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Parallel stretching lineations and fold axes oblique to a shear displacement direction—a model and observations

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Abstract—Spatial variations in shear strain rate are expected in ductile shear zones. Where the variation is a change in shear strain perpendicular to the displacement direction, the effect is to rotate the shear slip planes. This is a mechanism for giving a rotation of fold axes into parallelism with the slip and extension direction in a rock. If such a variation in shear strain affects rocks with a strong planar anisotropy it is possible to produce a fabric with an apparent stretching lineation parallel to fold axes, but both significantly oblique to the slip direction. A possible example of this is seen in strongly deformed quartz–mica schists from Syros, Greece, where a stretching lineation is seen parallel to fold hinges over a range of fold axes orientations of at least 40°.

INTRODUCTION

IT IS a frequently recorded feature of rocks from the deeper levels of orogenic terrains which have been intensely deformed in a shear context, that fold hinges lie parallel to a well-defined stretching lineation (Bryant & Read 1969, Sanderson 1973, Escher & Watterson 1974, Bell 1978). In such instances it is generally assumed that the stretching lineation indicates the transport, or shear direction of deformation; the fold axes having been rotated into parallelism with this direction either because small initial irregularities have become amplified in progressive strain (Cobbold & Quinquis 1980), or because the strain included a wrench-shear component (Coward & Potts 1983).

This paper explores some consequences of the latter suggestion, in particular the development of finite structures where a wrench shear affects rocks with a strong planar anisotropy. The predictions are compared with structures in a specific suite of metapelitic rocks with parallel stretching lineations and fold axes.

STRAIN INHOMOGENEITIES IN A STRAIN REGIME

In any shear deformation, the presence of local inhomogeneities in the rock will induce local variations in the rate of shear strain. Between areas of different strain rate, compatibility constraints require that the strain is no longer exactly simple shear. The strain in these regions can be regarded as simple shear plus a complementary extra strain component. If we consider only variations in strain rate within a single slip plane, two end-member types of strain inhomogeneity can be recognized (Fig. 1). There may be gradients in the magnitude of the shear strain perpendicular to, or parallel to the slip direction. In the former case the complementary extra strain produced is a shear strain within the slip plane (a wrench shear), in the latter case the extra strain is a pure shear with extension or compression parallel to the slip direction. The two cases are similar, respectively, to the lateral and the frontal (or the rear) 'tips' (the edges of the region over which slip has occurred) of the thrusts or shear zones discussed by Coward & Potts (1983).

Coward & Potts and Sanderson (1982) discussed in detail the finite strain patterns expected at such 'tips'. Of equal importance in the production of finite structures in rocks is the interaction between the finite strain and anisotropy (e.g. Cobbold & Watkinson 1981). Rocks that have been deformed on a regional scale in a shear context generally show a strong foliation effectively parallel to the shear slip plane. If spatial variations in the strain rate develop late in the strain history, they will affect a rock with an already developed, strong planar fabric.

GEOMETRY OF FOLDS FORMED IN ZONES OF WRENCH SHEAR

A wrench shear strain in a thrust belt will be developed where there is a gradient in the shear strain rate in a direction perpendicular to the slip direction. The complementary extra strain developed is a shear strain with the same displacement direction, but on planes at right angles to the main strain (Fig. 2). It is therefore a horizontal shear strain on vertical planes, that is a wrench shear. The resultant strain formed on the addition of two simple shear strains is always itself a simple shear (e.g. Flinn 1979). The net strain in the case here, where a thrust and a wrench shear are added together, is a simple shear on inclined shear planes.

Certain simplifications need to be made before it is possible to predict the geometry of folds formed in such a shear regime. That folds form in such a strain regime has been shown in finite-element modelling of the development of small perturbations by Casey & Ridley

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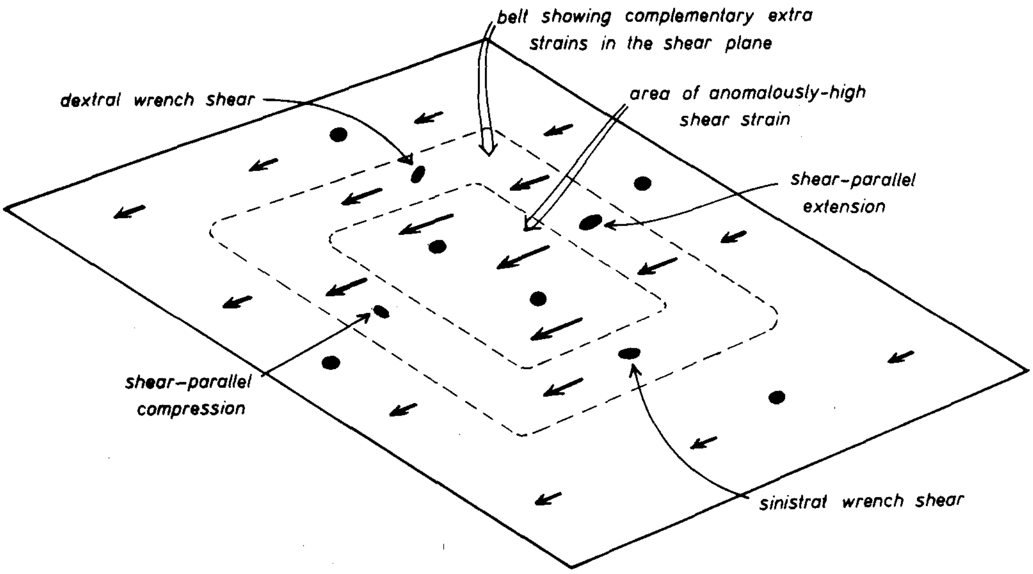

Fig. 1. A possible strain inhomogeneity on a slip plane in a shear zone. If the strain or displacement rate (represented by an arrow) is everywhere the same within the shear zone, the slip plane is everywhere a plane of no finite strain. If the displacement rate is not everywhere the same, finite strains develop within the slip plane (illustrated here by schematic strain ellipses) around each inhomogeneity. Where there is a gradient of shear strain parallel to the displacement direction, pure shears develop in the slip plane. Where there is a gradient of shear strain perpendicular to the displacement direction, shear strains develop in the shear plane.

(1984). It is assumed that the fold axial planes lie parallel to the flattening plane of the finite strain ellipsoid (the λ_1–λ_2 plane), the position of which can be calculated using the matrix methods of Flinn (1979). Fold axes will therefore lie on the intersection between this plane and the 'envelope' plane of the rock layering (Flinn 1962, Treagus & Treagus 1981). For the strain regime considered, this intersection is also the maximum extension direction within the plane of the layering; a direction which has also been suggested as that of fold axes on nucleation (see Treagus & Treagus 1981). As the shear displacement direction is parallel to the plane of the layering, the 'envelope' plane will not rotate during deformation, and the fold evolution can be traced simply by tracing the development of the finite-strain ellipsoid (Fig. 3).

Because the initial orientation of the fold axes is oblique to the shear slip plane in the combined thrust and wrench shear considered, they will be rotated towards the slip direction with progressive strain. Such a total strain may therefore produce a fabric with parallel fold hinges and a stretching lineation (Coward & Potts 1983). Figure 4 shows the angle between the predicted fold hinge direction and the shear displacement direction, and also between the fold hinge direction and the λ_1 axis of the finite strain ellipsoid for various strain states. If an obliquity between linear fabrics of 10° is considered indistinguishable in the field, it is seen that after a total shear strain of 10 and a wrench to thrust shear ratio of >0.5, fold hinges and the stretching lineation will appear

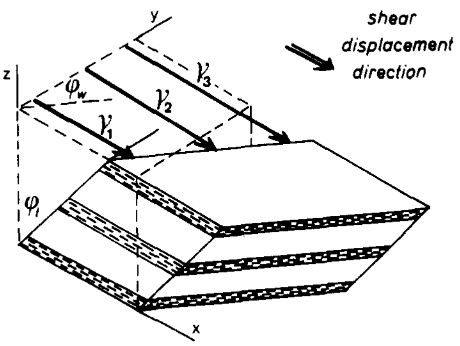

Fig. 2. Coordinate system for a combined wrench and thrust shear. A gradient in shear parallel to the layering (the 'xy' plane) with $\gamma_3 > \gamma_2 > \gamma_1$, produces a 'wrench shear' (γ_w) with shear planes parallel to the 'xz' plane. Both shears have the same displacement direction.

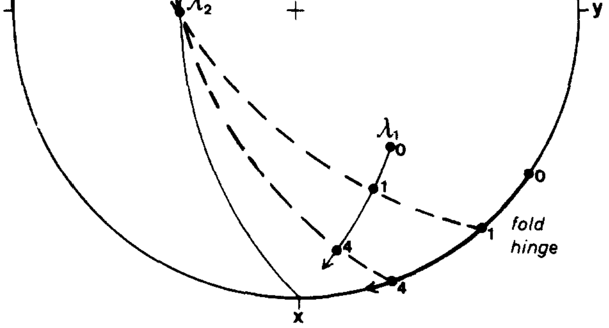

Fig. 3. Stereographic projection, showing the evolution of fold geometry with progressive strain (for the model assumed in this paper) under a fixed thrust to wrench shear ratio, in this case 1:1. The geometries for γ_{total} = 0, 1 and 4 are plotted. The fold axial plane is assumed to be parallel to the λ_1–λ_2 plane of finite strain. The fold axis lies on the intersection between this plane and the envelope plane of the layering, which remains horizontal.

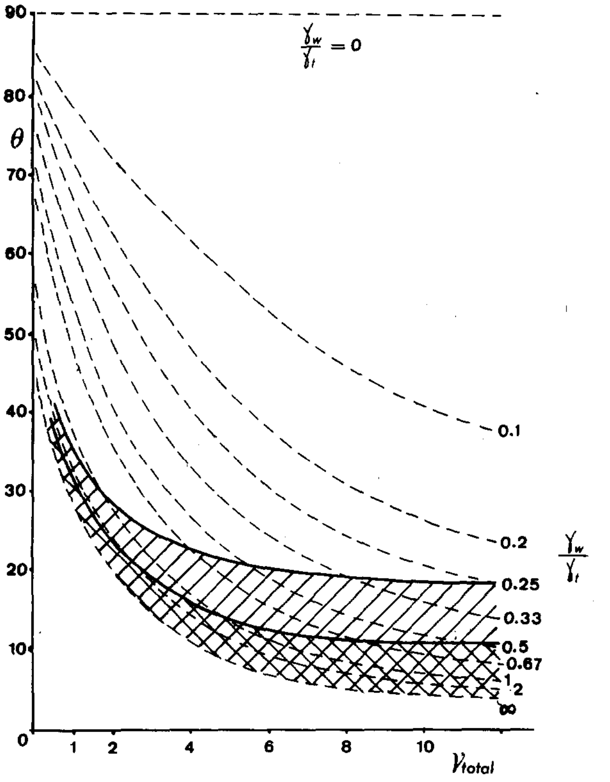

Fig. 4. The angle (θ) between fold hinges of the model folds and the shear slip direction, against strain state in terms of the total shear strain (γ_{total}) and the wrench to thrust shear ratio (γ_w/γ_t) (after Coward & Potts 1983). In the cross-hatched area the fold hinges will be orientated within 10° of the finite stretching direction, in the single-hatched region between 10 and 20°. The finite stretching direction is significantly oblique to the displacement direction at low total strains (Sanderson 1982).

parallel. The wrench to thrust shear ratio required to give this parallelism decreases with increasing total strain.

The orientation of the fold axial planes relative to the 'envelope' plane of the layering depends on the finite strain state. Figure 5 shows the states of combined wrench and thrust shear for which the fold axial planes will be at greater than 30° to this 'envelope' plane. The exact extent of this field is dependent on the assumption that folds form with axial planes parallel to the flattening plane. If folds initiate by buckling they will nucleate with axial planes perpendicular to the layering. For such a case (the shaded area of Fig. 5) the regime of upright, weakly asymmetric folds, is slightly enlarged (by approximately 3° parallel to the θ axis).

If Figs. 4 and 5 are considered together, it is seen that it is possible in thrust regimes to form (under different total strains and thrust to wrench shear ratios) folds with axes effectively parallel to the stretching lineation and slip direction that are either upright and weakly asymmetric or that are recumbent and strongly asymmetric. The formation of the latter type requires a higher total strain.

The geometrical analysis of the finite strain predicts the fold orientation, but not necessarily the fold tightness. The tightness of upright- to moderately-inclined folds formed in a strain regime in which wrench shear dominates over thrust shear (the shaded area of Fig. 5 at high total strains), is dependent on the exact mechanical partitioning of strain between homogeneous simple shear and buckling leading to folding. This is dependent

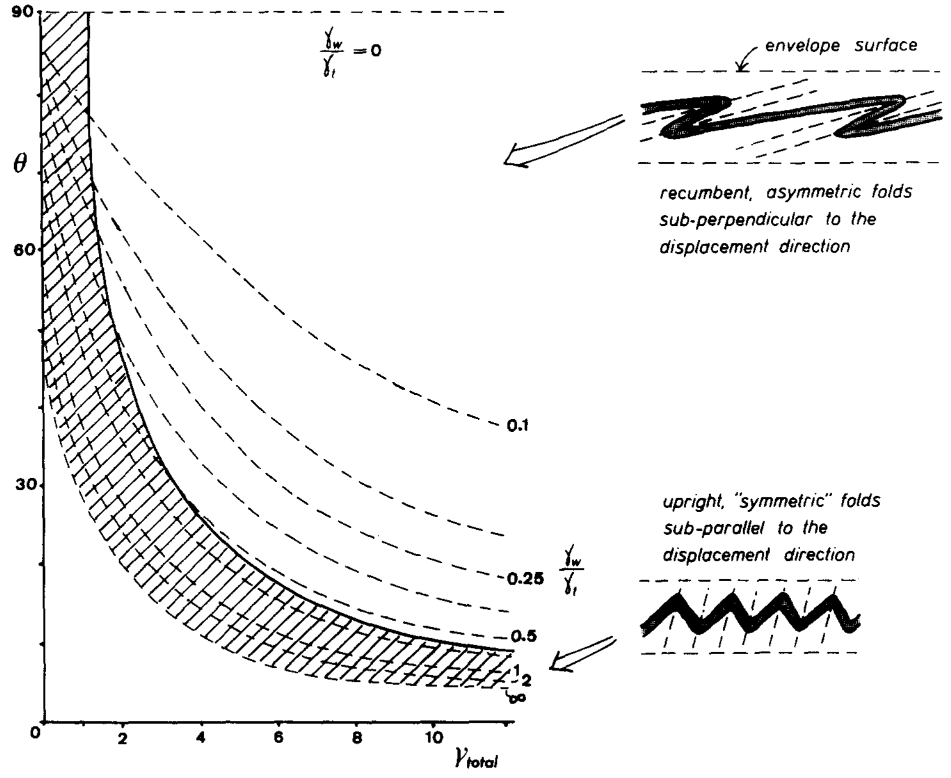

Fig. 5. As Fig. 4, but here showing the strain states for which the fold axial planes will be at greater than 30° to the trace of the original layering. The insets show the approximate fold geometry expected for two 'end-member' strain regimes.

on the material properties, as has been discussed by various authors for the case of folds formed under compression in pure shear regimes (e.g. Dietrich 1970, Hudleston & Stephansson 1973). Under certain conditions a high-magnitude wrench shear would be recorded by only relatively open, upright crenulations parallel to a stretching lineation.

EFFECT OF A PLANAR ANISOTROPY ON THE STRUCTURAL DEVELOPMENT

The analysis given in the preceding section is purely geometrical, treating the orientation of the folds and layering as passive markers of finite strain.

Consider, however, what will happen if different layers have different viscosities (e.g. a layered quartz–mica schist), or if there are planes of weakness parallel to the layering (as will be the case if the rock deforms on a microscopic scale in part by slip along the grain boundaries of aligned platy minerals, e.g. micas).

If the imposed strain is thrust shear parallel to the layering, strain will be concentrated in the weaker, lower-viscosity layers (Cobbold 1977). If, however, the strain is wrench shear, the rock is constrained to deform with an equal strain rate in the more- and the less-competent layers. For the general case of combined thrust and wrench shear, it can be considered that the two components are independently partitioned between the layers of different viscosity. The thrust shear will be concentrated in the lower-viscosity layers, and the more competent layers will be dominated by the wrench shear component (Fig. 6). In the hypothetical extreme case in which one set of layers has an infinite viscosity, these stronger layers will undergo wrench shear only.

Elongate minerals, quartz aggregates, or conglomerate clasts within the competent layers may experience a strain history significantly different from the bulk-rock strain. In the extreme case with layers of infinite viscosity contrast, the stretching lineation in the competent layers will be controlled only by the wrench shear component of the total strain. The orientation of the stretching lineation will therefore be given by the principal strain directions in the plane of the layering, rather than the λ_1 direction of the three-dimensional strain ellipsoid. In the general case, that is in any layered sequence with competency contrasts, the stretching lineation in the more competent layers will be more oblique to the displacement direction than predicted by the geometry of the bulk strain. The effect of this strain refraction on the orientation of folds is less clear. The fold orientation, especially if individual folds extend across several layers, will be a function of the combined response of competent and incompetent layers. Because of this, it is assumed that the fold orientation reflects the bulk strain. The presence of competency contrasts in a rock will therefore increase the likelihood of apparently parallel fold hinges and stretching lineations.

Figure 7 shows the relationship between the stretching lineation and fold hinge direction as would be seen in a layered sequence with infinite competency contrasts deformed in progressive strain with a constant specific wrench to thrust shear ratio, in this case 0.25. It is seen that the two lineations become effectively parallel after a wrench shear (γ_w) of between 1 and 2. If the shear displacement direction (Fig. 1) can be equated with the tectonic displacement direction of the regional deformation, this has potentially important consequences in the interpretation of structures in orogenic terrains. The orientation of folds in rocks which have suffered a

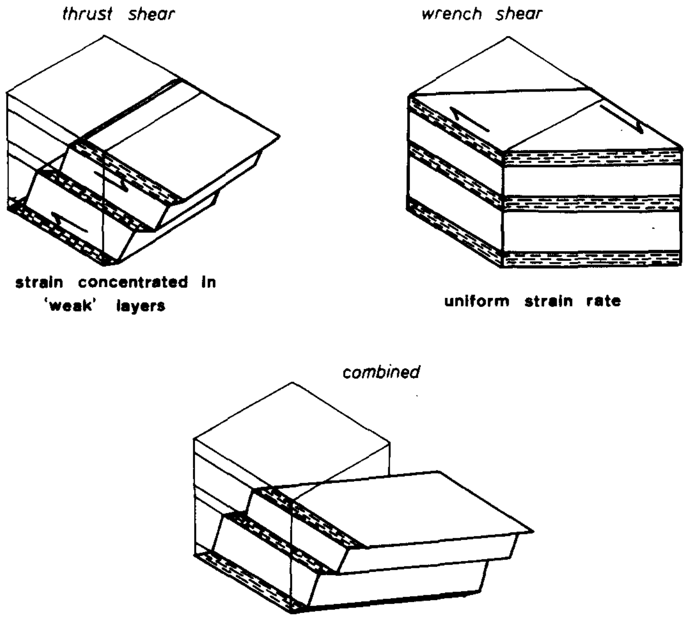

Fig. 6. Response of a rock with a planar anisotropy to different shear strains. Under combined thrust and wrench shear the wrench to thrust shear ratio relative to the bulk strain will be increased in the competent layers and decreased in the incompetent.

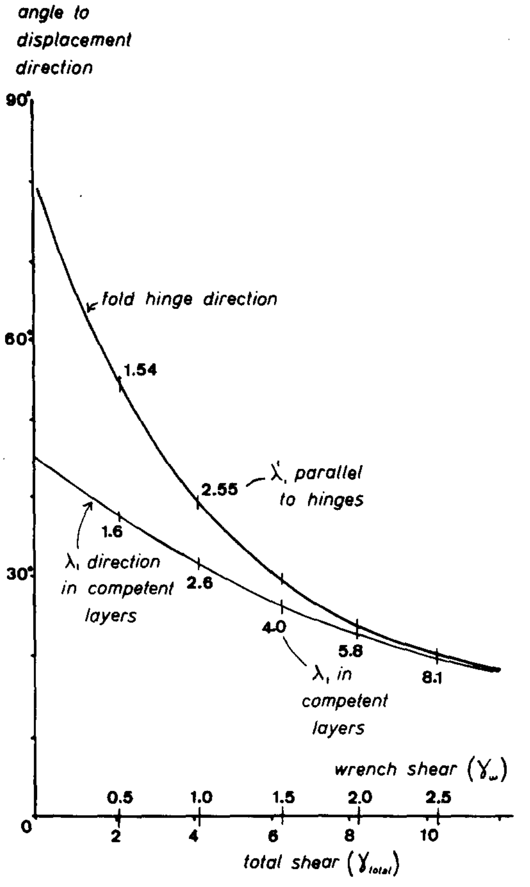

Fig. 7. Rotation of fold hinges towards the slip direction for a wrench to thrust shear ratio of 0.25, and the orientation of the finite stretching lineation that would be seen in the competent layers of a layered sequence of almost infinite competency contrast. Within these layers the finite strain would be given almost entirely by the wrench shear component of the total strain. In such a strain regime the bulk stretching direction always lies within 5° of the displacement direction.

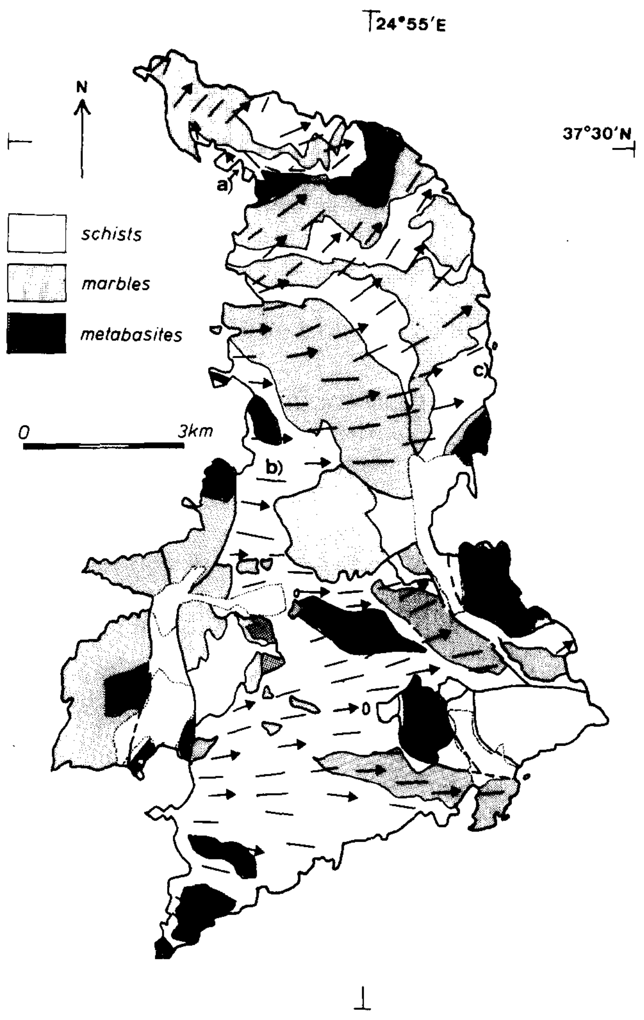

Fig. 8. Simplified geological map of Syros showing the trend of the dominant lineation. Each lineation mark represents the average of 10–20 field measurements. The dip of the lithology and schistosity is almost everywhere gentle or moderate to the north or northeast.

wrench shear (γ_w) of approximately 1.0 would be 45° oblique to the displacement direction, yet such rocks may show a marked hinge-parallel stretching lineation.

The likelihood that, because of these effects, linear markers do not reflect the bulk strain will depend on the mechanisms of rock deformation on the scale of each potential linear marker. Any foliated rock will have a mechanical anisotropy. If this anisotropy is related only to a layering, the linear markers would have to be embedded in the more viscous layers to have become orientated at a high angle to the displacement direction. If, however, the anisotropy is the result of the presence of continuous or semi-continuous discrete easy-slip horizons on a microscopic scale, any linear marker of finite dimensions will act as if embedded in a competent layer. The formation of a fabric with parallel fold axes and a stretching lineation seems strongly favoured in this latter case.

FOLD GEOMETRIES AND STRETCHING LINEATIONS FROM THE ISLAND OF SYROS, GREECE

The dominant lineation in the highly deformed, blueschist-facies rocks of Syros, Greece, shows systematic variations in trend over distances of a few kilometres (Fig. 8). Because the foliation shows a fairly constantly directed moderate dip, these variations can be analysed simply in terms of the lineation azimuth. A full analysis of the variations in the fabric is outside the scope of this paper. The important point here, is that this is an example of a deformed body of rock in which the stretching lineation appears not to be everywhere parallel to the shear-displacement direction.

The lineation is everywhere parallel to the hinges of small- to intermediate-scale intrafolial folds. Over parts of the island, but not everywhere, it shows characteristics that would normally be ascribed to a stretching lineation. It is seen that there is a systematic correlation between the lineation trend and whether the dominant lineation appears as a stretching lineation or not.

The variations in fabric orientation and composition have been interpreted as the result of deformation in a thrust shear regime with a spatially varying additional wrench shear. The 'best fit' thrust displacement direction is 130 ± 10° (Ridley 1982). Structures are clearest in quartz-rich semipelites: quartz–phengite–glaucophane schists with a pervasive quartz–mica layering on a centimetric scale. These form about half the sequence. The small- and medium-scale folds always fold an already-developed, layer-parallel mica fabric, that is the folds conform to the situation considered above in that they were developed in rocks with a strong planar anisotropy. The dominant lineation can be interpreted as a crenulation lineation, or as an intersection lineation between the earlier planar fabric and the axial planes of the folds, even though no axial-planar mineral fabric is developed. For the purpose of this discussion the fabrics from three areas will be described, where, respectively, the lineation trends at 040–060°, 120–130° and 090–100°, that is, at right angles, approximately parallel to, and oblique to the proposed thrust-shear displacement direction.

Where the lineation trend is approximately NE no obviously consistent stretching lineation is developed. In some lithologies a mineral lineation is developed at a high angle to the fold hinges, but this is relatively rare. Folds are sporadically developed, generally gently inclined or recumbent, and show a constant Z asymmetry when viewed to the northeast. These folds have characteristics similar to those described from many shear zones (e.g. Carreras *et al.* 1977). They are regarded as being the result, either of the influence of local heterogeneities in the rock disturbing layer-parallel shear, or of the imposed strain, including a component of shortening parallel to the shear-displacement direction (Coward & Potts 1983). The strain regime inferred (cf. Figs. 4 and 5) for this locality is of a large, but undetermined, thrust shear ($\gamma_t > 5$), and effectively no wrench shear ($\gamma_w/\gamma_t < 0.05$).

Where the lineation trends approximately SE the fold geometry is completely different. Small-scale (<1 cm wavelength) crenulations of the mica fabric are pervasive. These crenulations are generally upright to moderately inclined, and only weakly asymmetric. Fold axis orientations are constant over large areas, and there is a strong, hinge-parallel stretching lineation. Strain shadows (of granular, possibly recrystallized quartz) about garnet porphyroblasts may be elongate by up to several times the porphyroblast diameter. The strain regime inferred is of a high wrench- to thrust-shear ratio (>1), and total shear (γ_{total}) > 8–10.

Where the lineation has an intermediate, easterly trend, the structures are again different. Folds are recumbent or gently inclined but differ from those in the areas where they trend NE in that they are more pervasively developed, and show markedly cylindrical, straight, and often rodded hinges. In these areas there is a marked fold–hinge-parallel stretching lineation. From the fold geometry, the strain regime inferred for these areas is of a total strain (γ_{total}) > 5 and a low, but significant wrench to thrust shear ratio (0.1–0.3).

DISCUSSION

The three fabric types discussed are illustrated schematically in Fig. 9. There is a range of about 40–50° of fold-hinge orientations over which the fold hinges are parallel to the apparent stretching lineation in the rock; at one end of this range the folds are symmetric, at the other end strongly asymmetric. These differences in the details of the style and geometry of the folds where the lineation trends in different orientations suggest that the strain regimes forming the fabric were different, and not, for instance, that the fabric was locally reorientated by a second phase of deformation.

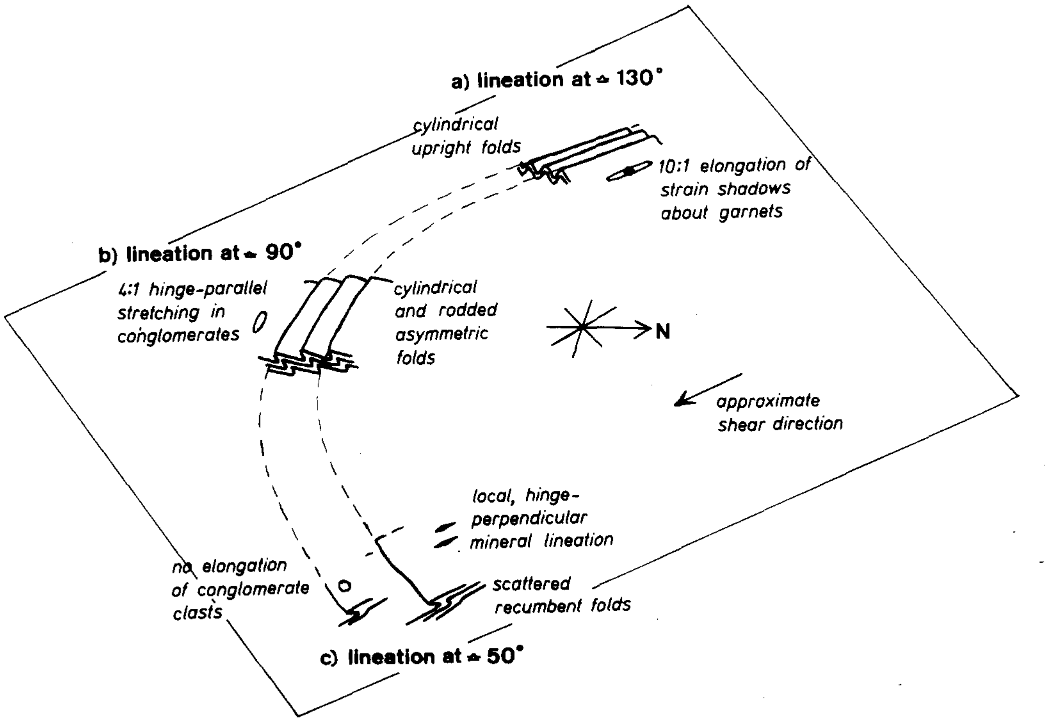

Fig. 9. Summary of the different fabrics seen in the areas of different lineation trend. The approximate spatial distribution of fabric types on Syros (cf. Fig. 8) is as shown in this diagram. The inferred shear displacement is towards the southeast. The diagram represents, schematically, an area approximately 2 km across.

There are two possible explanations for spatial variations of fabric type of the kind illustrated in Fig. 9.

(1) The fabric everywhere reflects the local bulk strain, and the variation in fabric is due to inhomogeneities in the strain regime. This possibility is ruled out for Syros because of problems of strain compatibility in any model which also explains the distribution of fabric types. No history, for instance, of the type considered by Milton & Chapman (1979) or Ramsay (1982) (that the fabric variations are the result of the superposition of a variable intensity tectonic strain on an original sedimentary fabric) has been found that reproduces all the features of the fabrics; the fold orientation and asymmetry, and the orientation and strength of the implied stretching.

(2) The fabric at each point reflects a mechanical interaction between the strain and the planar anisotropy of the rocks. If this is assumed, the variations in fabrics can be explained as the result of deformation in a strain field with variable intensity wrench shear superimposed on layer-parallel thrust shear. Consider two features. The $\lambda_1:\lambda_2$ axial ratio of the quartz clasts at locality 'b' (Fig. 9) is approximately 4:1. It is not known what the original shape of the clasts was. This is, however, the approximate elongation expected parallel to the fold hinges for a total wrench shear of 1–1.2, as is required to give the local fold orientation in combined thrust and wrench shear. At relatively high total shear strains ($\gamma_{\text{total}} > 5$), the fold hinge orientation is effectively a function only of the wrench shear component of the total strain. The clast shape is therefore consistent with a model in which, because of the rock planar anisotropy, the clast was deformed essentially by the wrench shear component of the total shear alone.

The extreme cylindricity, and occasional rodding of fold hinges at the same locality can be explained similarly. Experiments on folding in plane strain with the axis of no change perpendicular to the layering (Watkinson 1975) have produced extremely cylindrical folds, as the fold-axis-parallel extension dampens out any initial irregularities. In the strain regime proposed, there will be a significant real extension parallel to the fold axes. These will, in general, be orientated between λ_1 and λ_2.

CONCLUSIONS

A rock deformed by a combination of thrust shear parallel to a layering and wrench shear may show a fabric with parallel stretching lineations and fold axes. If the wrench-shear to thrust-shear ratio is high, the folds may appear as upright crenulations of the fabric. If this ratio is lower, and if the rock is anisotropic with layers weak in shear parallel to the layering, folds with an apparent parallel stretching lineation may form at a significant angle to the shear transport direction.

The variations in tectonic fabric in quartz–mica schists from Syros, Greece, cannot be explained by any simple history of strain superimposition if it is assumed that the fabrics strictly reflect the bulk strain. It is suggested that this is an example where the rock anisotropy has affected the fabrics produced, and consequently fold-hinge-parallel stretching lineations are orientated at up to about 40° to the bulk-rock extension direction.

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