrain. If there is no younging evidence present, as is commonly the case in metamorphic high-grade terrains, the structural geologist must rely on the various vergences and asymmetries that are available, and their relationships to the stretching or mineral elongation lineation (e.g. the mineral elongation lineation will tend to remain constant in direction whereas the intersection lineations and fold axes will tend to vary due to heterogeneous strain, cf. Sanderson 1973).

A considerable problem also arises if these folds are larger than the outcrop scale and the lithological boundaries cannot be traced (physically or by aerial photography). Even if fold transection were recognised, a severe problem in fold closure identification still exists if younging evidence is scarce or non-existent, as structural facing cannot be used (cf. Borradaile 1978). This problem also applies to any cleavage generating event that post-dates an earlier folding event that has no associated axial plane foliation (Ramsay 1963).

If it is possible to produce folds with or without an axial-plane cleavage, refold them and produce new cleavage all in the one deformation event, there would then be no limit to the number of apparent deformation events that could occur in one 'transected fold' episode. How can we separate multiply deformed and apparently multiply deformed terrains? Are all multiply deformed terrains products of transected fold events?

If it is considered that transected folds can form, what is the mechanism for their formation? Powell (1974) suggested a non-synchronous development of folding and cleavage, and Borradaile (1978) proposed that the cleavage may be synchronous with the folding if the fold axis forms by the 'cut-effect model' described above. The other interpretation for these structures is that they are the result of polyphase deformation.

To date, experimental work has not been able to produce structures similar to transected folds, and experiments on layered models where the layers were oblique to all principal axes of the bulk strain ellipsoid (e.g. McBirney & Best 1961, Treagus 1972) indicate that the relationships of the nucleation direction of the fold axis to the bulk strain ellipsoid is still uncertain. Treagus (1972, p. 89) found that "The fold axes are different in attitude from the predicted fold axes" (i.e. they do not lie in the cut section of the bulk strain ellipsoid) ". . . nor do they lie in the bulk *XY* plane (cleavage)".

One possible method of demonstrating the relationship of a fold axis to the cleavage, is to select a simply folded area of rocks which contains a series of veins that were originally at different attitudes to one another. If some form of the cut-effect model operates for the orientation and nucleation of the fold axes, then fold axes measured from various folded veins should lie in, or oblique to, the local cleavage, depending on their original orientation. If all the fold axes lie in the local cleavage planes, no matter what the orientation of the original vein, then it would appear that the cut-effect model is not the mechanism of fold axis nucleation.

If folds nucleate by heterogeneous strain, the fold axes could possibly be expected to develop within or close to the *XY* plane of the local finite strain ellipsoid (for deformations with bulk strain ellipsoids of the form $K < \infty$). Any homogeneous layer will reorient by flattening, shear or body rotation towards the *XY* plane of the local finite strain ellipsoid during deformation. If the layer is heterogeneous, as presumably all geological materials must be, then any layer oblique or parallel to the axes of the local strain ellipsoid will strain heterogeneously. For example, a heterogeneous layer oblique to all three axes of the local strain ellipsoid (Fig. 7a) will deform inhomogeneously (Fig. 7b). Initially the planar surface will develop random anastomosing dome and basin type perturbation structures due to grain or large-scale inhomogeneities. Once departures from the

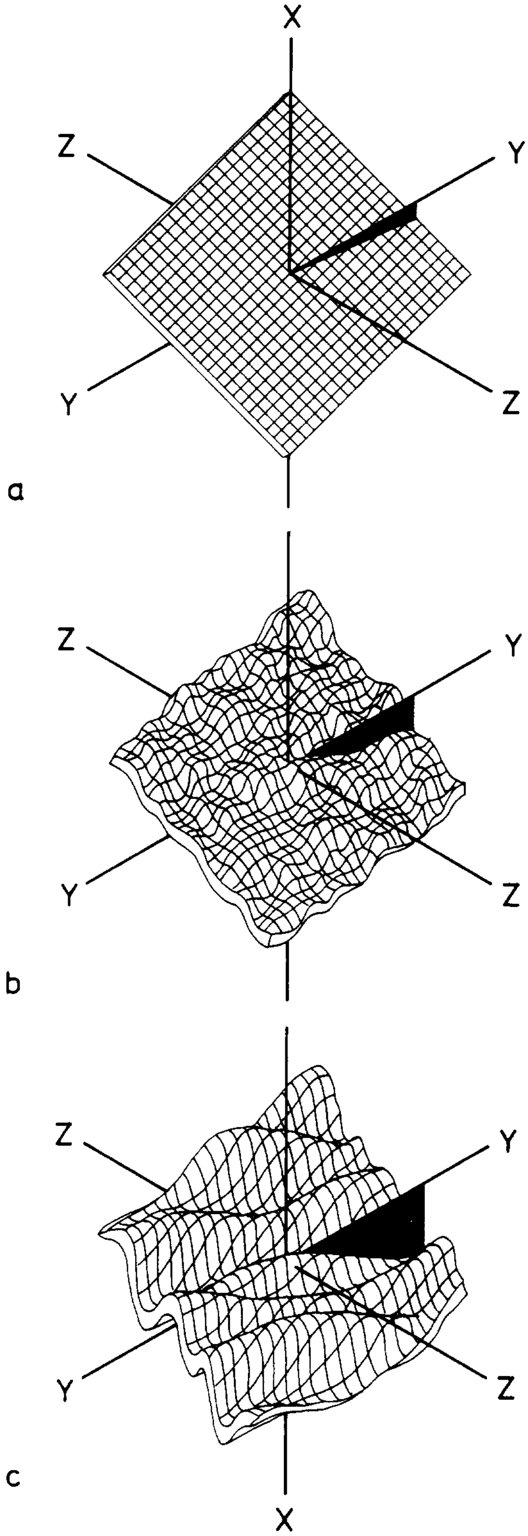

Fig. 7. Example of fold nucleation and formation by heterogeneous strain. Shaded zones indicate the trace of the *XY* plane of the bulk strain ellipsoid. (a) Three-dimensional layer oblique to all three axes of the bulk strain ellipsoid. (b) Perturbations generated in the layer by heterogeneous strain. Maximum shortening of any volume will be perpendicular to the *XY* plane of the local strain ellipsoid. The maximum flow of any particle will occur in the *X*-axis direction of the local strain ellipsoids. (c) Continuation from (b). The perturbations have continued to develop, flatten and propagate in the *XY* plane producing anastomosing and doubly plunging folds. With continued strain the fold axes will tend to rotate into the *X*-axis direction of the strain ellipsoid.

initial planar surface develop within the layer, these perturbations will be amplified with continuing deformation. Any surface oblique to the *XY* plane will flatten and rotate towards it, and surfaces at a high angle to the *XY* plane will tend to shorten by layer-parallel shortening and extend in the *XY* plane. Therefore the perturbations or dome and basin structures will extend and flatten in the plane at right-angles to the maximum compressive strain in the local three-dimensional strain field. The combination and growth of these structures will produce anastomosing, doubly plunging fold structures that will lie in the *XY* plane of the local finite strain ellipsoid (Fig. 7c). With continuing heterogeneous strain the folds will continue to grow and flatten in the *XY* plane and the fold axes will rotate towards the maximum elongation direction (*X* axis). Where some layers in a rock have a low to moderate viscosity contrast with adjacent layers, or where strains are high, the cleavage and axial surfaces should approximate to the *XY* plane of the bulk strain ellipsoid as suggested by the experimental work of McBirney & Best (1961). They showed that a layer oblique to the three principal axes of the strain ellipsoid, folded with the fold axis parallel to the *XY* plane of the finite strain ellipsoid during bulk homogeneous pure shear and plane strain deformation.

CONCLUSIONS

The postulated phenomenon of transected folds should be examined more closely because of its implications for geometric analysis (i.e. fundamental assumptions of layering/schistosity relationships may not apply). To demonstrate satisfactorily that transected folds exist, it must be shown that the folds and the transecting cleavage were produced during one event (i.e. a deformation that produced a group of geometrically related structures) and that there is no evidence at any scale for a polyphase deformation history.

Structures at Sulphur Creek, observed in the field and in thin section, are consistent with a polyphase deformation history but not with a transecting fold episode. Those who wish to argue that a transecting cleavage is a product of the same deformation that produced the folds must be able to demonstrate convincingly that the geometry is not a result of polyphase deformation.

There appear to be many problems and uncertainties yet to be answered about the mechanism of fold nucleation and the original orientation of a fold axis with respect to the cleavage plane or the local and bulk *XY* plane of the strain ellipsoid.

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