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The role of discrete heterogeneities and linear fabrics in the formation of crenulations

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Abstract—The fabric elements in pelitic rocks of Brioverian age in South Finistere (France) consist of three main components; planar, linear and discrete, corresponding to schistosity, elongate mineral alignment and porphyroblast distribution respectively. Each component plays a role in the initiation, propagation and evolution of crenulations which deform the planar anisotropy.

Strain associated with the initiation of crenulation is heterogeneous on the thin section scale, producing spatially associated, contemporaneous microshears and kink-structures. The influence of porphyroblasts becomes increasingly evident as crenulation develops and microshearing becomes the dominant mode of deformation. Linear fabric appears to influence the orientation of crenulation structures and slip directions on microshear planes.

INTRODUCTION

CRENULATIONS are commonly observed structures in highly anisotropic rocks such as slates, schists and mylonites. Numerous descriptions exist in the literature (reviews in Cosgrove 1976, Gray 1977a) but few examine the initiation and subsequent evolution of crenulation in natural rocks (cf. Marlow & Etheridge 1977). Furthermore, studies of crenulations have concentrated on physical, theoretical and natural materials dominated by a simple planar anisotropy (Etheridge 1973, Cosgrove 1976, Gray 1977a, b, 1978, Marlow & Etheridge 1977). However, it is a common observation that deformation structures (buckles, kinks, shears) are related to linear structures and discrete perturbations within the otherwise planar anisotropy of deforming materials (e.g. Willis 1893, Biot 1965, Cobbold *et al.* 1971, Watkinson & Cobbold 1973).

A variety of quite distinct microstructures have been commonly classed within the all embracing term crenulation. These are divided into discrete and zonal types (Gray 1977a, b) with a normal or reverse sense of relative displacement (e.g. Cosgrove 1976). Reverse sense zonal structures are kink bands, whereas normal sense ones are simple microshears (Cobbold *et al.* 1971, Etheridge 1973). Zonal microstructures may be modified by pressure solution giving rise to discrete planes enriched in insoluble residues (Cosgrove 1976, Gray 1977b) and alternating quartz-rich/quartz-poor domains aligned parallel to the planar element of the crenulation structure (e.g. Williams 1972, Marlow & Etheridge 1977).

The crenulation in the Brioverian rocks of South Finistere (France) is developed in slates and schists with planar, linear and discrete fabric elements. These elements correspond to three physical structures in the rock; (a) schistosity (S_1), (b) a strong penetrative mineral alignment lineation (L_1), (c) abundant millimetric to centimetric porphyroblasts of biotite, andalusite or staurolite. Each of these elements has played a role in the formation of the crenulation. Crenulation structures initiate either as kink bands or as microshears which may be spatially associated on the millimetric scale. They are symmetrically or asymmetrically disposed with respect to the initial orientation of the planar anisotropy which they deform. Initial crenulation structures are of zonal type. Discrete structures, that is pressure solution seams, only appear towards the final stages of development. The initiation, propagation and subsequent development of the crenulation are controlled to varying degrees by the presence of porphyroblasts. This is especially evident where the latter have rotated relative to their matrix.

This paper attempts to examine the following questions. How do crenulations initiate, and what is the sequence leading to a well developed crenulation? How are crenulation initiation and development influenced by linear fabrics and discrete heterogeneities?

GEOLOGICAL SETTING

The material examined was collected from an area of fine grained, late Proterozoic (Brioverian) metasediments located between Quimper and Scaer, South Finistere (Fig. 1). To the south, the Brioverian has been intruded by the 330 Ma (Vidal 1973) Hercynian leucogranite belt. These granites were emplaced during movement along a major ESE trending dextral wrench (Cogné 1957), the South Armorican Shear Zone (Berthé *et al.* 1979). Furthermore, the Brioverian was deformed synchronously with the granite emplacement (Le Corre 1977, Hanmer 1978). The deformed Brioverian carries an upright (S_1) schistosity (Fig. 2a) with a well developed, gently plunging (L_1) mineral alignment lineation (Fig. 2b). S_1 is crenulated such that the crenulation is always co-axial with L_1, whatever the orientation of the latter. Syntectonic metamorphic growth of biotite, andalusite and staurolite (0.2 – 4 cm) was probably provoked by granite emplacement in the

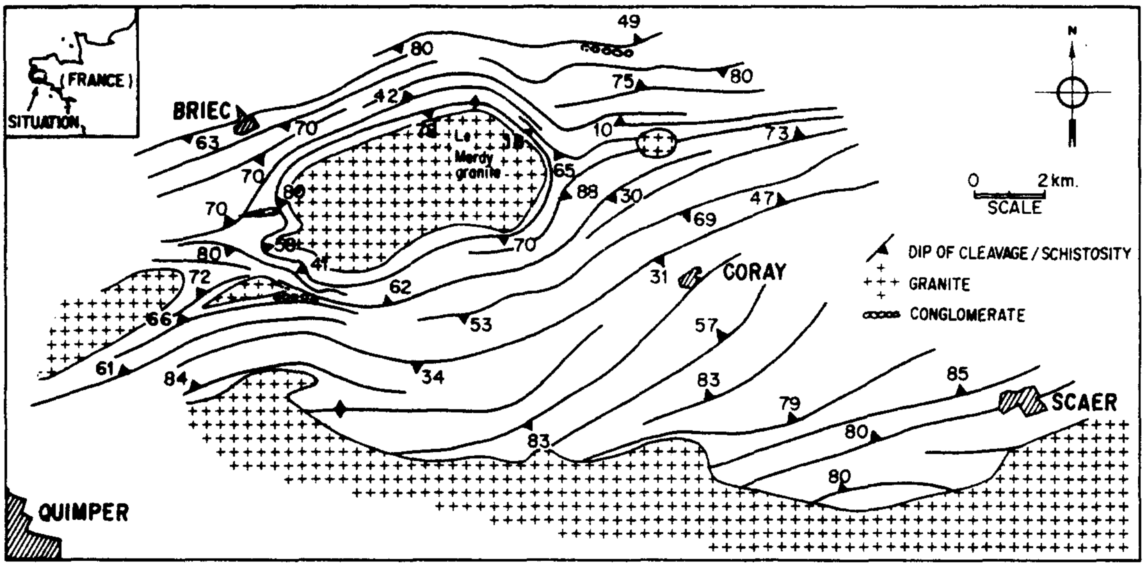

Fig. 1. Structural map of Brioverian metasediments intruded by Hercynian leucogranites in S. W. Brittany. The trend of the S_1 schistosity in the Brioverian is indicated.

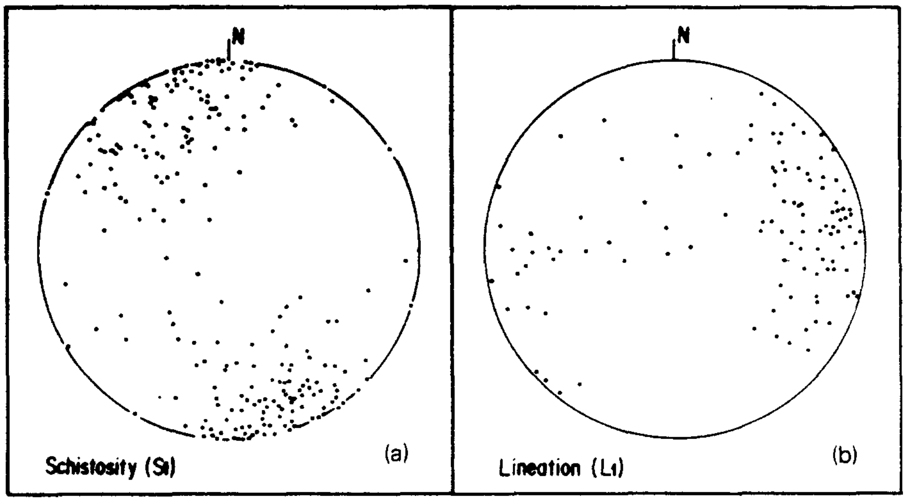

Fig. 2. (a) Poles to schistosity (S_1) in the Brioverian metasediments. (b) Mineral alignment stretching lineation (L_1).

Brioverian and continued from the early stages of S_1 development through S_1 to post-crenulation formation.

PROGRESSIVE CRENULATION DEVELOPMENT

Due to poor exposure and lithological variation within the Brioverian, it is not possible to examine the crenulation development as a function of an observable crenulation gradient. However, the consistency of microstructural relationships in the 200 thin sections examined, suggests a model for the progressive development of mature crenulation structures. The inferred sequence is presented here in three arbitrarily defined stages (Fig. 3); initiation, advanced and mature. Thin sections were cut both perpendicular and parallel to L_1. Angular relationships quoted are those observed in the *YZ* plane (Fig. 4).

Initiation

The initiation stage is visible only in the most pelitic lithologies, especially in quartz-free chlorite/mica layers. A superficial examination reveals only incipient undulations in the S_1 fabric, but careful observation of mica elongation or extinction directions indicates a systematic asymmetry in the undulations (Fig. 5). Both incipient kink bands (Figs. 5a & c) and incipient microshears (Figs. 5b & c) may be present, even in a single thin section. Of special interest are the following combinations: (1) conjugate or single kink-bands at 45° to S_1 plus conjugate or single microshears at < 45° to S_1 (Fig. 5c); (2) microshears at < 45° to S_1 plus microshears at > 45° to S_1 (Fig. 5a). In type (1) combinations there is always an inverse relationship between the relative displacements across kink bands and similarly inclined microshears (Fig. 6). Note that there is generally a spatial

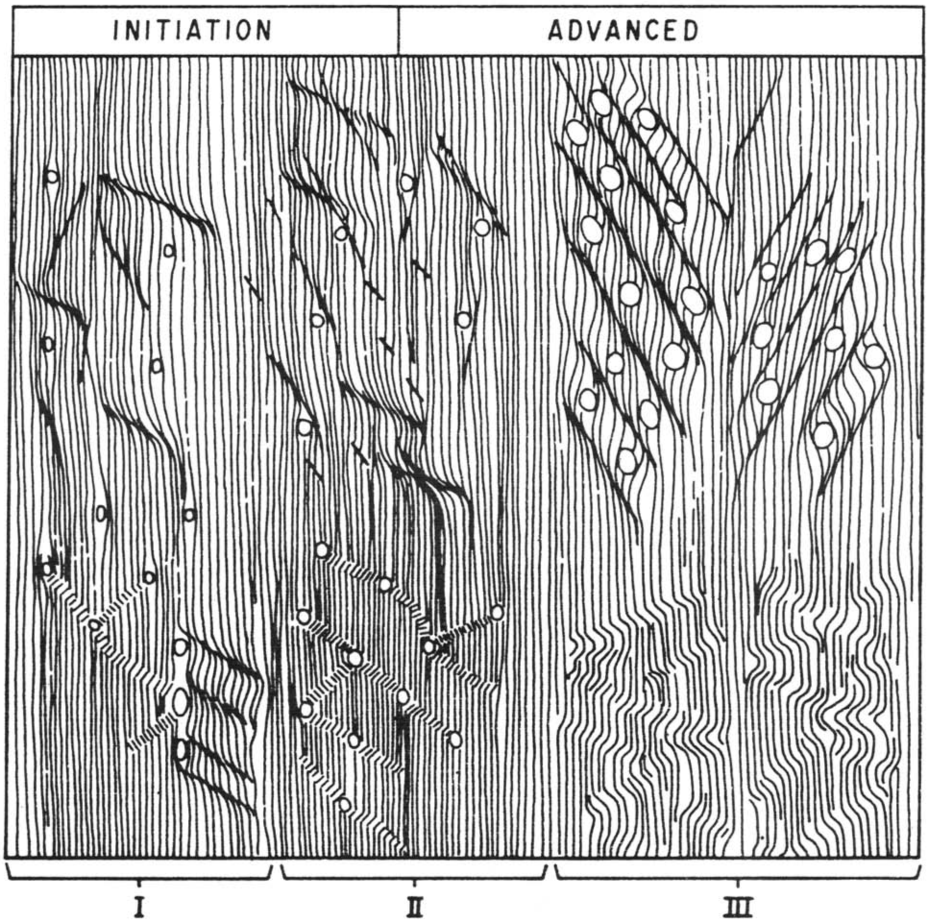

Fig. 3. Schematic summary of crenulation development. (I) Heterogeneous, biomodal initiation of crenulation with kink band and microshear (at < 45° and > 45° to S_1) formation. Note that kinks are more closely related to the presence of porphyroblasts than are microshears. (II) Microdomains of I increase in size with clear macroscopic spatial separation of microshearing (top) and kink modes (bottom). Microshears at < 45° and > 45° to S_1 develop synchronously, those at < 45° to S_1 and adjacent to porphyroblasts are preferentially selected. (III) Microshear location and orientation continues to be influenced by presence of porphyroblasts even when the density of shear planes is elevated. Metamorphic differentiation active. As more S_1 surfaces are incorporated into the microfolds (bottom) the influence of porphyroblasts wanes.

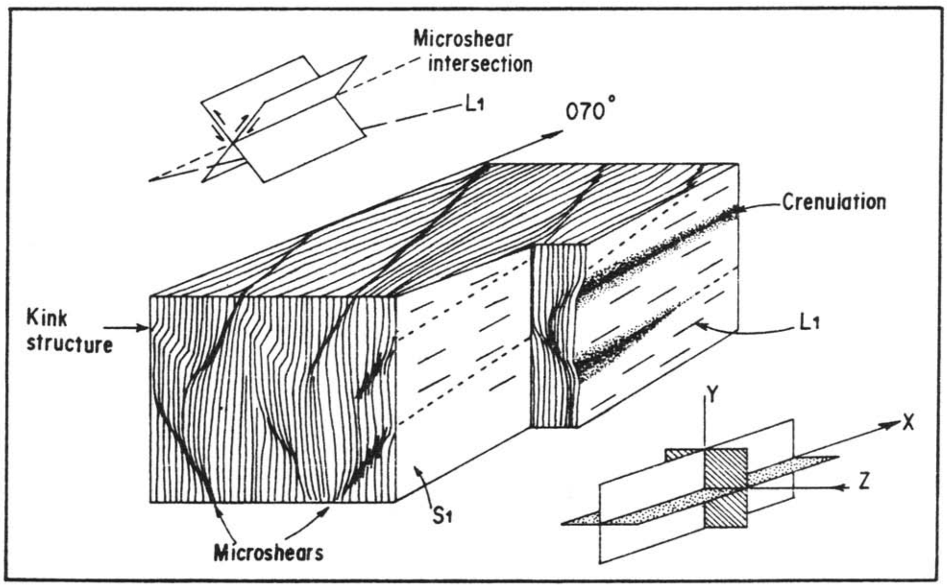

Fig. 4. Schematic diagram illustrating vertical, ENE trending S_1 cleavage surfaces bearing a subhorizontal mineral alignment lineation (L_1). Orientated thin sections were cut parallel to the *XZ* and *YZ* planes. Kink structures are most clearly visible in *YZ* sections. Angles cited in text between planar elements of kinks and microshears and S_1 are measured in the *YZ* plane.

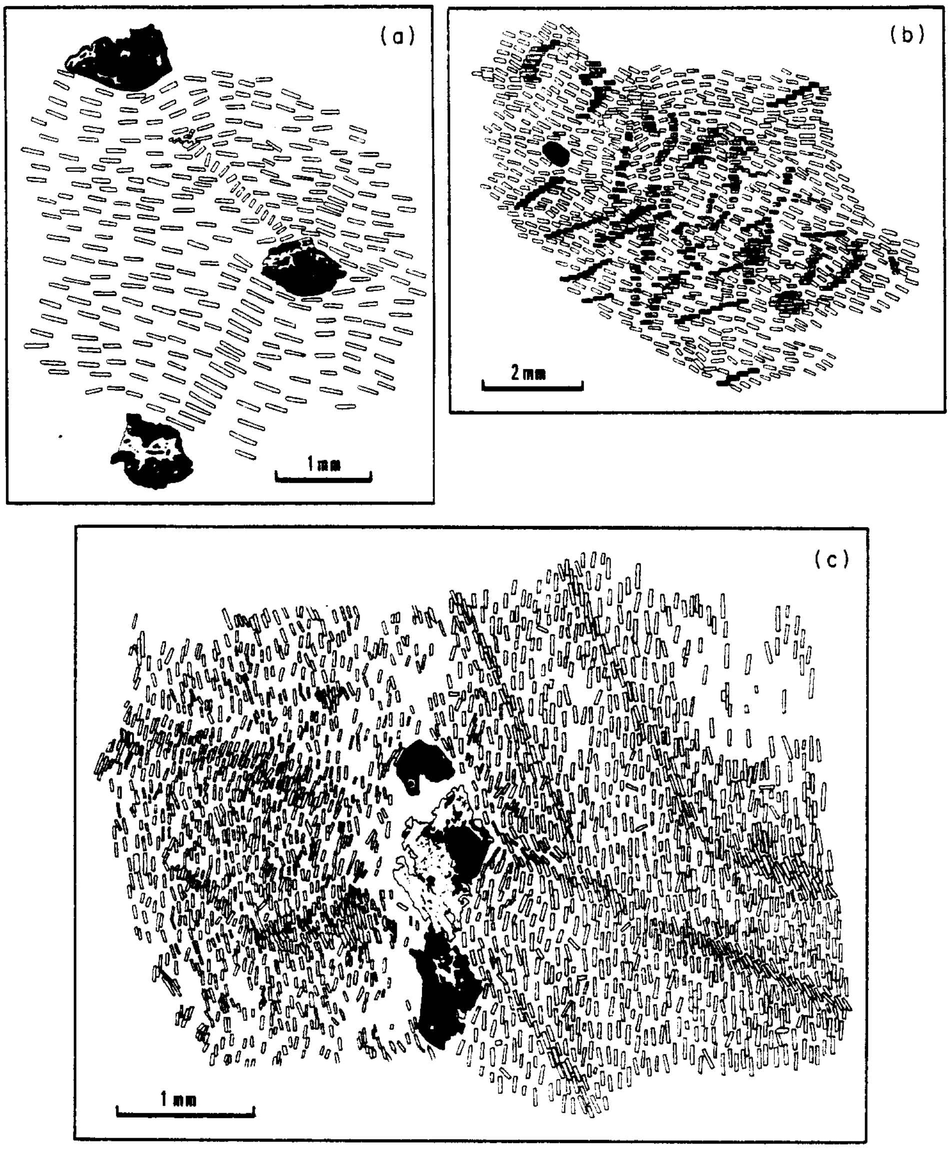

Fig. 5. Initiation stage crenulation microstructures. (a) Initiation of conjugate kink bands controlled by porphyroblast distribution. (b) Contemporaneous initiation of microshears at < 45° (solid) and > 45° (grey) to S_1 micas, which mutually intersect without systematic displacement or attenuation of the one by the other. (c) Conjugate kink bands initiating on porphyroblast edge (left) and microshears at < 45° and > 45° to S_1 (right). An alignment of 3 porphyroblasts separates the kink and microshear domains (tracings from photomicrographs).

separation of the kink bands and microshears (Fig. 5c). In type (2) combinations, microshears at both > 45° and < 45° to S_1 mutually interfere, but neither set systematically displaces or attenuates the other (Fig. 5b).

The kink bands are clearly seen to initiate on porphyroblast edges at points where the tangent to the edge makes a moderate angle with the non-crenulated S_1 direction (Figs. 5a & c). Where continuous inclusion trails indicate a systematic relative rotation between porphyroblast and matrix, the relative displacements on both the associated kink bands and microshears show a systematic relationship (Fig. 6) to the porphyroblast rotation (in sections at an high angle to the axis of rotation). The crenulation structures are therefore asymmetrical with respect to S_1. Where the porphyroblasts have not rotated with respect to the matrix, the microstructures are conjugate, that is either or both a set of conjugate kinks or a set of conjugate microshears may develop, or both (Fig. 7).

These observations do not allow the timing of the initiation of kink bands to be separated from that of microshears. Similarly it is not possible to separate the initiation times of crenulation structures at < 45° to S_1

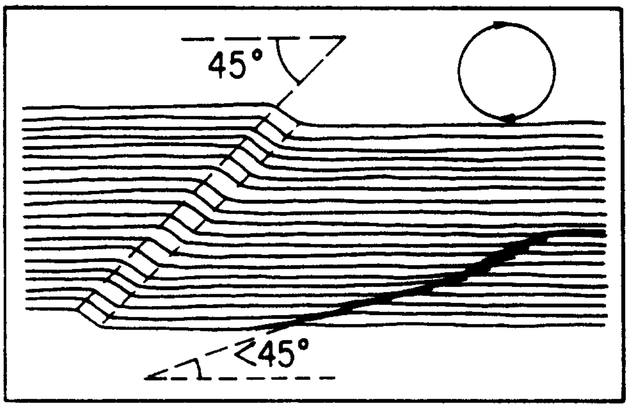

Fig. 6. Schematic representation of the most common relative displacement and angular relationships between kink bands, microshears (at < 45° to S_1) and apparent rotation of porphyroblasts (circle) adjacent to either or both of these microstructures.

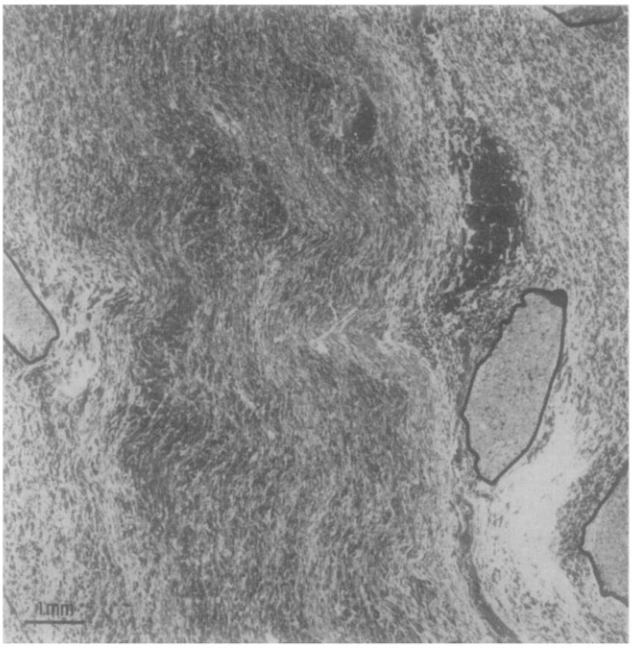

Fig. 7. Initiation to advanced stage symmetrical conjugate kinks. Note their rounded profile. A quartz vein (right) is folded such that culminations correspond to the nearby presence of porphyroblasts (bold outline). Kinks propagate from culminations towards a neighbouring porphyroblast (left). A marked chevron is developed (centre). The axial plane of the chevron lies along the straight-line join between two porphyroblasts. The black patch is an inflated part of quartz vein. (Reverse contact print.)

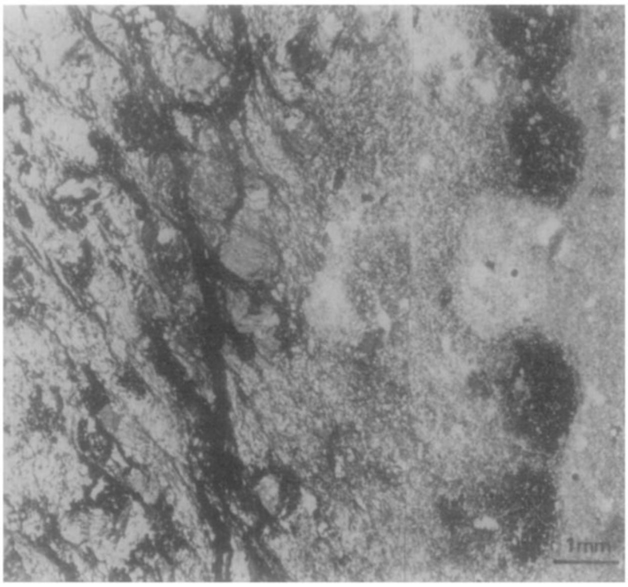

Fig. 8. Biotites concentrated in S_1-parallel band bounded by homogeneous layers (black patches to right are stains). Initiation to advanced stage microshears only develop within the porphyroblast bearing layer. (Reverse contact print.)

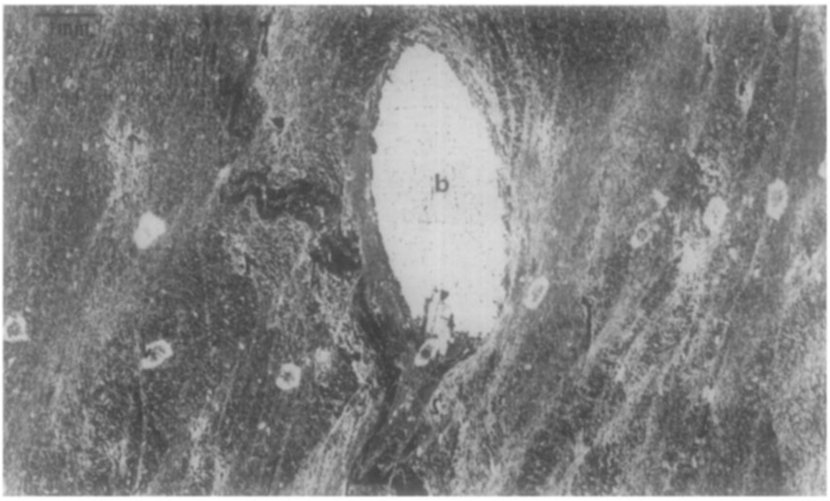

Fig. 9. Advanced stage microshears at < 45° (thin bands) and > 45° (wide bands) to S_1. The former may be attenuated or deflected (bottom left) or cut straight across the latter (right). Note the mild differentiation into mica rich and quartz rich zones, the latter forming the intershear spaces. b—biotite. S_1 slopes towards bottom right. (Reverse contact print.)

Fig. 10. Advanced stage asymmetrical microfolds of subangular to rounded profile. The folds initiate directly on porphyroblasts (bold outlines). Propagation is favoured in the space between suitably orientated porphyroblasts. Note the absence of microfolding outside of this propagation zone (top right). (Reverse contact print.)

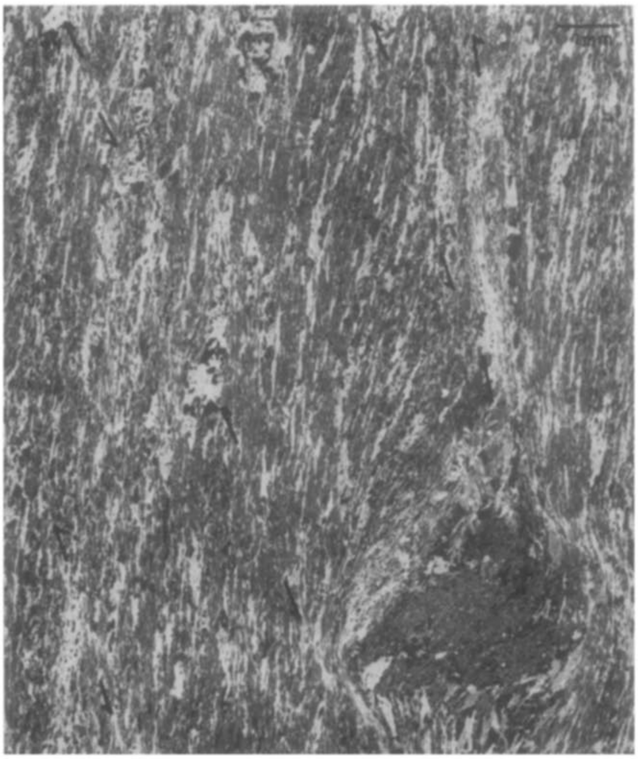

Fig. 11. Microshears of initiation stage aspect at < 45° to S, (arrows left and centre). The microshear adjacent to the relatively rotated, inclusion bearing porphyroblast (left) has accommodated anomalously greater strain and is of advanced stage aspect. (Reverse contact print.)

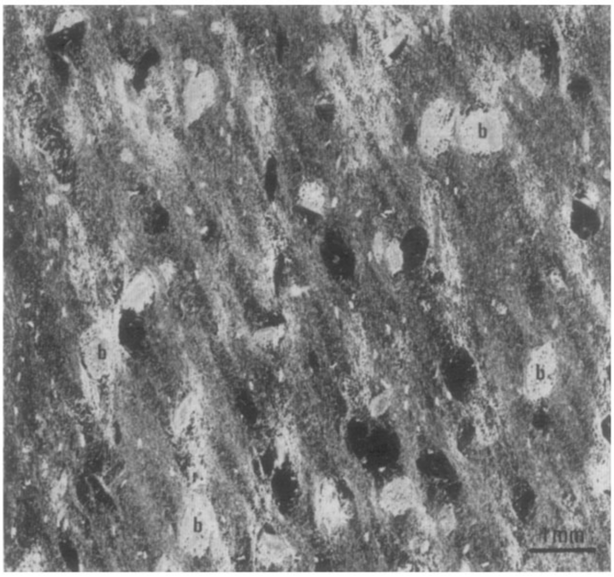

Fig. 12. Well advanced asymmetric microshears with developing micarich/quartz-rich domains corresponding to the microshears and intershear zones. Biotite-b and discrete quartz agregates (dark grey) are systematically sited within the quartz rich zones. Quartz-rich domains pass systematically from one porphyroblast to the next suitably located quartz or biotite grain. (Reverse contact print.)

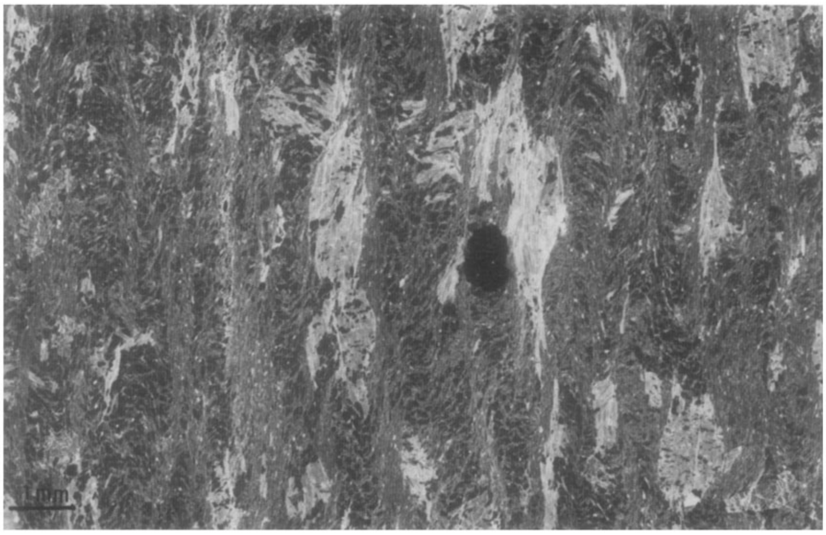

Fig. 13. Mature crenulation. Moderate to tight asymmetric microfolding of S_1 accompanied by marked metamorphic differentiation of the limb and hinge regions. Note the buckling of S_1 within the quartz-rich domains and the location of deformed biotites in the mica-rich domains. The initial quartz-rich domains were sited on the biotite porphyroblasts which have subsequently been incorporated into the mica-rich domains and deformed. (Reverse contact print.)

from those at > 45° to the same. I would therefore suggest that they all initiated more or less simultaneously in a given microscopic volume of rock.

Advanced stage

At this stage a relationship is established between the initiation and further development of microshears and porphyroblast distribution. In Fig. 8, microshears are confined to a microband which is parallel to S_1 and within which biotite porphyroblasts are present, whereas both porphyroblasts and microshears are absent in the remainder of the thin section. Also note that type (1) and (2) combinations of microstructure are less common than in the initiation stage. The term kink is avoided at this stage since the rounded class 2 (Ramsay 1967, p. 367) microfold morphology of the individual structures commonly does not allow one to distinguish between initial kink bands now modified by pressure solution effects and structures resulting from the development of initial microshears. Individual thin sections contain either microfolds or recognizable microshears at < 45° or > 45° to S_1. Where both types of microshear are observed, neither set systematically displaces the other, implying contemporaneous development from initiation through to the advanced stage (Fig. 9). The spatial relationship of microfolding to the presence and distribution of porphyroblasts remains evident (Fig. 10). Although the initiation of microshears shows little relation to the presence of porphyroblasts, the preferential development of selected microshears in close proximity to relatively rotated porphyroblasts becomes quite evident at this stage (Fig. 11).

This stage is further characterized by the development of quartz-rich and mica-rich domains. The latter, composed of muscovite, biotite and chlorite, correspond to the microshear zones and the long limbs of asymmetrical microfolds. Where the density of crenulations is high, the quartz-rich domains correspond to either microfold hinge-zones and short limbs, or to zones lying between adjacent microshears. Moreover, the quartz-rich domains are generally sited on porphyroblasts whereas the mica domains lie tangentially between them (Fig. 12).

Mature stage

Here the observations correspond closely to detailed descriptions by Marlow & Etheridge (1977) of similar rocks. A single type of crenulation microstructure is visible, comprising a set of symmetrical or asymmetrical, tight to isoclinal microfolds deforming *all* the S_1 schistosity of any given thin section. The wavelength and orientation of the crenulation may partially conserve the spatial relationship to porphyroblast distribution noted in the preceeding stages (Fig. 13). The separation into domains, first developed during the advanced stage, is the dominant feature of the microstructure, with quartz and mica domains being of equal volumetric importance. The individual mica laths are always oblique (> 5°) to the microfold axial planes and domain boundaries. Micas in the quartz domains may still mark a relict S_1 fabric but are also commonly decussate.

Effect of a linear fabric component

An L/S fabric presents least resistance to folding when the fold axes are coaxial to the linear component. The role of the linear fabric is illustrated in Fig. 14. The microshear planes have a monoclinic symmetry with respect to the S_1 cleavage and the L_1 lineation. As a result of differential movement along and deflection of S_1 into the shear planes, the S_1 fabric in the intermicroshear spaces is folded. In a planar anisotropic material the resultant fold axes are parallel to the intersection of the shear planes and the deforming surfaces (Ramsay 1962). Here, where a strong linear fabric element is added to the planar component (L/S), the fold

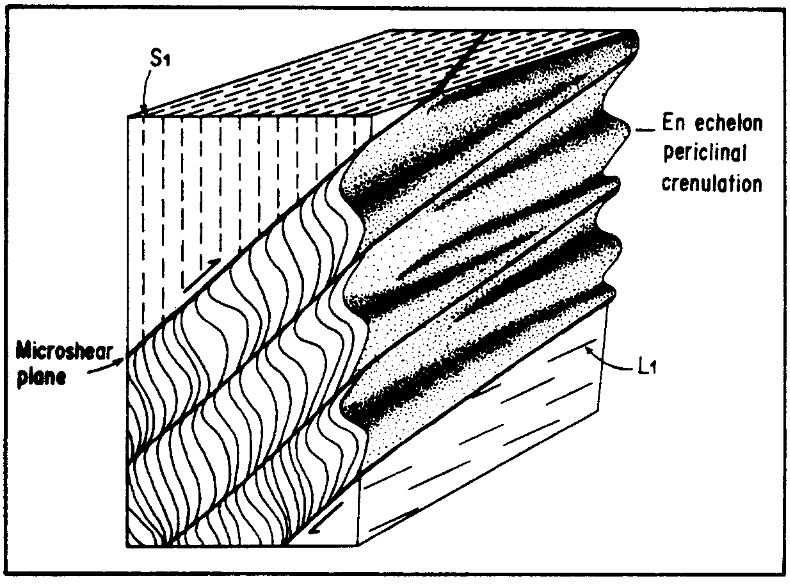

Fig. 14. The relationship between the orientation of microshear planes, linear anisotropy and crenulation axes (see text for details).

axes are oblique to the shear plane/cleavage intersection and parallel to the linear fabric. Therefore the role of the linear fabric is to provide a direction of least resistance to flexuring in a layer-parallel slip mode, and hence refract the local strains.

DISCUSSION

Mature crenulations bear a superficial resemblance to each other and this resemblance may lead to incorrect inferences regarding their modes of formation. The variable nature of crenulation initiation within a limited volume of rock and the final production of fold-like structures by the dominant operation of microshears, underline this statement. The apparent division of the thin section area into domains of kink band and microshear initiation structures indicates the co-existence of regions of layer-parallel compression (Ramsay 1962, Paterson & Weiss 1962, 1966, Donath 1968, Johnson 1970, Cobbold *et al.* 1971, Gay & Weiss 1974) and of layer normal compression (Cobbold *et al.* 1971, 1971, Etheridge 1973) at a very small scale.

There is clearly a problem posed by the close juxtaposition of the two types of initiation stage domain. However, the co-existence of the domains shows that deformation was heterogeneous on the thin section scale during crenulation initiation and it is noteworthy that in some examples porphyroblasts lie along the domain boundaries, though this is not always evident. It may be possible to investigate this problem further by means of physical models containing discrete heterogeneities. Such experiments are in preparation.

Although most of the illustrations in this paper show single sets of microshears, it must be emphasized that these structures are conjugate above the thin section scale. In many published studies, with the exception of Watkinson & Cobbold (1973) and Choukroune & Lagarde (1977), the axis of rotation and the intersection of conjugate shear planes are found to lie parallel to the intermediate finite strain axis (e.g. Ramsay & Graham 1970). However most of these studies deal only with planar anisotropy. Watkinson & Cobbold (1973) report plane strain experiments deforming linear–planar fabrics. The resulting microshears formed a tetrahedral pattern composed of two families of conjugate shears. I suggest that a well developed linear fabric will induce a marked direction of least resistance to slip and may favour the conjugate set whose intersection is closest to the lineation.

CONCLUSIONS

The development of crenulations in natural rocks may be influenced by three fabric elements in the deforming material; planar, linear and discrete, corresponding to cleavage, penetrative mineral alignment and porphyroblasts (or large grains) respectively.

The influence exerted by discrete heterogeneities encompasses: (1) spatial control over initiation and propagation of crenulation microstructures and crenulation spacing (wavelength); (b) a possible, but so far inexplicable, role in the origin and separation of initiation stage domains of layer-parallel and layer-normal compression.

The influence of linear fabrics encompasses: (a) control over the orientation of conjugate shear planes; (b) strain refraction within inter-shear plane spaces.

Crenulation initiation may be heterogeneous and bimodal, with the formation of microshears at greater or less than 45° to cleavage and kink bands at 45° to cleavage. Each mode characterizes a domain, several of which may be juxtaposed within a microscopic volume of rock. The time of initiation of kink bands cannot be separated from that of associated microshears. The succeeding stages of crenulation development, advanced and mature, are accompanied by an increase in the dimensions of the domains beyond the scale of the thin section.

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