Development of an axial plane mica foliation

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Abstract

Development of an axial plane mica foliation in shale clast sediments from Woody Island in Newfoundland is described and analysed. The foliation is shown to develop largely by crenulation of an earlier surface that is mimetic after a shaly parting within the clasts. Analysis is facilitated by the presence of bedding in some clasts, because by making the reasonable assumption that the clasts were originally elongate parallel to bedding, it is possible to recognise the original long dimension of the clasts, irrespective of their present shape. Where strain magnitude is large the crenulations completely transpose the original foliation into the new orientation. The resulting mica fabric is commonly bimodal and symmetrical about the generalised orientation of the foliation. Some clasts are rotated without being crenulated so that the foliation is defined by the original foliation rotated into the new orientation as well as by the length of the clast. It is generally true that bimodal fabrics are common in rocks with axial plane foliations defined by layersilicates. It is concluded therefore that transposition and mimetic growth are important processes in the development of axial plane foliations, not only on Woody Island but elsewhere.

The crenulation cleavage is generally differentiated and attention is draw to the simple relationship that exists between the compositional domains and strain partitioning. The observations are best explained by shear parallel to the length of the mica-rich domains and extension parallel to the length of the quartz-rich domains.

Conceptual modeling of the foliation development indicates that folding involved a large component of bulk shortening perpendicular to the axial plane of the fold throughout deformation. This may be generally true of folded pelitic sediments.

Introduction

It has been demonstrated experimentally (Means, 1968; Etheridge and Hobbs, 1974; Williams *et al.*, 1977), that when deformed layersilicates are replaced by new layersilicate grains of the same or different composition or structure, the new grains tend to grow with one of two relationships to the host grain. Either the new grains tend to mimic the orientation of the host grain or they tend to grow along kinkband boundaries within the host with (001) parallel to the kinkband boundary. The first of these relationships may be epitaxial and the second may simply be a case of growth-selection, with grains oriented with their fast growth direction (parallel to (001)) parallel to the kinkband, growing preferentially along a zone of highly disordered lattice. A consequence of these relationships, in the development of axial plane foliations, is that if an old layersilicate foliation is transposed by folding into the new axial plane orientation and the layersilicates are recrystallised during or after deformation, the orientation of the transposed foliation will be preserved if growth is epitaxial (*e.g.* Williams, 1985) and enhanced if there is growth parallel to the axial planes of micro-kinks. Together these processes are mechanisms of mimetic growth which has been invoked as an important process in the development of axial plane foliations in layersilicate-rocks (Williams *et al.*, 1977).

Support for this model comes from preservation of relic kinks and crenulations, intrafolial to the new foliation (Williams *et al.*, 1977), and from the fact that such foliations are generally bimodal. If a layersilicate foliation develops from a previous foliation by transposition by folding, the new foliation is expected to have a bimodal (001) fabric, with the two maxima, corresponding to the alternate limbs of the micro-folds, overlapping and symmetrical about the new axial plane foliation. A similar bimodal fabric can develop without micro-folding if individual layersilicates rotate in a less ordered manner, in response to shortening parallel to the original foliation (Hobbs *et al.*, 1976, p. 247). At large strains the two maxima will merge, but many rocks do not reach this stage and careful observation of natural layersilicate fabrics very commonly reveals a bimodal distribution.

The micro-folding origin of crenulation cleavage is obvious, but it is less obvious that penetrative foliations commonly develop by micro-folding because the combined processes of transposition and recrystallisation tend to destroy the evidence. The rocks described here, from Woody Island in Notre Dame Bay, Newfoundland, are particularly good from the point of view of demonstrating that penetrative foliations can develop in this way. The rocks include shale clast conglomerates and microconglomerates and because of differences in strain history and because of unusual primary features they preserve much better evidence of their fabric development, than is generally true of foliated rocks. Of prime importance from this point of view, is the fact that internally bedded clasts make it possible to identify the orientation of the original shaly parting (parallel to internal bedding) and the original long dimension of the clasts (also parallel to internal bedding) in deformed clasts where, because of the intensity of transposition and recrystallisation, it would otherwise be impossible. These rocks are described here in detail, as an unusually instructive example of foliation development. An integrated qualitative analysis of clast shape and orientation, and associated microstructures, also makes it possible to show that fold development involved a large component of shortening perpendicular to the axial plane throughout the process and this has general implications.

Woody Island: Introduction

Introduction: Woody Island, shown on topographic maps as Green Island (map makers apparently renamed most topographic features in the area), is *ca*.8 kilometres NE of Carmanville in eastern Notre Dame Bay, on the "North Shore" of Newfoundland. It has excellent coastal exposure of Caradocian age Dunnage Zone (Williams, 1979) rocks, comprising greywackes, sandstones, conglomerates, siltstones, shales and mélange (Currie *et al.*, 1980). Grading is common and there are some complete Bouma beds. Abundant detrital shale clasts are commonly visible in some coarse sediments (Fig. 1) and there are chaotic rocks containing blocks of sandstone in an apparently argillaceous matrix. The microstructure of these rocks has been describe in detail by the writer (Williams, 1983) and the relevant points are summarised here, and new observations are added.

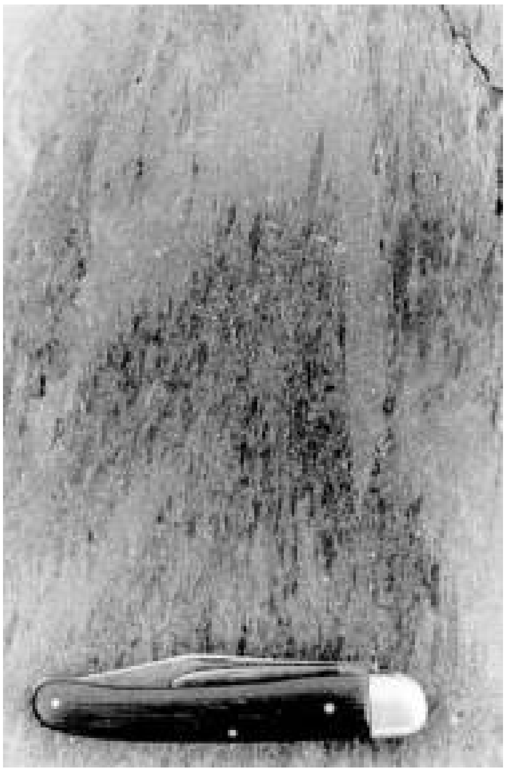

Fig. 1 Mesoscopic fold with an axial plane cleavage defined, in large part, by shale clasts. Clast colour varies from pale grey to black. Pocket knife is 10 cm long.

Metamorphic grade appears to vary. In many outcrops, the only hand specimen indication that the rocks may have been metamorphosed is the presence of a slaty or crenulation cleavage, and where cleavage is not developed there may be no evidence of metamorphism. However, in thin section, all such rocks that have been examined contain metamorphic biotite. In other outcrops, the rocks have a phyllitic sheen and small garnets and relic porphyroblasts are visible to the naked eye. In thin section the relic porphyroblasts are seen to be largely aggregates of layersilicates pseudomorphous after the original porphyroblasts. The pseudomorphs commonly have a clear hexagonal outline and were possibly staurolite.

Two generations of folds are recognised, but there is generally only one cleavage (S_2) which is axial planar to the F_2 folds. This cleavage is younger than the biotite and porphyroblasts, and the lack of strongly serrate boundaries in F_2- kinked biotite indicates that temperatures were too low for sufficient growth of biotite to obliterate earlier fabrics during F_2. Locally however, still later contact metamorphism has converted an S_2 crenulation cleavage into a coarse grained schistosity (Williams, 1985, Figs 5 & 6).

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Woody Island: Microstructure of S_2

S_2 (see table 1 for a summary of abbreviations used) is defined by a variety of features. In some coarse grained clastic rocks, there is an alignment of elongate shale clasts (Fig. 1) and of sand grains, primarily quartz. The latter are generally single crystals which at most show only weak undulose extinction, indicating that they have not undergone significant internal deformation. Their shapes may be primary or may have been modified by diffusion dependant processes. The possibility that the quartz sand grains have undergone recrystallisation is rejected because, practically all the grains are single crystals whereas rare chert grains are still fine grained (at least two orders finer than the quartz sand grains). These observations, and the evidence of localised recrystallisation, presented below, can only be explained by the quartz grains being only weakly deformed, and not recrystallised (cf. Williams, 1972). Their appearance contrasts with that of the quartz in veins in the same rocks and with grains in some of the purer quartz sandstones; both the latter commonly have a strong deformation substructure and are recrystallised. This is particularly true of the veins, which generally comprise fine grained polygonal aggregates with coarse, deformed, relic grains. Strikingly, detrital grains contiguous with quartz veins, commonly appear as deformed as the vein itself whereas adjacent grains surrounded by matrix, appear undeformed. This observation is interpreted in terms of the aspect ratio of the quartz domains. Low ratio detrital grains in matrix supported sediment are able to move and rotate in the layersilicate-rich matrix without deforming internally, whereas large ratio veins deform with the surrounding rock. Similarly the purer quartz sandstones, being clast supported, are unable to deform without internal deformation of the component quartz clasts. Some of the veins are seen to have quite strong crystallographic fabrics, by inspection with a gypsum plate,.

Description	General	External	Internal
Bedding		S_{se}	S_{si}
Bedding-parallel mica foliation			S_i
F2 axial plane cleavage	S_2	S_{2e}	S_{2i}

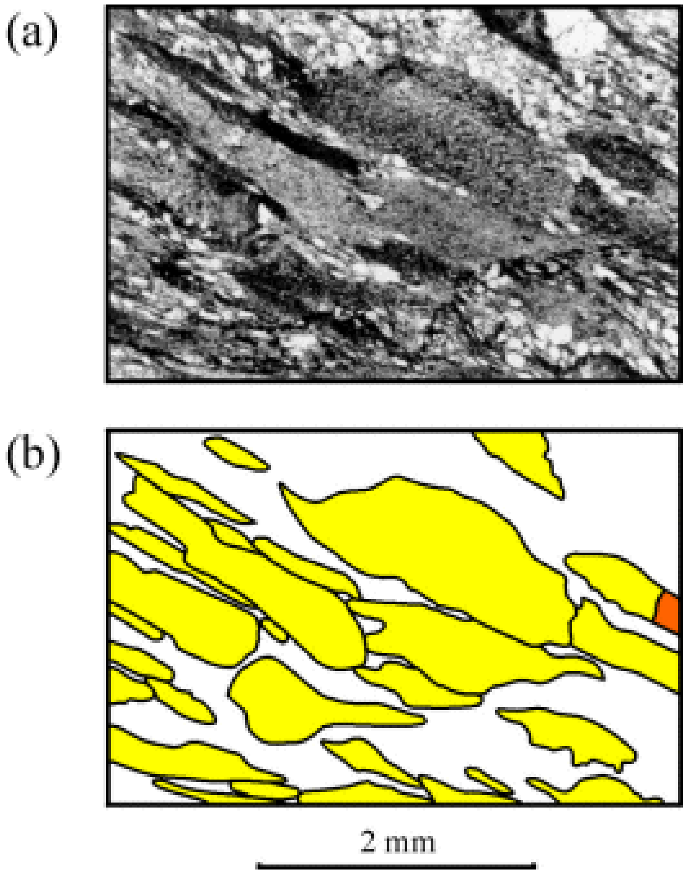
Table 1 Abbreviations used for various foliations. "External" and "internal" refer to foliations outside and inside of the shale clasts. S_2 is the general cleavage as seen in hand specimen or outcrop, made up of a combination of S_{2e} and S_{2i}.

In finer grained sandy and silty layers the foliation is commonly penetrative with most micas oriented parallel to the axial plane cleavage, or it is domainal, and defined primarily by anastomosing films composed mainly of elongate mica grains, oriented with (001) parallel to the film. As a consequence of the anastomosing nature of the films many of the domainal fabrics are bimodal. In addition there is commonly a third orientation group comprising sparse mica grains within the film-bounded lenticular domains. These micas are aligned approximately perpendicular to the cleavage and in contrast to the micas in the films they are elongate perpendicular to (001) (stacks of Voll, 1960; for a review see also van der Pluijm and Kaars-Sijpesteijn, 1984). They are believed to have grown on detrital micas (e.g. Hoeppener, 1956). In the most pelitic rocks the foliation may be a crenulation cleavage which may or may not be differentiated.

The penetrative foliation is most common in incompetent layers on the concave side of folds in competent layers, but may occur in all parts of tight folds. It is least common on the convex side of folds in competent layers. Bimodal fabric and crenulation cleavage are generally more common than penetrative foliation and are particularly common on the convex side of folds in competent layers. Where the fabric is clearly bimodal, relic kinks or crenulations are generally present in the mica.

It is the shale clast bearing units that are particularly interesting from a cleavage development point of view. They include not only the units that contain clasts clearly recognisable in hand specimen, but also the unit previously referred to as mélange (Pajari *et al.*, 1979). In the field the mélange appears to be a poorly sorted, fine grained rock with blocks of sandstone floating in the fine grained matrix, but in thin section the "matrix" is seen to be composed almost entirely of shale clasts in a sparse sandy or silty matrix (Fig. 2) (Williams, 1983). The shale clasts are recognisable in thin section because of variation in their, layersilicate, iron oxide and carbon content (Fig. 2), but this variation combined with their small grain size (generally between 0.5 and 5 mm) is insufficient to render the clasts visible in hand specimen. There is a compositional layering, presumably bedding, within many of the clasts (Fig. 3), which is also due to variation in layersilicate, iron oxide and carbon content. The S_2 foliation in these rocks is defined not only by the preferred orientation of shale clasts and matrix grains, but also by anastomosing mica-films in the matrix and by a foliation within the clasts. This "internal S_2 foliation" (S_{2i}) varies in nature in adjacent clasts, from symmetrical to asymmetrical crenulation cleavage, to a penetrative foliation. There is an obvious correlation between the shape of the clasts, the orientation of bedding where recognisable, the magnitude of strain and the nature of the foliation. The salient relationships are summarised below.

Fig. 2 Microphotograph of mélange showing various coloured shale clasts. These clasts are not visible in handspecimen in this particular rock, but appear as fine grained shaly matrix to coarser clasts too large to include in a thin section. **(b)** is a tracing of definite shale clasts (yellow and orange) recognised in **(a)**. The orange area in one clast represents a different compositional layer within the clast and the interface between yellow and orange represents a bedding plane within the clast. The white area is rich in quartz and is believed to be matrix, but may include additional large clasts. Photographs



in plane polarised light.

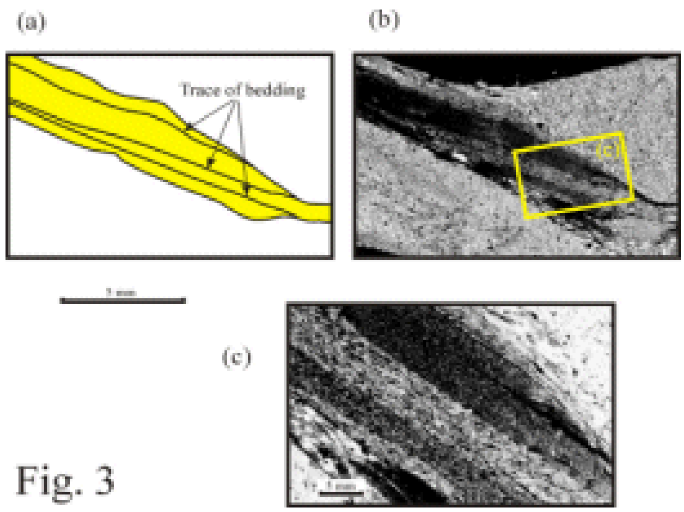


Fig 3 Bedded shale clast. **(a)** is a tracing of **(b)** which is a general view showing bedding-parallel to the long dimension of the clast. Clast is shown in yellow. **(c)** is an enlargement of the area indicated in (b) and shows the parallelism of the mica foliation and bedding. Photographs with crossed polarisers.

In most clasts that are recognisably layered there is a foliation defined by the preferred orientation of mica parallel to layering (Fig. 3b) and in the exceptions there is a similar foliation at a high angle to layering which shows evidence of being a transposition foliation. The layer-parallel fabric is typical of shales (e.g. Hobbs *et al.*, 1976, p.153; Siddans, 1976) and like the layering is interpreted as a bedding feature (S_{si}). Though defined now by metamorphic mica it is believed to be mimetic after a sedimentary layersilicate fabric. The possibility that this internal foliation (S_i) is a metamorphic fabric related to F_1 folds is eliminated because in all but the most strongly deformed clasts, S_i is parallel to bedding within the clast (S_{si}) and where they are not crenulated both are parallel to the long dimension of the clast. In summary, the mica fabric within the clasts is either parallel to bedding (S_{si}), or, if inclined to bedding, is seen to be a product of micro-scale transposition of an earlier foliation (*i.e.* it is S_{2i}). In the less transposed examples, this earlier foliation is seen to be parallel to (S_{si}), and is therefore interpreted as S_i.

The morphology of the bedded clasts is described below. Three end-member morphologies are recognised, based on the orientation of compositional bedding within the clasts (S_{si}), relative to the long dimension of the clasts and S_{2i} (Fig. 4d, e & f). To facilitate description, the clasts are grouped according to their resemblance to one of the end-members, but it should be noted that there is a seamless gradation in morphology, between members of the three groups.

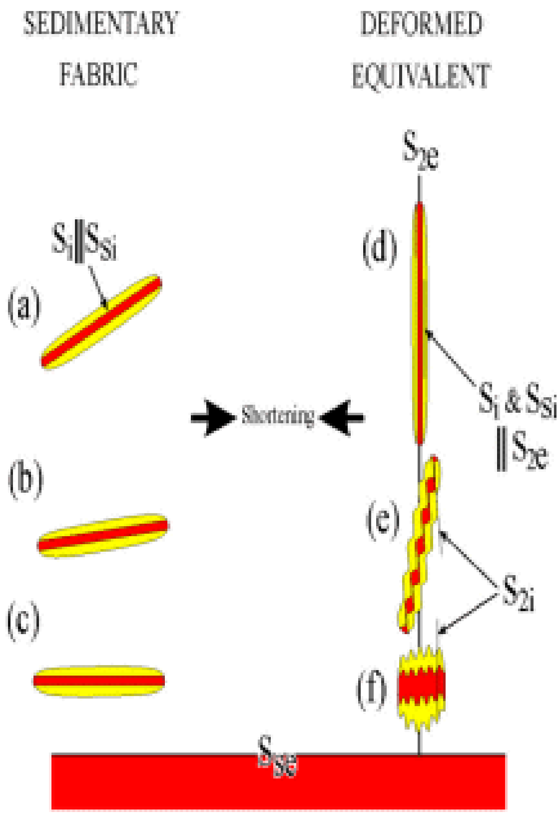


Fig. 4 Diagrammatic representation of bedded clasts. **(a-c)** Interpreted initial shape and orientation of clasts with respect to internal and external bedding (S_{si} and S_{se} respectively). **(d-f)** Observed end-member morphologies of shale clasts. The clasts are aligned with their interpreted initial form (*i.e.* (d) developed from (a) *etc*.). Shortening direction is the bulk shortening direction on the scale of the folds in S_{se}. See text for detailed discussion.

The first end-member is characterised by S_{2i} perpendicular to compositional bedding (S_{si})(Fig. 4f). In these clasts, both S_{si} and S_i are generally crenulated into a symmetrical differentiated crenulation cleavage (Fig. 5). This cleavage (S_{2i}) is parallel to S_{2e} in the surrounding rock (Fig. 4f). Clast outlines tend to be fairly equant with aspect ratios commonly less than 2:1 (*e.g.* Fig. 5c & d) and the long dimension commonly approximately parallel to S_{2e} (Fig. 5), but locally approximately perpendicular to S_{2e}. Outlines tend to be irregular or visibly folded (Fig. 5c & d). Locally, S_{2i} in these clasts is a penetrative foliation very much like S_i, but generally there is some evidence of crenulations preserved. Intermediate stages in the development of the transposed foliation show that tightening of crenulations is the main process involved, but in some clasts (*e.g.* Fig. 6), the intermediate stages preserved within a single microlithon indicate that transposition has occurred by unfolding of crenulations (*cf.* Williams and Schoneveld, 1981). Which process occurs, depends on whether adjacent limbs of crenulations have the same (unfolding) or opposite (tightening of folds) sense of rotation. This in turn depends on the initial tightness of the crenulations and their orientation with respect to the shortening direction.

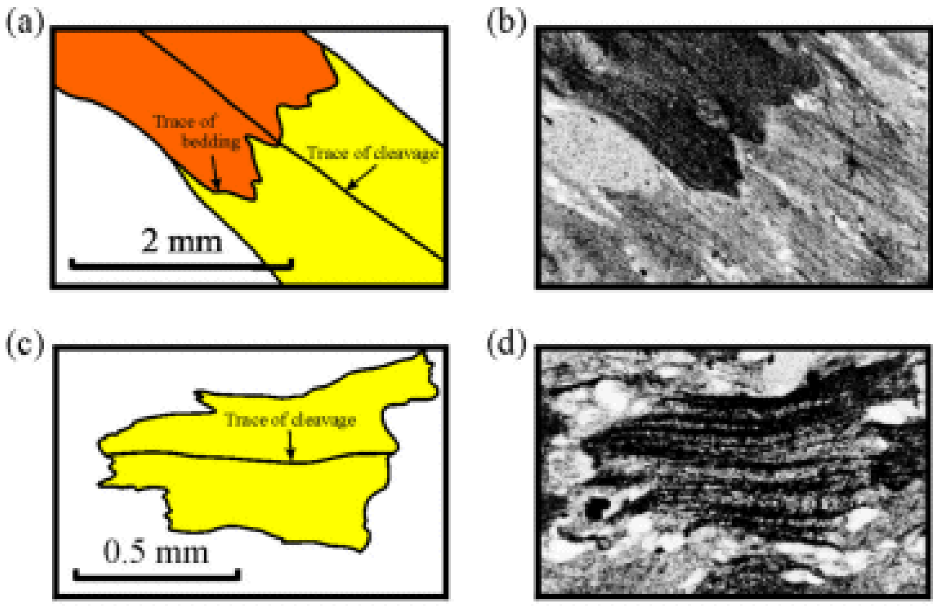


Fig 5 Symmetrical crenulations in deformed shale clasts (coloured orange and yellow). **(a)** is a tracing of **(b)** which shows a bedded clast with bedding, defined by dark and light layers (orange and yellow respectively in (a)), approximately perpendicular to the long dimension of the clast. The crenulation cleavage is axial planar to the small folds in the bedding-surface. The clast is only 20% longer than what is visible in the field of view. **(c)**, a tracing of **(d)**, shows a clast with no visible bedding, but a symmetrical crenulation cleavage, and a typical aspect ratio of symmetrically crenulated clasts. Photographs in plane polarised light.

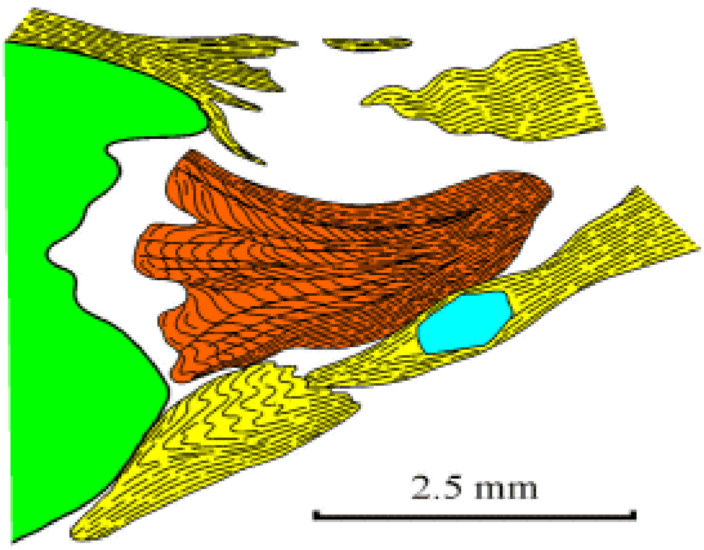


Fig. 6 Sketch of a shale clast (orange) located in the shadow of a strong igneous clast (green). Other shale clasts shown in yellow. The hexagonal blue area is a relic porphyroblast. At its more protected, less strained, left hand end, the shale clast is crenulated. The crenulations become more transposed towards the right, and at the most strained, right hand end, the foliation is essentially penetrative. In this example the transposition is seen to be achieved primarily by unfolding of the crenulations except along the lower side of the clast where there appears to be a tight fold.

The second end-member (Fig. 4e), has an asymmetrical differentiated crenulation cleavage (S_{2i}) (Fig. 7) which is inclined to the length of the clast, S_{si} and S_{2e}. The long dimension of the clast is parallel to S_{si} and is also generally inclined to S_{2e}. S_{2i} either lies between the long dimension and S_{2e} or the long dimension and S_{2i} are symmetrically disposed about S_{2e} (Fig. 4e). The clasts are generally elongate with aspect ratios commonly in excess of 3:1 and clast outlines may be asymmetrically crenulated, but tend to be smoother than those of the first group. On fold limbs the crenulation cleavage in these clasts is generally antithetic with respect to the fold. There are exceptional cases where the cleavage is synthetic, but there are insufficient observations to generalise on the orientation of such clasts and their cleavage, other than to say that they are approximately parallel to S_2.

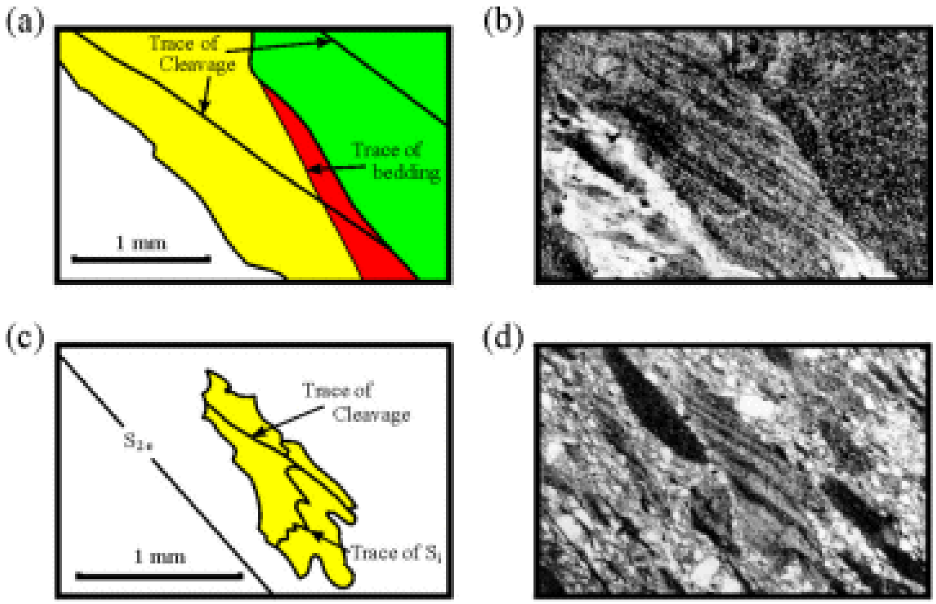


Fig 7 Asymmetrical crenulations in deformed shale clasts. **(a)** is a tracing of **(b)**. The orange and yellow clast has an asymmetrical crenulation cleavage developed in a penetrative foliation, that is parallel to bedding (indicated by orange and yellow layers) and is interpreted as the shaly parting, S_i. A neighbouring clast (green) has a penetrative foliation which is oriented between the crenulation cleavage in the orange and yellow clast and the length of the latter. **(c)** a tracing of **(d)** shows a clast oriented with its long dimension clockwise of the general trace of the foliation (S_{2e}), whereas the crenulation cleavage within the clast is anticlockwise of (S_{2e}). Note the typical aspect ratio of a clast with asymmetrical crenulation cleavage. Photographs in plane polarised light.

The third end-member (Fig. 4d.) lacks any evidence of crenulation cleavage. S_{si}, S_i and the long dimension of the clasts are all parallel and are approximately parallel to S_{2e}. S_i in such clasts is truly penetrative and shows no evidence of having developed by transposition (Fig. 3c), since there are no relic folds. These clasts are the most elongate with aspects ratios commonly in excess of 4:1, and have the smoothest outlines.

Most clasts lack compositional bedding (S_{si}), but otherwise exhibit exactly the same range of microstructures, aspect ratios, outlines and orientations as describe above. The only difference is the lack of bedding.

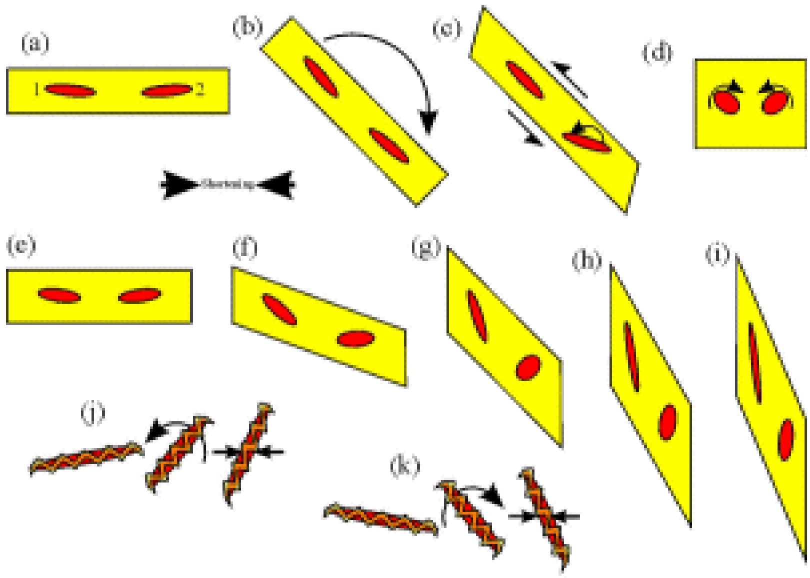
In a fold hinge the first end-member type (Fig. 4f) is the most abundant but all three groups are present. On the fold limbs it is the least abundant and the third type (Fig. 4d) is slightly more abundant than the second (Fig. 4e).

Woody Island: Kinematic interpretation of the microstructure

In undeformed sedimentary rocks, shale clasts are generally discoid with their short dimension perpendicular to the shaly parting and compositional bedding where present. It is reasonable therefore, to assume that this was the starting fabric of the clasts observed here, and in fact, such a relationship is observed in the least deformed clasts. It is also normal for discoid clasts in a sediment to have a strong preferred shape orientation with mean long and intermediate dimensions parallel to bedding, or, if the clasts are imbricated, at a small angle to bedding. Either way the statistical distribution of long and intermediate axes will tend to give a small variation symmetrical about the mean. This distribution is referred to as a bow-tie fabric because of the shape of the envelope of a ray-diagram showing frequency as a function of orientation in any section perpendicular to the planar fabric.

The deformation of a clast in a folding rock can be described in general, in terms of four kinematic components: (1) A bulk pure shear orthogonal with the axial plane of the fold (Fig. 8d). (2) A simple shear component parallel to bedding due to a flexural slip component of the folding (Fig. 8c). (3) A rigid body rotation due to rotation of the fold limb (Fig. 8b). (4) A simple shear parallel to the clast long dimension engendered by traction on the clast boundary due to rotation relative to its matrix.

Fig. 8 Summary of the interpretation of the foliation development. **(a)** Initial fabric with shale clasts (red) slightly inclined to either side of bedding (horizontal). **(b-d)** Kinematic components causing rotation of the long dimension of the clasts. **(b)** Spin of fold limb; clasts do not rotate with respect to bedding, but rotate relative to the axial plane of the fold (vertical). **(c)** Bedding-parallel shear; both clasts rotate anticlockwise with respect to bedding, but clast 1, having already reached parallelism with the shear plane is in a meta-stable orientation. **(d)** Bulk pure shear component with horizontal shortening; both clasts rotate with respect to bedding and the axial plane and their direction of rotation is determined by their orientation relative to the shortening direction. **(e-i)** Diagrammatic representation of the interpreted sequence of events during folding, showing contrasting histories of clasts 1 and 2. **(e)** Initial bedding-parallel shortening and clockwise and anticlockwise rotation



of clasts 1 & 2 respectively. **(f-h)** Rotation of clasts relative to bedding and the fold axial plane at dips of 20 , 45 & 60 . A combination of the limb-spin (b), simple shear (c) and pure shear (d) components has been assumed. **(i)** Additional pure shear component. **(j & k)** Diagrammatic representation of the deformation within crenulated clasts derived from clasts 2 & 1 respectively. The three stages in each represent initial shortening, rotation and subsequent shortening in a different direction. In reality, rotation and shortening are synchronous, but never-the-less non coaxial. See text for further discussion.

In the situation where S_{se} and S_2 are approximately perpendicular, in a symmetrical fold hinge, it is reasonable to assume that the bulk shortening was approximately parallel to bedding throughout the deformation. In such a situation a clast that was oriented with its long dimension and S_i foliation exactly parallel to the bulk shortening direction would shorten symmetrically by crenulation of the clast and its internal foliation (Fig. 4c & f). This would result in an irregular outline to the clast (Figs. 4f & 5c & d). There would be no rotation of the clast because of the symmetry with respect to the pure shear shortening component and because there is no bulk rotation of bedding or shear parallel to bedding as on a fold limb. There would therefore be no simple shear component within the clast. However, such clasts would be in a state of unstable equilibrium, with respect to the bulk shortening direction, in that the slightest clast-scale perturbations in flow, may jostle the clasts out of this special orientation. Such perturbations are inevitable in materials as mechanically heterogeneous as a sediment. When no longer parallel to the bulk shortening direction the clasts would begin to rotate, and the kinematics would become more complicated as discussed below.

In the same situation with respect to the fold, but with a clast initially slightly inclined to bedding or jostled into such an orientation, the clast is inclined to the pure shear shortening direction. Its history now becomes more complex and its long dimension will rotate (Fig. 4b & e). It may do so passively, *i.e.* the strain of clast and matrix may be homogeneous with no stain discontinuity along the clast boundary. Alternatively rotation may be active in that it has a rigid body rotation component relative to its matrix. Such an actively rotating clast may also be undergoing shortening parallel to the bulk shortening direction and there may also be an internal simple shear component parallel to its long dimension. The relative importance of the components at any given stage in the history will depend on the orientation of the clast relative to the bulk strain axes at that stage.

Starting with a clast that was close, but not exactly parallel to the bulk shortening direction, the pure shear component would tend to shorten the clast and to rotate (passive rotation) its long dimension (Fig. 4b & e). Shortening would produce symmetrical or near symmetrical crenulations and the nearer the initial orientation of the long dimension of the clast to the bulk shortening direction the better developed the crenulations would be. If the clast experienced a component of active rotation there would be shear parallel to its long dimension and the crenulations would become asymmetrical (*e.g.* Bayly, 1965). Passive rotation would also result in the crenulations becoming asymmetrical, but the two situations can be distinguished theoretically because active rotation results in overturning of the crenulations relative to the vertical S_{2e} (Fig. 8j & k). Unfortunately it has not been possible to make this distinction in an actual fold hinge. Most clasts in the hinge tend to be the symmetrical type (Fig. 4f), and the few asymmetrical clasts that do occur are not truly diagnostic because of irregularities and heterogeneity of strain. However, the crenulations look more like the passive type suggesting that there has been no active rotation. This is consistent with the fact that there is no reason to believe that the shale clasts are more competent than the matrix.

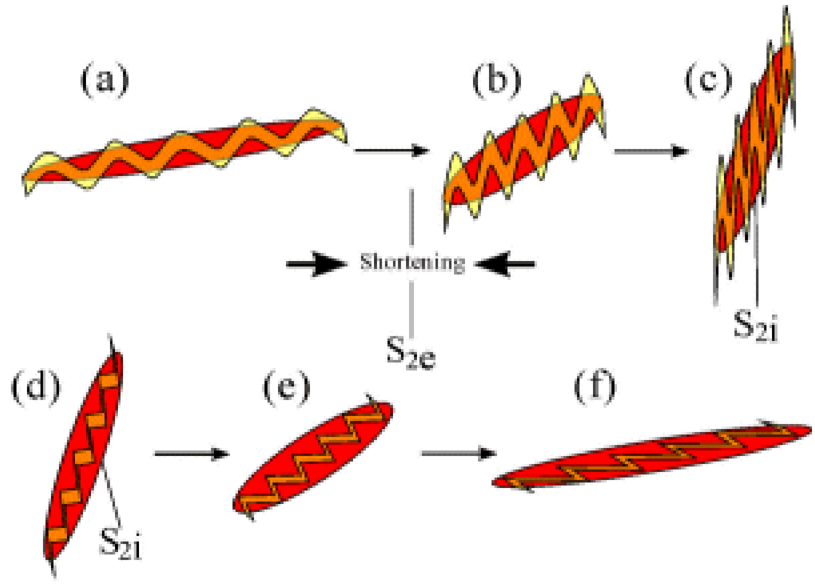
It is to be expected that the initial angle between some clasts and the bulk shortening direction would be sufficiently large that no crenulations would develop (Fig. 4a & d). Obviously this is true where the initial orientation of the long dimension is in the instantaneous stretching field of the bulk strain. However, even at lower angles, crenulations might not develop, simply because the magnitude of the shortening was insufficient; in experimental deformation there is generally a significant (15% plus) amount of shortening before crenulations become apparent. Further, if very open crenulations developed while the foliation was in the shortening field they could be unfolded, once the enveloping surface to the crenulations rotated (passively or actively) into the extensional field (*cf*. Williams and Schoneveld, 1981). Consequently it is to be expected that some clasts would rotate without evidence of crenulation. These clasts would rotate towards parallelism with S_{2e} and would increase in length as they rotated. The result would be a clast of increased length with its long dimension, S_{si} and S_i all parallel, and approximately parallel to S_{2e} (Fig. 4d). Such clasts would tend to have smooth outlines since their initial outline was probably smooth and there is no micro-scale folding to modify it (Fig. 3).

On the limb of a fold there are further complications. Clasts undergo a rigid body rotation (Fig. 8b), together with the rest of the fold limb, relative to the axial plane, and therefore relative to the bulk pure shear component. In addition there is potentially a component of simple shear parallel to bedding (Fig. 8c), which will tend to deform the clasts. If rotation of the limb is clockwise the simple shear component will result in anticlockwise rotation of a clast with respect to bedding (Fig. 8c). The pure shear component will rotate the clasts both ways relative to the axial plane depending on the orientation of the clast with respect to the shortening direction (Fig. 8d). The net rotation is the sum of the three components. There are too many unknowns to analyse the relative significance of these components in detail, however some general comments can be made.

Three of the kinematic components affecting clasts are shown diagrammatically in Figure 8. The fourth one, shear within the clasts in response to their active rotation relative to their matrix, is omitted because it is thought to be negligible in the Woody Island rocks. The points were already made that there is no obvious competence contrast and therefore no reason for active rotation, and that the geometry of crenulations in the hinge suggests that there is no active rotation. On the limbs the clast geometry (Fig. 4e) indicates that the clasts have undergone a non coaxial straining (see Fig. 9). However, in the limb environment the non coaxial deformation need not be a product of traction due to active rotation of the clasts, because the combined affect of the bedding parallel simple shear and the bulk pure shear can result in the overturned appearance (Fig. 8j & k). In view of this and the lack of evidence of competency contrast it is assumed that the rotation of the clasts is passive.

In Figure 8a two clasts dip gently in opposite directions symmetrical about the bedding plane. Only clast 2 is capable of developing an antithetic crenulation cleavage anticlockwise of the long dimension of the clast (see Fig. 8j). For clast 1 to develop such a geometry it would first have to rotate through the horizontal or through the axial plane and there is no mechanism for it to do so. Either clast has the potential to rotate without crenulating so that its long dimension is parallel to S_{2e} if initially inclined to bedding at a sufficiently large angle. Figure 8e-i shows a possible sequence of events that would lead to the observed characteristics of the foliation and clasts. Initial pure shear shortening rotates both clasts away from the bedding orientation towards the normal to bedding. Initially both clasts are shortened and there is the potential for crenulations to develop if the strain magnitude is sufficient. Folding, and therefore limb-rotation, starts (probably after a small amount of bedding-parallel shortening), so that clast 1 is rotated towards the pure shear extensional axis, and clast 2 is rotated towards the shortening axis. However, both rotations are reduced by the simple shear component, and the rotation of clast 2 is also reduced by the pure shear component. Given the right balance of the different components, orientations of clast 1 in the shortening field and clast 2 in the extensional field can be maintained without clast 2 rotating through the shortening axis (Fig. 8f-h). As the folds tighten and lock-up, the limb-rotation and limb-parallel shear decrease in importance and the pure shear component continues to rotate both clasts towards the extension direction (Fig. 8i). Since clast 2 spent much of its history in the shortening field it can be expected to be crenulated and by the end of deformation the crenulations will generally be asymmetrical and antithetic. In contrast clast 1 might have rotated into the extensional field early enough to remain uncrenulated. Similarly oriented clasts more nearly parallel to bedding might stay in the shortening field long enough to crenulate before rotating into the extensional field (Fig. 8k). In the Woody Island rocks these would be the rare clasts, which having rotated the opposite way to the limb, have a synthetic cleavage (Fig. 8k).

Fig. 9 Diagram showing that the observed morphology of the clasts cannot be achieved simply by a pure shear deformation. In **(a)** a clast has been shortened sufficiently to produce symmetrical crenulations. **(b & c)** Continued shortening perpendicular to the axial plane (parallel to S_{2e}) of developing F_2 folds, results in the crenulations becoming increasingly asymmetrical, as is observed in the Woody Island material. However, the resultant foliation S_{2i} (see c) is essentially parallel to S_{2e} and does not have the typical appearance of the asymmetrical crenulations. (Note that S_{2i} is parallel to the axial plane of the crenulations). **(d - f)** represents a different approach; **(d)** is the typical



observed morphology with S_{2i} anticlockwise of S_{2e}, and **(e & f)** represent stages in its unstraining, assuming pure shear. When almost parallel to bedding (horizontal) the crenulation is seen (f) to be very asymmetrical, which is considered unacceptable for the initial microstructure. See text for further discussion.

Finally, there is the possibility for some clasts, even on the fold limb, to deform symmetrically without any rotation. On the limb, this would be a fortuitous situation and therefore rare but given the right balance of rotations it is possible. This would explain the symmetrically crenulated clasts observed in the Woody Island fold limbs. If strain were large enough such clasts would be the ones that have a penetrative foliation (S_{2i}) perpendicular to S_{si}.

Several lines of evidence indicate that penetrative foliation on Woody Island has developed by this process of micro-transposition. First, the penetrative foliation is most common in high strain domains such as the concave side of competent layer folds or in clasts that have S_{si} approximately parallel to S_{se}, but are nevertheless elongate parallel to S_{2e}, suggesting high strain. Second, all gradations between crenulation, crenulation cleavage and the S_{2e}-parallel penetrative foliation are observed in different clasts. More significantly, the same gradation can be observed in a single tapered clast, the broad end of which, is protected from the strain experienced by the narrow end, by an adjacent strong clast. In the strain shadow area there is a crenulation cleavage which changes progressively into a penetrative foliation as traced into the high strain area (Fig. 6).

Thus the S_2 foliation in the Woody Island rocks is believed to have developed by a process of transposition at various scales. The transposed foliation is an early surface mimetic after a sedimentary foliation, defined by the preferred orientation of clasts and matrix micas and by S_i within the clasts. At clast-scale, transposition involves flattening and/or rotation of clasts as well as folding of bedding (S_{se}). Commonly, rotation of clasts involves no internal folding so that S_2 is defined by S_i which, if modified at all, is simply accentuated by flattening perpendicular to its original orientation (Fig. 4d). Elsewhere, deformation of clasts has produced symmetrical crenulations within the clasts which rotate S_i into the S_{2i} orientation (Fig. 4f). Mostly however, initial symmetrical crenulations have been converted by a complex interplay of the three kinematic components into asymmetrical crenulations (Fig. 4e). In domains where the strain magnitude is large enough the crenulations may become too tight to recognise as such and transposition may result in a penetrative S_{2i}. Mostly however, rare relic crenulations indicate the transposition origin.

The model outlined above was developed by conceptually forward modelling the deformation of an assumed initial fabric based on undeformed sediments. Where alternatives were possible a choice was made that was most consistent with the observations. The result is a model that is capable of explaining all features of the observed microstructures including the relative abundance of end-member types in the fold hinges and limbs. End-member 1 (Fig. 4f) is most common in the fold hinges because there is less tendency for clasts in that environment to rotate relative to the bulk pure shear component of deformation. It is the least common end-member on the fold limbs where end-member 3 (Fig. 4d) is the most common, because the tendency for rotation relative to the bulk pure shear component is large on the fold limbs.

This model is presented as the most reasonable interpretation of the microstructure of the Woody Island rocks.

Discussion: Foliation development

The different clasts in the material described here, are representative of different deformational environments in folds. The clasts oriented such that S_{si} and S_{se} are parallel and perpendicular to S_{2e} respectively (Fig. 4f), represent fold hinges and as in that environment the foliation in each layer or clast is oriented parallel to the general orientation of S_2. Clasts oriented with S_{si} perpendicular to S_{se} and therefore parallel to S_2 (Fig. 4d.) represent fold limbs that have rotated without first crenulating so that no axial plane cleavage has developed. The folded foliation has simply rotated towards parallelism with the axial plane of the fold. The clasts inclined to S_2 with asymmetrical crenulation cleavage (Fig. 4e), represent the limbs of folds where a crenulation developed prior to, or in the early stages of folding, and became increasingly asymmetrical as folding continued. Such axial plane foliations are generally inclined to the axial plane of the folds and in competent layers form a convergent fan such that the limb and cleavage are rotated in opposite directions relative to the axial plane. This is the same relationship as recorded within the shale clasts.

The transposition model invoked here for the development of an axial plane foliation has previously been proposed on the basis of observations of folded layers in pelite (*e.g.* Hobbs *et al.*, 1976, p.242). The Woody Island rocks allow us to successfully test the model. It provides different constraints to those implicit in the original data set but does not require any modifications to the model. The whole interpretation is internally consistent with all of the observations including variation in clast shape and orientation, cleavage morphology and the orientation of bedding within the clasts.

Crenulation cleavage is a feature of S_{2i} in the shale clasts and of S_{2e} in some of the most mica-rich layers. Where not a crenulation cleavage, S_2 is mostly a bimodal fabric. It may be defined for example by anastomosing mica-films or by the orientation of the long dimension of the clasts. It is suggested here that the processes operating in the development of the crenulation cleavage and of the various bimodal fabrics are essentially the same, except that deformation in the non-crenulated rocks is less ordered. Depending on their initial orientation with respect to the bedding-parallel bulk shortening direction, shale clasts and mica grains may rotate in opposite directions towards the same S_2 orientation (Hobbs *et al.*, 1976, p. 247; Means *et al.*, 1984). There is no order to the sense of rotation of the individual grains and the result is a bimodal fabric unless the magnitude of strain is sufficient for the two maxima to coalesce. In the case of crenulations, rotation of the individual mica grains is subordinate to crenulation of the foliation so that there is a gradual variation in orientation from grain to grain.

Neither crenulations nor bimodal fabrics are likely to form in situations where large-scale folding has a predominant dynamic component from the start, *i.e.* where folding is largely a buckling process with little deformation achieved by homogeneous bulk shortening parallel to the initial bedding orientation (*cf.* Fletcher, 1974). This is because the spin of the limbs will rapidly rotate all grains and clasts to an orientation clockwise of the shortening direction on a clockwise rotating limb (Fig. 8b) and anticlockwise on an anticlockwise rotating limb. All rotation relative to the axial plane, will then be in the same direction on a given limb and neither microfabric will be able to develop. Either fabric however, will still be able to develop in the fold hinge which explains why folds in some areas have crenulations and/or cleavage in the hinge but not on the limbs.

Crenulation cleavage is typically developed in layersilicate-rich rocks and it is very noticeable in rhythmic sediments such as turbidites that the foliation can change in appearance from crenulation cleavage to, for example, an anastomosing foliation, in going from layersilicate-rich horizons to horizons rich also in quartz and lithic clasts. This suggests that the rotation mechanism, i.e. by folding or by rotation of individual grains, is controlled by the perfection of the initial anisotropy and/or the homogeneity of the initial grain-scale fabric. The presence in a sedimentary rock of quartz and lithic grains, which are less elongate than the layersilicates, generally tends to reduce the degree of preferred orientation of the latter, thus reducing the anisotropy. In addition, the mere presence of scattered strong grains must have an affect that is independent of its influence on the mica fabric. Intuitively, increasing the number of strong grains that lack internal planar anisotropy, will cause deflections in the stress axes and will render the anisotropy less penetrative even if the grains are as elongate as the layersilicates, and have a similar preferred shape orientation. The situation will be further exacerbated if the strong grains are less elongate and/or lack preferred shape orientation. Grain-scale heterogeneity in the orientation of the stress axes and reduction in the planarity of the foliation will cause grains or clasts to rotate independently, rather than following a pattern dictated by the folding of the initial foliation.

Bimodal fabrics are common in layersilicate rocks, most slates and schists are bimodal and crenulation cleavage can be considered a special case of a bimodal fabric. It is suggested therefore that rotation of layersilicate grains either by crenulation of earlier foliation or by rotation of individual grains in a less organised manner is a major mechanism for the development of axial plane foliations.

Discussion: Implications for folding

If folding were purely dynamic (Fletcher, 1974) with no homogeneous pure shear component, it would have to be accommodated by some form of flexural slip (can include tangential longitudinal strain in isolated layers). In layers accommodating the flexural slip component on a clockwise rotating limb, all clasts would rotate anticlockwise (Fig. 8c), relative to bedding. For a spherical clast the maximum rotation possible (assuming homogeneous flexural flow) is given by $\phi = \alpha/2$, where α is the dip of the limb (Williams and Jiang, *in press*). Thus on the clockwise rotating limb of an isoclinal fold a spherical object may rotate 45° anticlockwise relative to bedding. It would thus rotate 45° clockwise with respect to the axial plane of the fold. It is possible to increase the amount of rotation by localising the simple shear component of the flexural slip (*cf*. N-value of Jiang, 1994). However, large N-values are required to prevent the clasts rotating clockwise with respect to the axial plane and the problem is exacerbated by the fact that for non spherical objects, which do not rotate at a constant rate as a function of shear, the rotation is minimised when the clasts are parallel to the shear-plane. Thus clasts initially oriented parallel to bedding could never be rotated to define an axial plane cleavage unless it was in a very narrow layer with a very high N-value. There would then be no mechanism for developing an axial plane foliation in the fold hinge or the limb.

If folding were purely kinematic (Fletcher, 1974) and a product of homogenous pure shear, folds could only form by amplification of pre-existing perturbations and assuming that the shortening was parallel to the initial orientation of bedding, clasts with an initial variation as in Figure 8a, would rotate both ways on the same limb and both synthetic and antithetic cleavages would exist in equal numbers.

The data presented here indicate that both dynamic and kinematic components of folding operated synchronously during deformation. It is probable that the bulk pure shear component was particularly large in relative terms at the beginning and end of the process, as is commonly believed (*e.g.* Ghosh, 1993, p.273). However, this component must have been large enough throughout the deformation, assisted by a weak simple shear component, to prevent at least a large percentage of the clasts, dipping in the opposite direction to the host-limb, from rotating so that they dipped in the same direction as the host-limb. A more thorough analysis of this material might place quantitative constrains on the relative importance of the dynamic and kinematic components, but is outside the scope of this paper.

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Discussion: Metamorphic differentiation

The differentiated crenulation cleavage, within the clasts described here, is typical of crenulation cleavage in general (*e.g*. Hobbs *et al*., 1976, p. 217). There are alternating layersilicate-rich and quartz-rich domains and the folded surface S_i is most nearly parallel to the domain boundary, and therefore to the crenulation foliation, in the layersilicate-rich domains. This indicates that there is some significant difference in the conditions developed in the two cleavage domains during deformation. It strongly suggests that partitioning of the strain is the important factor with a controlling influence on the process of differentiation. The question is, how might it influence the process?

If we consider a clast that is inclined at a small angle to S_{se} in which S_i is symmetrically crenulated, as the clast rotates towards S_{2e} one set of alternate limbs of the crenulations (Q domains) rotates towards horizontal and the other (M domains) rotates towards vertical (Fig. 8j). In terms of the pure shear component, S_i in the Q domains is rotating towards the shortening field whereas in the M domains it is in, or is rotating towards the extensional field. The domain boundaries lie in, and remain in the extensional field. The domains therefore have to increase in relative length. Three mechanisms are available for deformation within the domains - slip on S_i, homogeneous change in shape involving change in the shape of individual grains (intragranular mechanism), and fracturing. Of these mechanisms, under some conditions at least, slip is known to be a weak mechanism compared to the intragranular mechanism (Price and Torok, 1989; Williams and Vernon, *in press*). In the presence of a fluid, fracture, where there is extension perpendicular to S_i, is also likely to be a weak mechanism and at high strain rates is likely to be weaker than the intragranular mechanism.

Figure 10 shows the same process in a folding situation where the strain is assumed to be homogeneous on the scale of a fold limb (analogous to one of the clasts). Here the domains as seen in profile, do not change in area and their relative widths are maintained. The crenulations become asymmetrical because in the Q domains the principal shortening direction is only slightly inclined to the crenulated surface whereas in the M domains it is more nearly perpendicular. Thus in the Q domains the folded surfaces shorten and move apart and in the M domains they lengthen and move closer together. This statement is true for a variety of initial interlimb angles. In this situation, in a strongly anisotropic material that is weak perpendicular to the folded surface and is weaker in tension than in compression (a general feature of rocks) there would be a natural tendency for slip to be the weak mechanism in the M domains and extensional fracturing to be the weak mechanism in the Q domains, leading to the situation modeled above. Once a reasonable fold is established it is not so important that the bulk strain path be noncoaxial as is demonstrated in Figure 10. In going from a limb dip of 45 to 60 the difference between a bulk simple shear parallel to the enveloping surface plus a rotation, and a bulk pure shear perpendicular to the axial plane of the fold is small (compare Fig. 10c & d,).

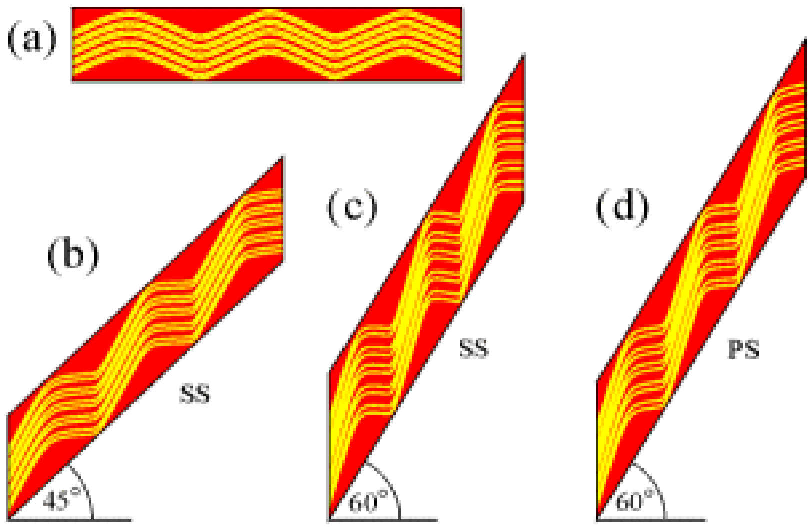

Fig. 10

Fig. 10 Development of asymmetry in crenulations by enveloping-surface-parallel shear. **(a)** Initial shortening results in symmetrical crenulations. **(b)** Flexural slip is accompanied by spin of- and simple shear parallel to bedding. The crenulations become asymmetrical. **(c)** A further increment of simple shear and spin increases the limb dip to 60 , and further increases the asymmetry of the crenulations. **(d)** For comparison the dip is increased from 45 (as in b) to 60 (as in c) by pure shear shortening perpendicular to the axial plane (vertical). See text for further discussion.

In the M domains simple shear parallel to S_i would result in a decrease in the angle between S_i and the domain boundary and would increase the length of the domain thus satisfying bulk strain requirements. In the Q domain, slip on S_i accompanied by folding would be an adequate mechanism, but the initial width of the crenulation has already been determined by the wavelength for the foliated rock, and so still finer-scale folding might not be favoured. This is consistent with the fact that we do not see crenulations within the Q domains within the Woody Island rocks. This is generally true of differentiated crenulation. Another feasible mechanism in the Q domains would be opening of fractures parallel to S_i. This would accommodate the extension but would not produce a compensating shortening. However, if the process of slip on S_i in M domains and fracturing parallel to S_i in Q domains was accompanied by removal of quartz from the M domains and deposition of mica in the Q domains, a compensating shortening could be achieved at the scale of the combined M and Q domains. The mica stacks are readily explained as metamorphic mica growing epitaxially on detrital (or earlier S_i-parallel) micas (Hoeppener, 1956) that localised fracturing. Transfer of quartz and mica from M to Q domains would result in the prescribe strain. Removal of quartz from the system combined in some permutation with transfer or introduction of mica could be even better.

What actually drives the solution and deposition of quartz and mica remains a problem (see Fletcher, this volume). It is generally believed to be due to some mass transfer process either along a pressure gradient or from highly stressed to less stressed grain boundaries or simply due to flushing along channelways. Attempts to model the process using sophisticated numerical methods result in clogging of the channelways with quartz rather than removal of quartz (B.E. Hobbs, *pers com.* 1999). However, if it is assumed that the initial fabric is strong parallel to the crenulated foliation and weak perpendicular to it, the models predict a pressure difference between the two domains with high pressure coinciding with the M domains.

Another possibility is that shear in the M domains results in deformation of the quartz, at least near the surface (core and mantle style) and therefore in local high dislocation densities, whereas fracture, within mica grains, in the Q domains leaves the quartz grains essentially undamaged. The undeformed quartz might then grow at the expense of the deformed grains (*e.g.* Means, 1968; Meike and Wenk, 1988), or in a flushing situation, the deformed grains would tend to dissolve preferentially and be removed from the system.

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Discussion: Relationship between foliation and strain

The mechanism proposed here will produce a foliation that rotates progressively towards the principal plane of finite strain defined by the maximum and intermediate elongations. Where the axial plane foliation is defined by symmetrical crenulations it will be truly parallel to the principal plane and will have tracked that plane during development of the foliation. This would be the situation in a fold hinge.

Wherever the foliation is defined by asymmetrical crenulations and there has been non coaxiality of deformation, the foliation will not have tracked the principal plane and will not be truly parallel to that plane. Lack of symmetry across domain boundaries, in the strain experienced by M (shear parallel to S_i) and Q (extension perpendicular to S_i) domains, requires that the strain on the scale of multiple domains have a component of shear parallel to the domain boundaries (S_{2i}). The greater the degree of non coaxiality the greater the possible discrepancy in orientation between the foliation and the principal plane of strain on the scale of a fold limb.

Conclusions

(1) In the Woody Island rocks, rotation is the single most important process in the development of preferred orientation of clasts and mica grains to define an axial plane foliation. The mica grains are of metamorphic origin and probably mimetic after sedimentary grains. The rotation may occur at a clast or granular-scale and may be random or it may be more spatially organised and a product of micro-folding (crenulation) of the initial foliation. At large strains crenulations may tighten until they completely transpose the original foliation into a new foliation. Rotation tends to produce bimodal fabrics and the ubiquity of such fabrics elsewhere, suggests that this mechanism is a very common one in the development of axial plane foliations in general.

(2) Folding on Woody Island involves dynamic and kinematic components and the kinematic component appears to be large. The fact that the foliations and folds are typical of those seen elsewhere in similar sedimentary sequences, including for example turbidites, suggests that this may generally be true in sedimentary sequences.

(3) Whatever the mass transfer mechanism for differentiation in rocks, there is a correlation between strain path partitioning and compositional domains.

(4) Axial plane foliations developed by the mechanism proposed here will not track strain axes and will not ultimately lie precisely parallel to a principal plane of strain. They are likely to be close to a principal plane however, and how close will depend on the relative importance of dynamic and kinematic components during folding. The larger the kinematic component the closer the orientation.

(5) Rocks that contain more than the usual amount of evidence of their history are by definition unusual and therefore less common than most. **It is important to recognise the value of such rocks.** Particularly important in the Woody Island rocks are the shale clasts, especially those that contain recognisable bedding. The bedding makes it possible to recognise S_i as opposed to S_{2i}, and to know whether a clast has maximised rotation or shortening, because its original shape can reasonably be assumed once bedding is recognised (the long dimension is generally parallel to bedding in shale clasts). By the same argument, irrespective of its origin, since it is observed to be parallel to bedding, S_i must also have been parallel to the original long dimension of the clast. Since S_i is now a metamorphic foliation (albeit mimetic after bedding), in the absence of compositional bedding, its orientation with respect to clast shape would be unknown.

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