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The texture of cross-micas in rocks affected by schistosity-parallel displacements

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Abstract—Cross-micas are described in a rock for which relative displacements from sliding on schistosity planes have previously been demonstrated. Individual cross-micas in these rocks have incurred similar displacements along (001) surfaces. Shear strain on planes parallel to (001) in each cross-mica is determined and plotted on a map of the surface being investigated. The distribution illustrates that higher shear strains are found in cross-micas that are close to translation surfaces along which garnet porphyroblasts have been sliced into tabular sections.

The study illustrated in this paper could be extended to other types of cross-micas and may prove to be a useful method for the investigation of strain history in foliated rocks.

INTRODUCTION

CROSS-MICAS are porphyroblastic micas which lie across a pervasive foliation or layering in a metamorphic rock and are typically larger than those which define the schistosity. In general, cross-micas may exhibit varying relationships to the dominant schistosity; in some examples they are post-kinematic with respect to foliation development whereas in others they are pre-kinematic (for a discussion refer to Spry 1969).

The particular cross-micas described here occur in a rock specimen containing initially idioblastic garnet porphyroblasts that have been sliced into tabular sections by schistosity-parallel displacements (Gregg 1978). Evidence is now presented which shows that the cross-micas in the same specimen have been deformed in a manner consistent with this observed displacement.

DESCRIPTION OF ROCK TYPES

The specimen discussed here is a garnet-rich, chlorite-muscovite schist from the Moretown member of the Ordovician Missisquoi Formation. The locality sampled is situated in the vicinity of Ludlow, Vermont, U.S.A. within 10 m of the Central Vermont ultramafic zone. The metamorphic facies is epidote-amphibolite (Thompson 1950).

The dominant foliation in both gneissic and schistose units of the Moretown member consists of a fine secondary foliation (S_2), defined by alternating mica-rich layers and quartzofeldspathic microlithons (Fig. 1). The mica-rich layers typically contain fine muscovite and chlorite. Between these mica-rich layers can be found an earlier S_1 layering which is also believed to be secondary in nature. This S_1 layering is folded on a mesoscopic scale and the later S_2 layering is developed as an axial surface foliation to these folds (Fig. 1). S_1 layering is similar in morphology and composition to S_2, with the exception that mica-rich domains of S_1 contain abundant biotite. On S_2 surfaces these biotite grains define an intersection lineation which is typically parallel to the axes of microfolds that deform S_1 (Fig. 2). This L_2 lineation is ubiquitous in the Moretown rocks of the study area (Gregg 1975). S_2 surfaces also display idioblastic outlines of garnet crystals (Fig. 2). These crystals show a button-like shape when removed from the S_2 surface.

When examined on a surface cut at 90° to S_2 (Fig. 3), the biotite grains in this same specimen appear as parallel cross-micas. Because previous experience has shown them to be elements of S_1, it is assumed that the orientation of the biotite reflects that of S_1 in the specimen. Garnet crystals on this surface are 'sliced' into segments offset along S_2 (Gregg 1978). The relationships between these elements are schematically illustrated in Fig. 4. There is a consistency in the direction of offset shown by sliced garnet sections and displaced sections of biotite crystals.

Figure 5 illustrates the microstructure of a cross-mica that has not been deformed by dislocation along (001). Within this grain a few inclusions of quartz and opaque minerals are present. The origin of these inclusions is uncertain, but similar ones in sliced garnets have been shown to be continuous with the late quartz-rich planar fabric developed during slicing (Gregg 1978). Quartz rich pressure shadows are well-developed and S_2 layering is deflected around the grain boundaries of the biotite. These textures are further evidence that the cross-micas predate the development of S_2 (see Spry 1969, pp. 251–252).

DEFORMATION OF CROSS-BIOTITE

The cross-micas in this specimen range from 0.5 to 3.0 mm in length and illustrate variation in forms as illustrated in Fig. 6. The grains typically display planar grain boundaries parallel to (001) whereas the opposing grain boundaries may be either stepped in appearance or planar. In many examples which display stepped grain boundaries [e.g. grains (c) and (d) in Fig. 6] it is possible to

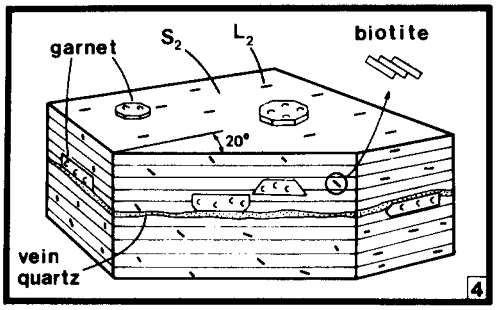

Fig. 4. Schematic diagram illustrating relationship of cross-micas in S_1 (biotite) to various structural elements discussed in text. The front surface of the block represents that shown in Fig. 3 and the top (S_2) surface that in Fig. 2. Lineation (L_2) is produced by the intersection of the cross-biotites with S_2 schistosity surfaces. Cross-biotites are parallel to S_1 layering in most Moretown specimens. Quartz-rich veins are typically associated with displacement surfaces along which garnet crystals are offset.

restore the boundary to planarity by translation of sections parallel to (001). When such translations are made, the grain typically takes on a more idioblastic shape of somewhat lower aspect ratio. Figure 7 illustrates such a restoration of a typical cross-mica. Note that the fine internal quartz layering (s–s') in the biotite is brought into registration by the translation along line t–t'. A comparison of this restoration with the original shape of the grain (Fig. 6c) suggests that displacement along (001) has occurred. The rock specimen investigated contains hundreds of such 'stepped' grains, and there is a consistency in the direction of supposed displacement as indicated in Fig. 6.

A detailed study was performed on 53 cross-micas in the specimen, concentrated on the area shown in Fig. 3. Measurements taken with the aid of a binocular microscope included the β-angle, measured as the acute angle of two grain boundaries; the length 'a' of the diagonal extending from the origin of the β-angle and the length 'b' of a line measured perpendicular to 'a' at the midpoint of 'a'. In addition the angle α was measured as the acute angle between the rock schistosity and the direction of (001) in each biotite grain (Fig. 8). Lines 'a' and 'b' were used for determining aspect ratio because they are the most easily measured lines throughout the range of β-angles.

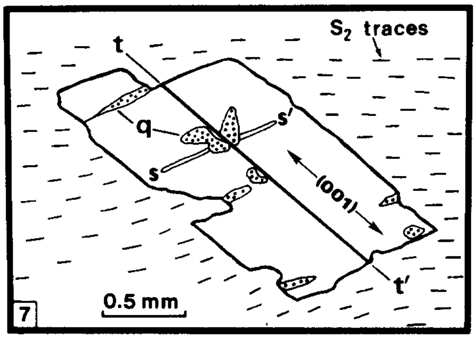

Fig. 7. Restoration of cross-biotite (c) of Fig. 6. The restoration was performed by translation of one segment along line t–t' which is parallel to the trace of (001). The irregular patches labeled 'q' are quartz rich aggregates which appear to post-date the displacements. The linear feature labeled s–s' is a typical early structure which is brought back into registration by translation along t–t'. In thin section these appear as quartz-rich planar elements. Restorations such as this suggest that slip on (001) may be responsible for the stepped appearance of the grains in Fig. 6.

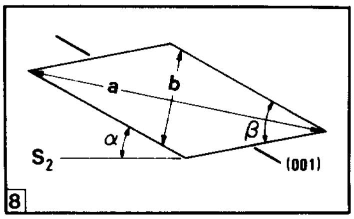

Fig. 8. Sketch illustrating the relationship of various measurements taken by the author. The aspect ratio (a/b) is used to express the overall shape of each cross-mica. The dimensions 'a' and 'b' were chosen because the author's experience showed those directions to be most easily measured in a binocular microscope. The angle β is used as an indication of the relative amount of displacement along (001) in each grain, and α is used as a measure of the degree of parallelism of (001) and the schistosity (S_2).

Figure 9 illustrates the distribution of the β-angle with respect to the aspect ratio (a/b) of the cross-biotites in this specimen. The curves depicted represent changes calculated from models of homogeneous simple shear in objects varying from square in initial cross-section to those of rectangular shape with initial aspect ratios as high as 4 : 1. For example, the 1 : 1 curve represents the shape changes in a square object as the β-angle goes from 90° in the undeformed state to lower values with increasing deformation. The points plotted represent measurements of actual biotites from this specimen, and a close approximation to the curves is shown. The spread in points could be explained in part by variations in initial aspect ratio of the cross-micas, as well as by relatively inhomogeneous displacements compared with the homogeneously deformed models.

RELATIONSHIP OF SCHISTOSITY-PARALLEL DISPLACEMENTS AND DEFORMATION IN CROSS-MICAS

Visual inspection of the rock specimen suggests a relationship between deformation in the cross-biotites and their proximity to the quartz-rich discontinuities which parallel the late schistosity (Fig. 4). In Gregg (1978) it was shown that these quartz-rich zones define the translation planes of garnet segments which have been offset by displacements parallel to the schistosity. Evidence is now given which documents these relationships in detail.

Figure 10 illustrates data taken from the same cross-biotites plotted in Fig. 9, all of which are from the specimen illustrated in Fig. 3. Figure 10 shows that micas with (001) at low angles to schistosity have high aspect ratios whereas those at high angles to schistosity have lower aspect ratios more typical of porphyroblastic micas. This would imply that highly strained cross-micas (those with smaller β-angles) have not only changed shape but have suffered rotation of (001) toward parallelism with the schistosity. This suggests a relationship between the deformation of the micas and the larger scale displacements in the schistosity documented in Gregg (1978). This

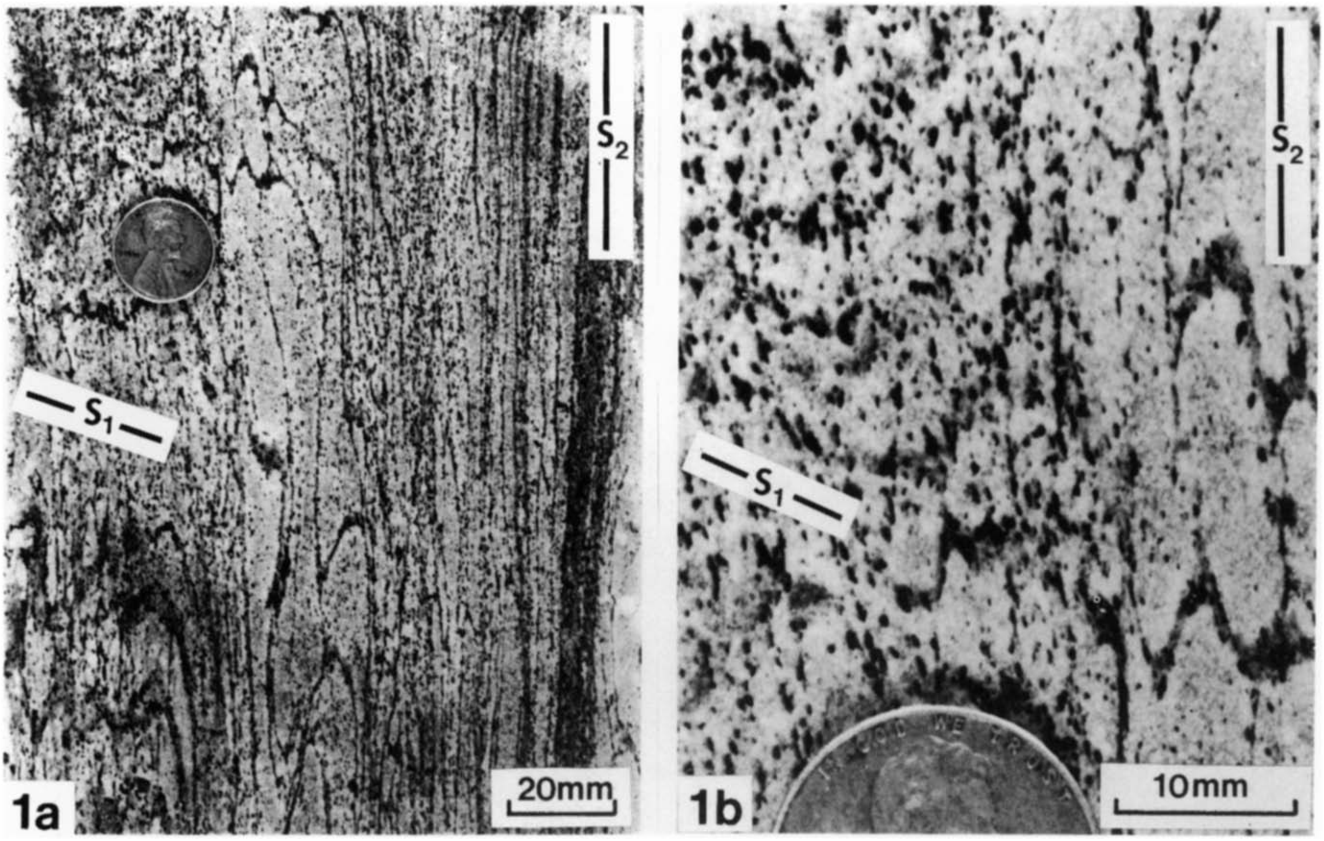

Fig. 1. (a) Polished surface of a typical Moretown specimen from Ludlow, Vermont (U.S.A.), showing early S_1 layering disposed in B_2 folds. S_2 is developed as an axial surface layering to these folds and trends vertically in the photograph, whereas S_1 crosses the photograph irregularly from upper left to lower right. S_1 layering is obscured in regions that contain strongly developed S_2 mica-rich domains, as on the right hand side of the photograph. (b) Close up of an area above coin in Fig. 1(a) showing fine detail of S_1 (folded) and S_2 (vertical) layering. When present, biotite cross-micas are parallel to S_1 layering and pre-date the development of S_2. The structural elements illustrated here are ubiquitous in the rocks of the Moretown member.

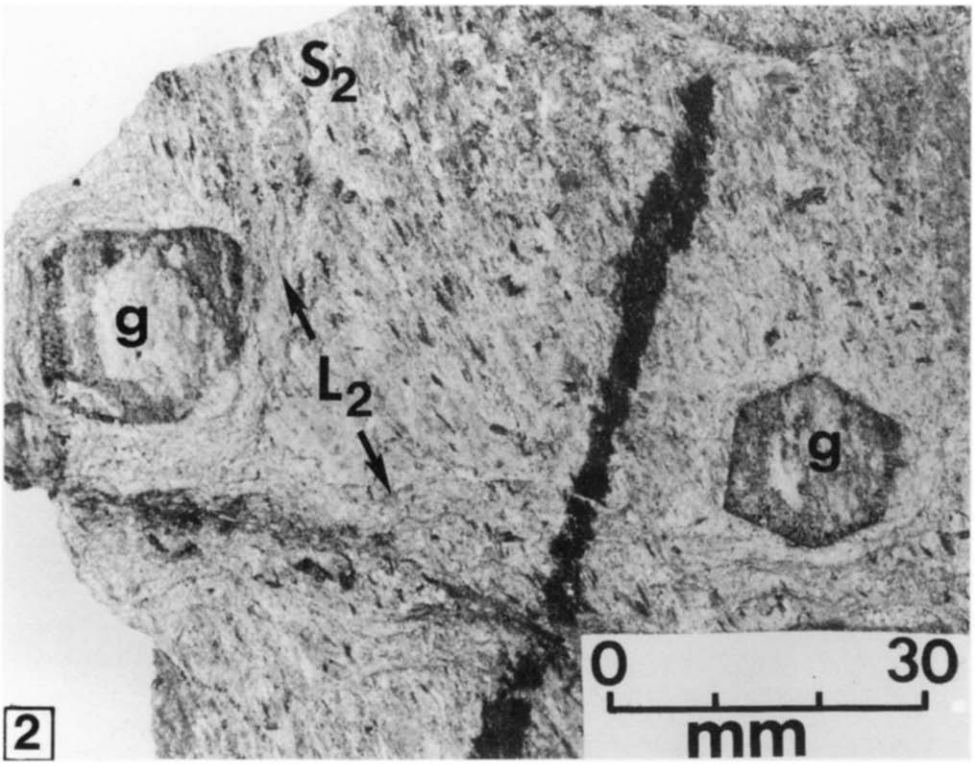

Fig. 2. Typical example of the intersection lineation (L_2) formed on an S_2 surface by elements of S_1. In this example the elements of S_1 are small biotite grains that trend toward the upper left. Note the idioblastic shape of garnets (g) in this view. These garnets are tabular in shape and have been sliced into displaced segments along S_2. This specimen is further illustrated in Fig. 3. Heavy black line is an orientation mark.

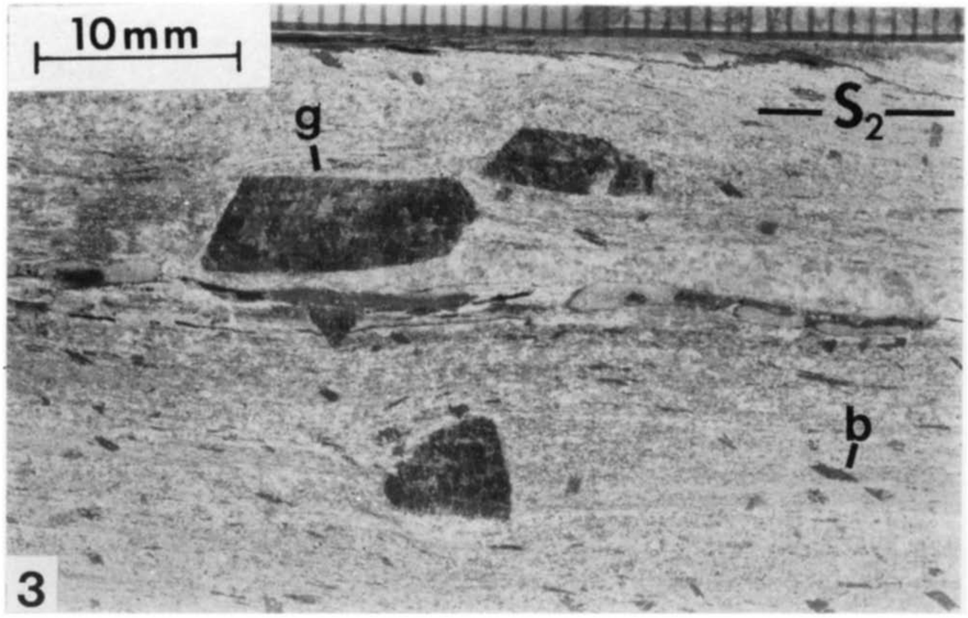

Fig. 3. Tabular garnets (g) from the same specimen shown in Fig. 2. The garnet sections have been formed by the slicing and displacement of initially idioblastic garnets parallel to schistosity. The surfaces along which grains have translated are marked by quartz-rich layers containing minute fragments of garnet (see Fig. 4 and Gregg 1978). Cross-micas (b) which pre-date S_2 schistosity appear as small black grains oriented diagonally from right to left in the photograph. These cross-micas parallel an earlier (S_1) foliation and their traces along the schistosity surface are illustrated in Fig. 2.

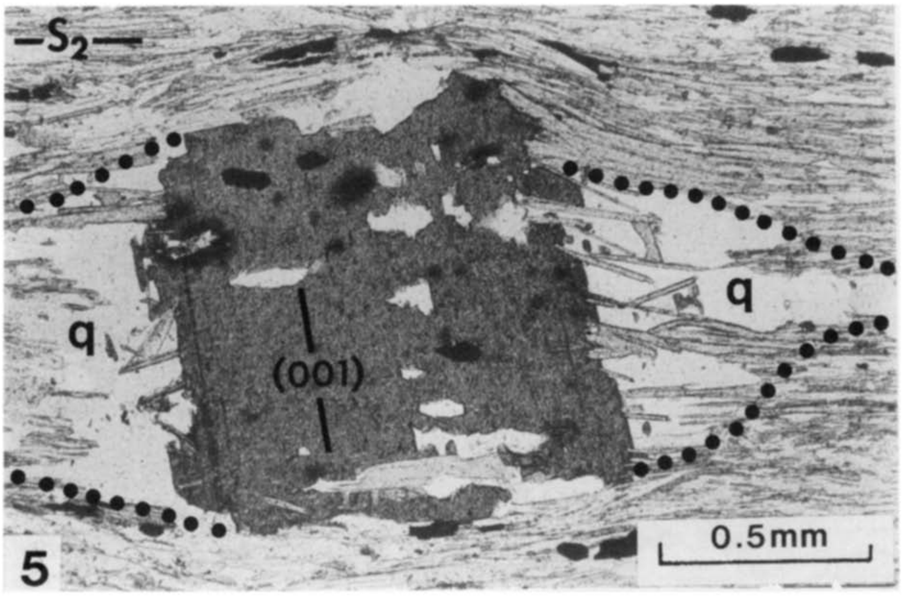

Fig. 5. Microstructure of a slightly deformed cross-biotite illustrating well developed 'pressure shadows' of quartz (q), penetration of the porphyroblast by fine micas in the late schistosity (S_2), and deflection of the schistosity around the edges of the cross-biotite. These textural elements are indicative of an early, pre-S_2 origin of the cross-biotites.

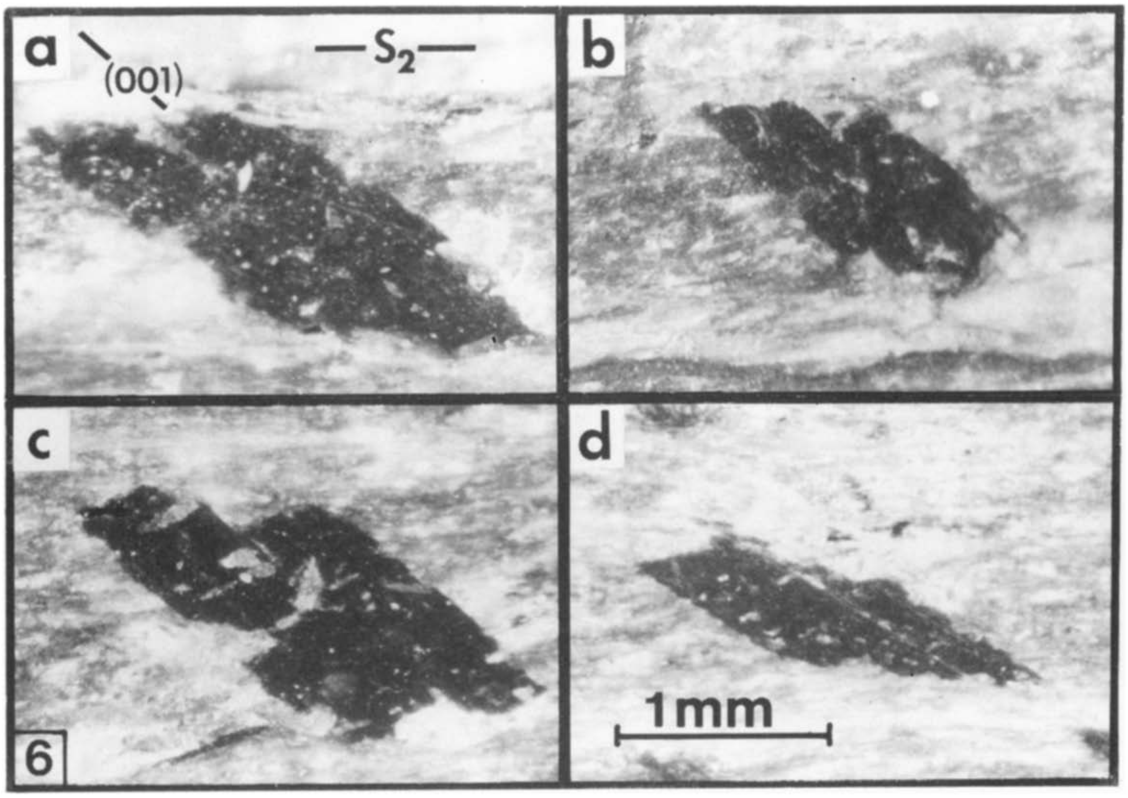

Fig. 6. Details of cross-biotites in Fig. 3, illustrating 'slipped' appearance common in most grains. Grain (c) is further illustrated in Fig. 7 where it has been restored to a more equant form by translation along an (001) plane. Note especially the slipped 'card-deck' appearance of grain (d). The specimens are illustrated in exactly the same orientation as they appear in Fig. 3. Note the consistency in direction of apparent offset along (001).

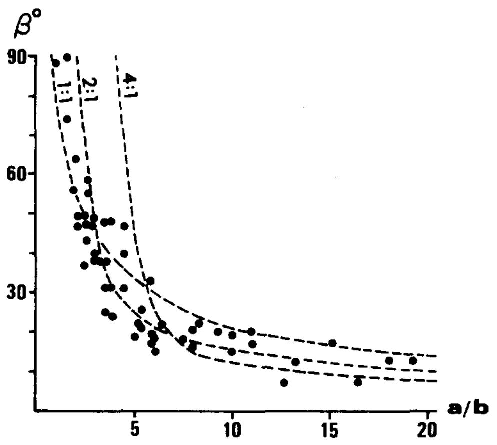

Fig. 9. The overall pattern by which cross-micas have deformed in this specimen can be shown by plotting the β-angle vs aspect ratio for each of 53 biotite grains. It is assumed that the changes observed in space can be compared with increasing strain in time. The data can be compared to a series of calculated curves based on changes in shape of various micas with different initial aspect ratios as shown. The curves show the calculated shape changes associated with increasing homogeneous displacements on (001). These curves are based on the familiar 'card-deck' model of deformation with the sliding surfaces in the model correlated with (001) in the actual cross-mica.

suggestion is supported by the fact that, with few exceptions, there is a uniform sense of displacement in individual grains that is consistent with the sense of displacement shown by garnet porphyroblasts. This is well shown by Figs. 3 and 6 in which the examples are presented in the same relative orientations.

DISTRIBUTION OF CROSS-MICA SHEAR STRAIN COMPONENT IN THE SCHISTOSITY

The evidence presented in the preceding figures indicates that cross-micas have been deformed by displacement along (001) surfaces, and that the β-angle appears to reflect the amount of displacement incurred in the individual cross-mica. Visual inspection of the cross-micas present in the specimen has shown that buckling or kinking of (001) planes is generally absent. It is therefore assumed that strain in the cross-micas can be approximated by the familiar 'card-deck' model of simple shear. In this case the sliding surfaces of the cards represent (001) in the cross-mica. With these assumptions in mind; the shear strain on planes parallel to (001) in each grain can be calculated as $\gamma = \tan(90 - \beta)$; however, it is impossible to determine how much of the total strain in each cross mica is represented by such a calculation.

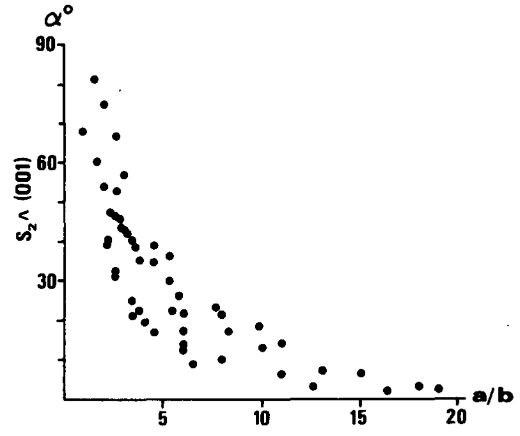

Fig. 10. The relationship between aspect ratio and orientation with respect to schistosity (S_2) is illustrated for the same grain population illustrated in Fig. 9. Equant grains have (001) traces at high angles to schistosity whereas grains with high aspect ratio have (001) traces at low angles to schistosity. This figure shows that with increasing strain (001) in cross-biotites is progressively rotated towards the schistosity.

In Fig. 11 the magnitude of shear strain on planes parallel to (001) within individual cross-biotites is illustrated. The location of each cross-biotite corresponds to the centre of each circle. The relationship between shear strain in the cross-biotite and the previously demonstrated displacements parallel to the schistosity is again illustrated. Those cross-micas lying close to the quartz-rich layers show higher shear strains than those at greater distances. These quartz-rich layers have been shown to be translation surfaces along which shear displacements of garnet grains occur (Gregg 1978). It must be emphasized that the cross-micas are not passive markers and therefore do not provide an accurate measure of shear strain in the local schistosity. However, it is possible that shear strain on schistosity planes in the overall rock specimen is as heterogeneous as the variation in shear strain in the cross-micas would imply. As previously stated the microstructure of the material surrounding the cross-micas contains no evidence of cataclastic texture and gives no indication of the displacements which are indicated by both garnet and biotite porphyroblasts.

The nature of the deformation in planes at various angles to the surface investigated is unknown; however, previous studies (Gregg 1978) have shown that this surface appears to be nearly parallel to the direction of maximum displacement of deformed garnet porphyroblasts. It is possible that the changes due to displacement along (001) in the cross-biotites are similarly distributed.

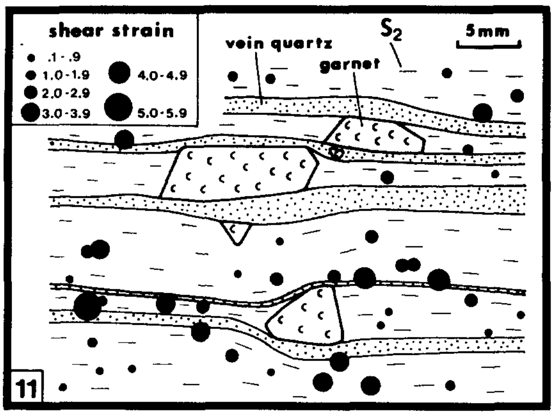

Fig. 11. In this figure the shear strain on planes parallel to (001) in each grain is illustrated. Shear strain is calculated by $\gamma = (90 - \beta)$. The micas are not passive markers and thus strain in the matrix is completely unknown. The figure illustrates that the most highly deformed grains lie near the 'vein quartz' surfaces along which garnet segments have been displaced. The shear strain calculation is used only to compare relative amount of strain on (001) between individual cross-mica grains. The relationship of this strain quantity to total strain in each cross-mica has not been established.

DISCUSSION

A great number of workers have illustrated coarse-grained micas which have been kinked or dislocated near cleavage domain boundaries or have been bent into parallelism with these boundaries (e.g. Williams 1972, fig. 6, Borradaile 1977, plate 1, Hoeppener 1956, abb. 11, Boulter 1977, plate AV3, Dunn 1977, plate AM7). In many cases the suggestion has been made that the shape of a particular coarse mica was due to shear displacements on (001) (e.g. Leith 1905, pp. 25–27, Hoeppener 1956, p. 258, fig. 11, Weber 1976, plate 9, fig. 3). Many of the examples presented are convincing and it appears that cross-micas might be useful in rocks which otherwise lack strain indicators.

The cross-micas presented here pre-date the late schistosity. In this respect they differ from other types of cross-micas that are considered to be post-kinematic with respect to late schistosity (e.g. Spry 1969, fig. 61b). In some cases post-kinematic micas may not have as strong an initial preferred orientation as the ones depicted here and thus may be less desirable objects of investigation. Fortunately, the literature abounds with examples of another type of mica which seems to have fairly strong initial preferred orientation and appears to be common in weakly and moderately cleaved siltstones and slates throughout the world. These consist of white-mica-chlorite aggregates typically parallel to microscopic bedding traces. A number of investigators have discussed these objects (e.g. Moseback 1951, Holeywell & Tullis 1975, Loeschke & Weber 1973, White & Knipe 1978, Beutner 1978, Weber 1976, Roy 1978) and Hoeppener (1956) has established a case in which (001) in these deformed mica grains is rotated with progressive foliation development. The ideas expressed in the present study might be extended to micas of this type, and thus the following criteria are suggested for the demonstration of shear strain in cross-micas.

(1) The presence of grains showing large offsets as in Fig. 6(c) whereby restoration returns the grain to a more equant shape and/or causes registration of an early planar fabric in the grain.

(2) The presence of mica grains with 'stepped' edges as illustrated in Fig. 5, especially in examples where the β-angle measured along the entire edge of the grain is significantly less than that observed for each 'step'.

(3) An overall distribution of β-angles with respect to aspect ratios which corresponds to the theoretical distribution in Fig. 9.

It is recommended that all of the above criteria be sufficiently demonstrated before this mechanism is suggested in a particular example. Cross-micas which appear to have incurred the additional effects of corrosion by solution transfer should not be used to establish the β-distribution unless this can be shown not to have appreciably altered the aspect ratio or β-angle. Because of this problem there may be much difficulty encountered in rocks where mica films or cleavage domains are closely spaced.

In general, the recognition of micas such as those described here will be rendered more obscure by other factors such as recrystallization, irregular initial porphyroblastic shapes or additional non-rotational strain components. It is also probable that many undeformed cross-micas may mimic the shapes illustrated in Fig. 6 by normal growth; however, the relationship between aspect ratio and β-angle for large numbers of such grains should not show the distribution illustrated in Fig. 9. Finally, in the example illustrated here, the slicing of large garnet porphyroblasts gave some indication as to the direction of maximum schistosity-parallel shear displacements which could then be compared with the geometry of the cross-biotites. In examples which lack such markers a more detailed three-dimensional analysis of cross-mica geometry will be necessary before the relationship with a pervasive foliation can be established.

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