

Solution transfer, mechanical rotation and kink-band boundary migration during crenulation-cleavage development

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Abstract—Detailed microstructural investigation of an anastomosing axial-plane crenulation cleavage in low-grade metamorphic rocks revealed that the following microstructural processes operated independently, or in some combination, during its development: (1) mass transfer by dissolution or strain-induced chemical reactions; (2) mechanical rotation by grain-boundary sliding and (3) kink-band-boundary migration and consequent growth of microfold limbs at the expense of the hinges. Differences in composition and/or pre-existing fabric between folded pelitic layers determine the relative importance of these processes.

INTRODUCTION

TWO MESOSCOPIC folds from the Barron River Metamorphics in North Queensland, Australia (Figs. 1 and 2) were examined in detail. This sequence of lower-greenschist metamorphic rocks consists mainly of interbedded pelitic and quartzitic layers (de Keyser 1964). Cohen (1975) described two phases of deformation, the first of which (D_1) produced a regionally pervasive slaty cleavage (S_1) nearly parallel to bedding, S_0 . D_2 resulted in open to isoclinal folding of S_0 and S_1 structures, with local development of an axial-plane crenulation cleavage, S_2 .

Differences in the distribution patterns of the L_1^0 lineation, formed by intersection of S_0 and S_1 (terminology after Bell & Duncan 1978) around D_2 folds (i.e. from small-circle to great-circle distributions), were attributed to heterogeneities in the D_2 deformation event on a regional scale (Cohen 1975). The two specimens were selected to determine the relationship between the microstructural development of the S_2 crenulation cleavage and the folded L_1^0 distributions, which indicate minor (Fig. 2a) and major flattening (Fig. 2b) of the mesoscopic folds (Ramsay 1967, Cohen 1975).

Both specimens show a well-developed crenulation cleavage, which is more closely spaced in specimen 82b (Swager 1982). Microstructurally, the crenulation cleavage varies more within, than between the two specimens, and this variation appears to be related to the composition of the folded pelitic layers. The different L_1^0 distributions appear not to be reflected in the microstructures, but rather to be a function of the different proportions of quartz-rich and pelitic layers in the two specimens (Fig. 2) (Swager 1982)—the quartz-rich specimen being the more flattened (Ramsay 1967). Compositional differences in the pelitic layers provide evidence for a number of simultaneous processes during the development of crenulation cleavage in these rocks, which had essentially a similar bulk-strain history.

The following descriptions and discussion are mainly based on observations from specimen 104, which has a

larger proportion of pelitic layers (Fig. 2a). The inferences are compared with observations from specimen 82b only where significant differences occur.

MICROSTRUCTURES

Introduction

The fold specimens contain thin alternating quartz-rich and pelitic layers (Fig. 2). The latter vary in composition from (a) white mica, chlorite and carbonaceous matter with or without some quartz in the impure pelitic layers of both specimens (Figs. 3a & b), to (b) white-mica rich layers which consist of massive aggregates of white mica and some chlorite in specimen 104 and less massive, more fine-grained white mica with chlorite and variable amounts of quartz in specimen 82b (cf. Figs. 3c & d). The white-mica rich layers in both specimens may contain relatively minor amounts of carbonaceous matter. Microfolding and associated crenulation-cleavage development have affected the pelitic layers differently depending on the composition and/or preexisting fabric of these layers (Fig. 3). Microfolds are commonly very disharmonic across the mesoscopic folds. The microfolds vary in tightness and asymmetry and in places this results in the dying-out of a particular microfold and associated S_2 cleavage (Figs. 3 and 4) or in coalescence of two or more cleavages if the microfolding is highly asymmetric (Fig. 4). Other disharmonic features such as (reverse) millipede-type microstructures (Bell & Rubenach 1980) have been observed locally in both hinges and limbs of the mesoscopic folds (cf. Fig. 4).

Crenulation-cleavage formation

Two morphologically distinct types of S_2 development have been recognized. (1) Styloitic (Powell 1979) or discrete (Gray 1977a, 1979) cleavage is defined by thin, locally irregular, dark seams (Figs. 3a & b) and has developed only in the impure pelitic layers. (2) Zonal

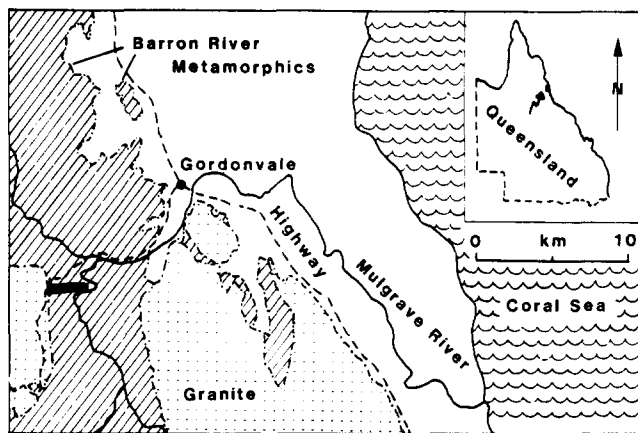


Fig. 1. Location map of the area (black) where the specimens were collected (Cohen 1975).

cleavage (Gray 1977a, 1979) is defined by the limbs of (a-) symmetrical microfolds. It consists of white mica in the white-mica rich layers (Figs. 3c & d) or white mica and carbonaceous matter in the impure pelitic layers (Fig. 3b). The zonal cleavage development in the white-mica rich layers in the more strongly flattened specimen (82b) is less well developed and less continuous than in specimen 104 (Figs. 3c & d).

Both types of cleavage have compositions different from adjacent microlithons suggesting a rearrangement of chemical phases during cleavage formation (Gray 1979). Examples of mass-transfer processes in low-grade metamorphic rocks have been well documented (Durney 1972, Elliott 1973) and are commonly attributed to solution-transfer mechanisms accompanying microfolding (Gray 1977b, 1979, Gray & Durney 1979). The stylolitic cleavage appears to have formed as a result of passive concentration of insoluble carbonaceous matter or opaques, while other more soluble phases (white mica, chlorite, quartz) were dissolved. Generally, this cleavage is closely associated with microfolds, although in some places microfolds are weak (Fig. 3a).

The zonal cleavage is defined by 'insoluble' white mica with or without carbonaceous matter in, respectively, the impure pelitic and white-mica rich layers. In the former, the carbonaceous matter is concentrated in thin dark seams oriented parallel to (001) of the white mica (Fig. 3b), indicating that grain-boundary sliding accompanied solution transfer during formation of the microfold limbs (Gray 1979). In the final stage, this zonal cleavage closely resembles a discrete or stylolitic cleavage, provided solution transfer continued to operate during rotation, dissolving the white micas sandwiched in between the seams (cf. Gray 1979). However, in the white-mica rich layers solution transfer associated with cleavage formation can only be inferred by the absence of chlorite (and/or quartz in specimen 82b) in the cleavage and its presence in the adjacent microlithons.

Despite the microstructural differences between zonal and discrete cleavages, they both form an anastomosing pattern, which in places has culminated in cleavage coalescence either by disharmony or asymmetric micro-

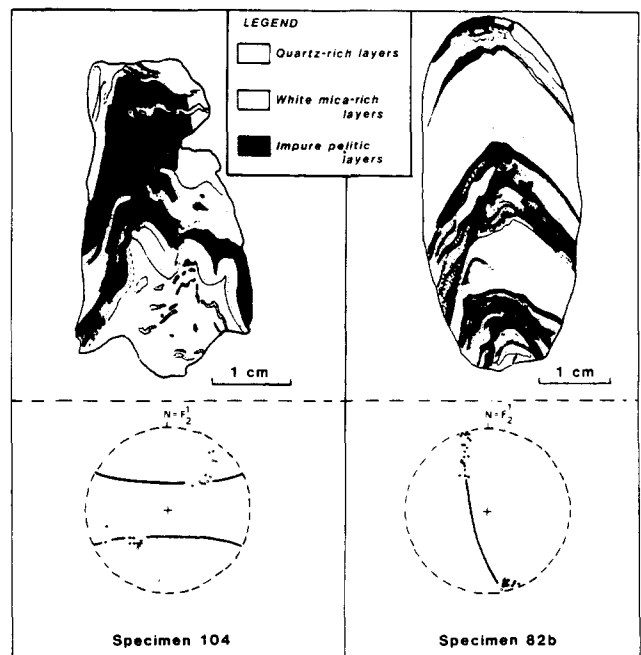


Fig. 2. Fold profiles and corresponding lineation-distribution patterns (after Cohen 1975) of specimens 104 and 82b. The points represent poles of the measured lineations. Lower-hemisphere equal-area diagrams.

folds (Figs. 3c and 4) or 'dissolution' of (a-)symmetric microfold hinges (Figs. 3b, 4, 5a & b).

'Dissolution' of microfold hinges

'Dissolution' of microfold hinges appears to have resulted in the coalescence of discrete cleavages in impure pelitic layers (Fig. 3b) and of zonal cleavages in both impure pelitic and white-mica rich layers (Figs. 3b, 4 and 5a & b). However, microstructurally this process of 'dissolution' appears to be more complex in the white-mica rich layers than in the impure pelitic layers. The development of a zonal crenulation cleavage in the white-mica rich layers not only involved microfolding and rotation of layer silicates on the limbs by grain-boundary sliding (possibly associated with dissolution of chlorite) but also the development of thin, sharp discontinuities, which separate the microfold hinges from the limbs (Figs. 4 and 5a & b). In places, the discontinuities envelop 'islands of hinge' preserved between almost fully coalesced limbs (Fig. 4). Patterns of (optical) extinction of micas indicate that changes in mica (001) orientation across the discontinuities become more abrupt along their length where they clearly separate the microfold hinges from the limbs (see some of the limbs in Fig. 4). The discontinuities are generally strongly serrated and/or bulging (Fig. 4) or relatively straight with minor bulging, where the layer silicates defining the cleavage are nearly parallel to the overall S_2 orientation (Figs. 5a & b). The presence of small 'islands of hinge' (Figs. 4, 5a & b), preserved between almost fully coalesced limbs and separated from the microfold limbs by these discontinuities, suggests that the latter are involved in the 'dissolution' of the hinges.

Deformation processes during crenulation-cleavage development

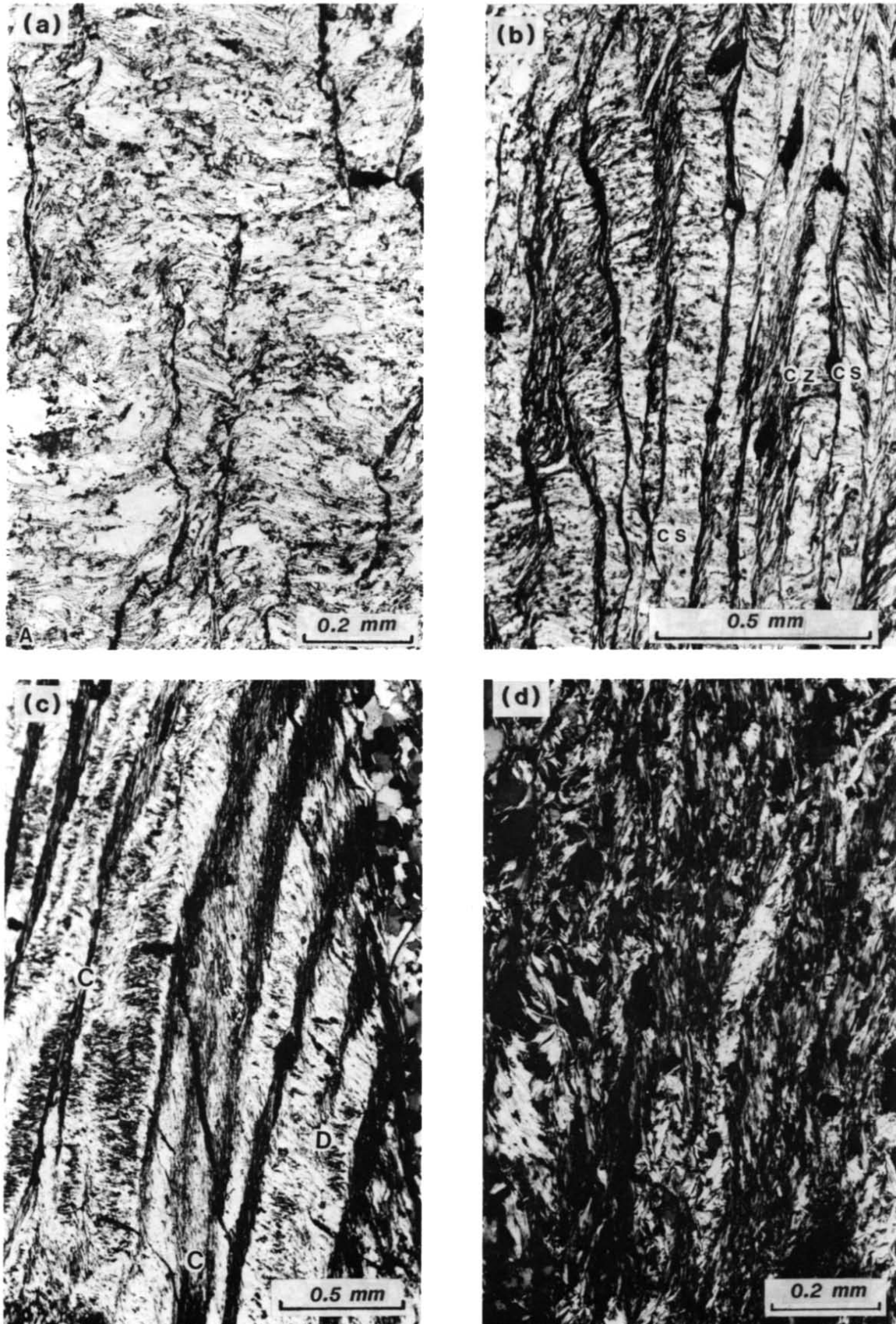


Fig. 3. (a) Photomicrograph of stylolitic cleavage in a parasitic open hinge of specimen 104. Note that microfolding is minor compared with cleavage development. PPL. (b) Stylolitic and zonal cleavages in an impure pelitic layer of specimen 104. Note the abrupt transitions between the two cleavages and the coalescence of stylolitic (cs) and zonal cleavages (cz). PPL. (c) Zonal cleavages in a white-mica rich layer of specimen 104. Note the discontinuity (D) of one cleavage and the coalescence (C) of others. XN. (d) Less well-defined and less continuous zonal cleavages in a white-mica rich layer of specimen 82b. XN.



Fig. 4. Photomicrograph of coalescence of limbs of asymmetrical microfolds by 'apparent dissolution' of microfold hinges or disharmonic microfolding. D, 'islands of hinge' preserved between coalescing cleavages. Also note the millipede-type microstructures (E and arrows), and the discontinuous cleavage (dc) just below. See text for further explanation. XN.

Deformation processes during crenulation-cleavage development

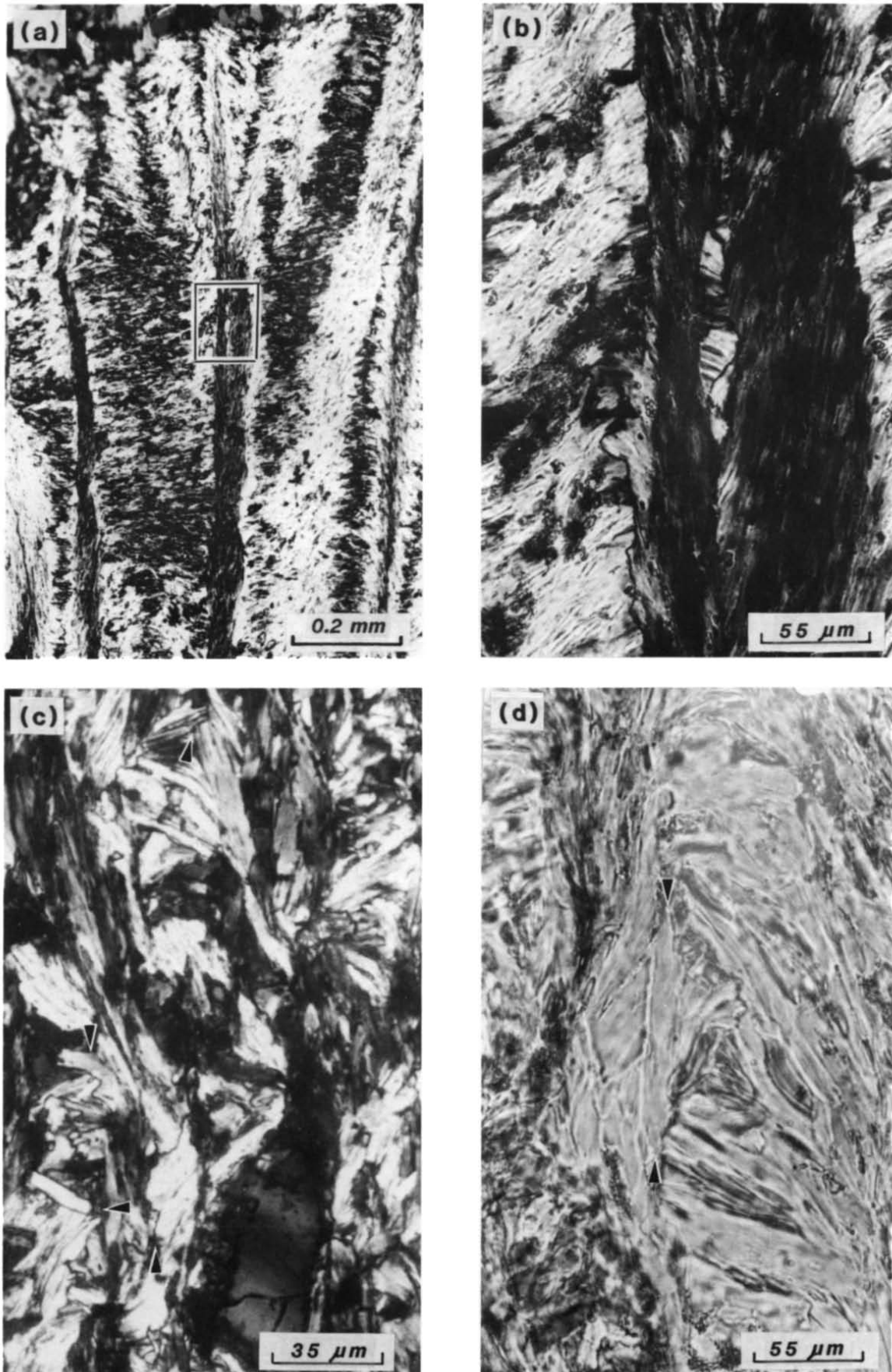


Fig. 5. (a) Photomicrograph of coalescence of limbs of a more symmetrical microfold. XN. (b) Detail of box in (a). XN. (c) Impingement-type microstructures (arrows). XN. (d) Growth of a white mica (arrows) in an S_2 orientation. PPL.

In contrast, microstructures in the more heterogeneous white-mica rich layers of specimen 82b show less evidence of 'apparent dissolution' but more evidence of impingement microstructures between hinges and limbs of microfolds (cf. Figs. 3d and 5c). In some places (re-?) crystallization of white mica in a near S_2 orientation was observed (Fig. 5d, cf. Etheridge & Hobbs 1974, Bell 1979).

DISCUSSION

Solution transfer during cleavage formation

The formation of the dark seams defining a stylolitic cleavage or forming part of a zonal cleavage in the impure pelitic layers (Figs. 3a & b) involved solution transfer of quartz (if present) and layer silicates. Chlorite was dissolved preferentially during the development of a zonal cleavage in these layers, which may be attributed to its greater unit-cell volume compared with white mica (Cosgrove 1976). In contrast, the zonal cleavage in the white-mica rich layers does not show these concentrations of insoluble matter parallel to the rotated layer silicates. Solution-transfer processes in these layers can be inferred only by the absence of chlorite on the limbs of the microfolds and its presence in the hinges. Similarly, strain-induced chemical reactions related to volume-change anisotropies (i.e. from chlorite to white mica) could have resulted in the disappearance of chlorite on the limbs (Cosgrove 1976, Marlow & Etheridge 1977, Beach 1979). The presence of 'impurities' in the other pelitic layers may not only have enhanced the solubility or solution-transfer rates of both chlorite and, to a lesser extent, white mica, but could also have prevented the occurrence of strain-induced reactions (cf. Spry 1969).

Although microfolding is commonly associated with solution-transfer processes (Gray 1979), it is relatively rare in the open parasitic hinge of specimen 104 (Fig. 3a), where the widely spaced stylolitic cleavage is comparatively well developed. This relationship may suggest that under low strain rates, solution transfer was able to accommodate most of the strain, at the same time preventing large-scale microfolding. A higher initial strain rate in this part of specimen 104 may have resulted in abundant microfolding and subsequent stylolitic and zonal cleavage development, as is commonly the case in the impure pelitic layers of this specimen (Fig. 3b). It could be argued that fold lock-up has been responsible for the propagation of stylolitic cleavages, although this seems unlikely for a weakly deformed part in a layer which elsewhere shows abundant microfolding.

These microstructures illustrate that care is required when attempting to interpret the formation of a crenulation cleavage in impure pelitic rocks. In this case, microstructures appear to provide evidence for development of stylolitic cleavages before, during and/or after microfolding. Furthermore, a microstructurally indistinguishable cleavage may have developed from a zonal cleavage if solution transfer has continued to operate during formation of the cleavage (Gray 1979).

'Apparent dissolution' of microfold hinges: caused by solution transfer?

The formation of the discontinuities in the white-mica rich layers of specimen 104 and the apparent dissolution of the microfold hinges appear to be closely related. These microstructures can be interpreted in several ways. (1) The discontinuities are similar to the stylolitic cleavage and represent irregular faces along which solution transfer has taken place. Layer silicates at high angles to these faces or fronts (i.e. the microfold hinges) are more soluble, possibly due to a higher internal stored strain energy, which consequently resulted in their preferential dissolution. However, if this is true, one would expect to find similar microstructures in the impure pelitic layers. Although the dissolution of microfold hinges against stylolitic cleavages has resulted in a roughly similar (though less well-developed) microstructure (cf. Figs. 3b and 4), the stylolitic cleavages cannot be traced to less abrupt discontinuities, which were subsequently enhanced by the passive concentration of insoluble matter. The transition between stylolitic and zonal cleavages is commonly abrupt (Fig. 3b). (2) Microstructurally, the discontinuities closely resemble kink-band boundaries (KBBs), which are commonly developed in single, strongly deformed, coarse-grained micas (cf. Etheridge & Hobbs 1974). Migration of these KBBs resulted in the growth of the limbs at the expense of the hinges, leading to the 'apparent dissolution' of the microfold hinges. A similar process of hinge consumption has been described by Knipe (1981) for a slaty cleavage, although growth was in this case commonly preceded by grain-size reduction along the highly deformed interfaces between cleavage (P-) and hinge (Q-) domains.

Driving forces for KBB formation and migration

If the discontinuities are KBBs, their migration (leading to apparent dissolution of the hinges) may be considered similar to any other grain-growth process characteristic of deformed fabrics (Hobbs *et al.* 1976). Generally, grain growth is a process which reduces internal stored strain energy (Nicolas & Poirier 1976, Hobbs *et al.* 1976, Vernon 1976) or grain-boundary surface energy (cf. Knipe 1981). Lesser-strained grains and/or grains with a favourable orientation with respect to the stress/strain regime commonly grow at the expense of stronger deformed (fine) grains with a less favourable orientation (Hobbs *et al.* 1976). Since the process of KBB migration does not appear to involve grain-size reduction, a difference in stored strain energy or dislocation density on either side of the KBB (Nicolas & Poirier 1976, Vernon 1976) might be a possible driving force. The uniform extinction of the layer silicates defining the limbs (at high angles to the maximum shortening direction) suggests an even dislocation distribution, if any at all, with little stored strain energy, whereas the undulose extinction of the layer silicates in the hinges (at low angles to the maximum shortening direction) suggests a relatively

high stored strain energy (Hobbs *et al.* 1976). The low strain-energy state of the limbs may be explained by a predominance of grain-boundary sliding on the limbs during microfolding, involving relatively little intracrystalline deformation. The presence of insoluble seams in the impure pelitic layers parallel to rotated layer silicates confirms that grain-boundary sliding can be an important rotation mechanism on the limbs. In contrast, the low angle between the mica (001) direction in the hinges and the shortening direction resulted in continued intracrystalline deformation and, consequently, in accumulation of internal stored strain energy. The observation that the white mica on the limbs grows at the expense of white mica and minor chlorite in the hinges could suggest that free energy differences between white mica and chlorite have added momentum to the recrystallization process (cf. Etheridge & Hobbs 1974).

KBB formation is restricted to massive homogeneous white-mica rich layers, which suggests that specific conditions were required. These may be found by comparing the white-mica rich layers with the impure pelitic layers where evidence for this process has not been found. The presence of impurities in the impure pelitic layers may have prevented the migration of KBBs (Spry 1969) but not necessarily their formation. One would expect KBBs, once formed, to become enhanced by subsequent concentration of insoluble matter due to solution transfer of the adjacent microfold hinge. However, a transition from stylolitic seams to less abrupt discontinuities has not been observed. This could be explained by a predominance of solution transfer in these layers leading to the dissolution of strained layer silicates before sufficient stored strain energy was accumulated for KBB formation. This implies that the process of KBB formation and migration requires more stored strain energy (or higher temperatures of deformation, cf. Nicolas & Poirier 1976) than solution-transfer processes. Thus the stored strain energy, first, necessary for KBB formation and, secondly, driving its migration, may not have accumulated if solution transfer had been more dominant in the white-mica rich layers. In contrast, the microstructures in the white-mica rich layers of specimen 82b suggest that the relative heterogeneity of these layers prevented 'large-scale' KBB migration. Instead, internal stored strain energies have in places induced (re-?)crystallization and growth of single (rather than an aggregate of) white micas (Figs. 5c & d).

These microstructures illustrate that recrystallization processes involving (extensive) grain growth can also occur at relatively low temperatures of metamorphism (cf. Nicolas & Poirier 1976, Vernon 1976), provided that deformed layer silicates are not readily dissolved.

Coalescence of zonal cleavages: due to 'apparent dissolution' or disharmonic microfolds?

As KBB migration results in the growth of the limbs at the expense of the hinges, the limbs eventually coalesce (Figs. 4 and 5a & b). However, coalescence of limbs of

asymmetrical microfolds by KBB migration appears to be indistinguishable from coalescence due to disharmony of the microfolds. The effect of both phenomena can be seen in Fig. 4: coalescence at *A* is due to disharmonic microfolding. The cause of incipient coalescence at *B* is less obvious but appears to be due to hinge consumption as the limbs below the zone of coalescence show clearly developed KBBs. At *C* it could have been the result of either 'apparent dissolution' of the hinge or disharmony of the microfolds. One cannot tell optically whether the 'islands of hinge' (above and left of *B*) were part of the same microfold hinge, or whether the upper island was part of a now totally 'dissolved' microfold hinge, which may have been present between the 'light' and 'dark' limbs to the right of *B*. Hinge consumption in more symmetrical microfolds is easier to recognize by the small misorientation between the layer silicates from the opposite limbs (Figs. 5a & b). Again, these microstructures highlight the difficulties of interpretation encountered when dealing with a crenulation cleavage. Complete 'apparent dissolution' could result in bimodal or slaty cleavage fabric, devoid of microfolds, depending on their original asymmetry (cf. Figs. 4 and 5a & b).

CONCLUDING REMARKS

The L_1^0 distributions appear to bear little influence on the microstructures which have been described. Considering the fact that specimen 82b is the more flattened specimen according to its L_1^0 distribution, the microstructures provide relatively little evidence to this effect, apart from a closer spacing in the cleavage in the impure pelitic layers (Swager 1982). The crenulation cleavage in the white-mica rich layers of specimen 82b appears to be even less well developed and less continuous than the cleavage in layers of similar composition in specimen 104 (Figs. 3c & d). The comparison may, however, be at fault as the pre-existing fabric in specimen 82b appears to be far less homogeneous, resulting in the 'lesser-developed' cleavage. In detail, evidence for recrystallization is abundant, although microstructurally different from specimen 104. How much this is due to more extensive flattening or the comparative heterogeneity of the pre-existing fabric in specimen 82b, cannot be determined.

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