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Component migration patterns during the formation of a metamorphic layering, Mount Franks area, Willyama Complex, N.S.W., Australia

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Abstract—Mineral shapes, sizes and proportions in mica rich (M) and quartz–mica (QM) domains of an S_4 metamorphic layering have been compared in two mutually perpendicular orientations with shapes, sizes and proportions in mildly crenulated S_2 enclaves preserved within a rock from part of the Willyama Complex, N.S.W., Australia. The study has shown that data from two orientations are necessary to place constraints on the movement of mineral components dissolved in solution during formation of the layering. Comparison of mineral data has shown that SiO_2 has been dissolved from quartz grains in both M and QM domains. The SiO_2 lost from M domains has not migrated into QM domains. Measurements have also shown that biotite has undergone less solution than quartz. Most of the biotite components have probably undergone reaction to form probable syn—S_4 muscovite and chlorite. The muscovite-forming reaction requires some silica on the left-hand side of the reaction, probably more than can be supplied by the chlorite-forming reaction. Some of this extra silica was supplied from dissolved quartz grains. However, only a small amount is needed for this purpose and most of the SiO_2 has left the system. Some syn—S_4 muscovite may have formed in M domains where it lies within the crenulated S_2. Direct evidence for its growth is hard to find.

INTRODUCTION

This paper discusses the migration of mineral components during the formation of a metamorphic layering from a crenulated early schistosity. Sufficient evidence has now accumulated in the literature to show that, especially in low-grade metamorphic rocks, the development of a metamorphic layering, consisting of alternating mica-rich (M) and quartz–mica-rich (QM) domains, involves interaction between the rock and a fluid phase present during deformation (e.g. Marlow & Etheridge 1977, Gray 1979). Selective parts of the rock, generally limb areas of microfolds to which the new layering is axial planar, have undergone more intense solution of some minerals than other parts of the rock. Complete solution of minerals such as quartz has been invoked to explain all (or a major part) of the differences in mineral proportion between these M domains and the undeformed (or only mildly deformed) rock. Partial solution has been invoked to explain changes in grain shapes between the M domains and the undeformed (or only mildly-deformed rock) (e.g. Gray 1979). Contribution to shape changes by intracrystalline deformation, leading to recovery and recrystallization, does not appear to be important.

A fundamental question is what happens to the SiO_2 in solution. Cosgrove (1976, p.170), Gray (1979, pp. 108–10 and p. 120) and others have demonstrated that SiO_2 removed from M domains is transported in solution to adjacent QM domains where it precipitates and grows as new grains or quartz overgrowths. On the other hand, Williams (1972, p. 38), Hobbs *et al.* (1976, p. 40) and Stephens *et al.* (1979, p. 145) have suggested that SiO_2 is transported over greater distances and may even migrate out of the system. With the exception of some work by Williams (1972), published studies are based on examination of grain shapes and proportions in one section only—that perpendicular to the axes of crenulations, and all discussion of volume changes is inferred from this section.

This paper attempts to explore what happened to SiO_2 dissolved from M domains in some rocks of the Willyama Complex, New South Wales, Australia. The quantitative studies reported here were carried out not only on sections perpendicular to the axes of crenulations but also on sections parallel to them. Changes in one orientation were not necessarily mirrored in the other. Although combining two sets of area data into volume data is hazardous, it appears that in the studied rocks there is no significant transfer of SiO_2 between domains. Rather, SiO_2 has generally left the system; small amounts having been utilized, together with biotite breakdown components, to form new muscovite.

GEOLOGICAL BACKGROUND

The crenulation study was carried out as part of a larger investigation into rocks of the Proterozoic Willyama Complex, cropping out in the Broken Hill area of western New South Wales, Australia. Samples were collected from the hinge zone of a macroscopic fourth-generation (F_4) synform in S_2 which lies just north of Mt. Franks. Details of the regional geology and of the Mt. Franks area can be found in Glen (1978, 1979, 1980), Glen *et al.* (1977) and Majoribanks *et al.* (1980). In the studied rocks, S_2, the crenulated schistosity, post-dates an S_1 foliation which is outlined by relicts of biotite, muscovite and ilmenite. S_2 also postdates the generally static growth of biotite and andalusite crystals. S_2 is defined by the crystal and shape orientation of muscovite grains, very rare biotite grains and the shape orientation of quartz ± rare feldspars and rotated early biotites (Glen 1980). Biotite grains are commonly cut by new, S_2, elongate muscovite grains aligned in S_2. Andalusite crystals in these rocks have undergone total replacement by 'sericite' aggregates, with 'sericite' grains being either randomly aligned or elongate in S_2 (Glen 1979). The grade of the accompanying metamorphism, indicated by widespread muscovite growth and only very limited biotite growth was probably towards the middle part of the greenschist facies.

The metamorphic event accompanying the D_4 deformation was marked by both biotite alteration and inferred biotite metastability, and probably occurred in the lower part of the greenschist facies. In many situations, biotite has undergone alteration to chlorite psuedomorphs (only a few per cent in the rock) and to muscovite. Some muscovite pseudomorphs whole biotite grains or replaces parts of grains, resulting in the formation of biotite–muscovite aggregates. Elsewhere, biotite grains are cut by long muscovite grains. Some of these muscovites are strained in F_4 hinges and are thus probably pre-S_4 in age. Others are unstrained, cut through deformed biotite and are probably syn-S_4 in age. The formation of the syn-S_4 muscovite may have played an important part in the development of the S_4 microstructure and is discussed later. Within 'sericite' aggregates, 'sericite' grains are either deformed about F_4 crenulations or lie in S_4.

DESCRIPTION OF S_4

The particular specimen studied in detail was sectioned both parallel and perpendicular to the axes of F_4 crenulations. With the exception of a more micaceous zone in the centre of the section perpendicular to F_4, S_4 in both sections is defined by variation in mineral ratios (Figs. 1a & b) : QM domains contain more quartz (± any rare feldspar) and biotite than M domains, but contain less muscovite (Table 1).

In the section parallel to F_4, M domains are characterized by mica and elongate quartz grains which lie in S_2. Because S_2 lies parallel to S_4 in these domains, quartz and mica also lie parallel to moderately well-defined S_4 domain boundaries (Fig. 1c). QM domains in the section parallel to F_4 may also be defined by grains elongate in S_2 and parallel to S_4 (Fig. 1c). However, elsewhere quartz grains may be more equant, and micas are either randomly aligned or are folded about F_4.

In contrast, in the section perpendicular to F_4, micas and quartz grains never lie parallel to S_4. Rather, in both M and QM domains they lie in crenulated S_2 (Fig. 1d). In this section, domain boundaries, defined by variations in mineral ratios, coincide with domain boundaries established by variations in the geometry of F_4 crenulations. Where crenulations are symmetrical, QM domains represent hinge zones. Where crenulations are asymmetrical, QM domains represent hinge zones plus the intervening short limb. Exceptions, of course, do occur. Thus in Fig. 2(a), M domains coincide, in part, with F_4 hinge zones.

In the section perpendicular to F_4, boundaries between domains vary from straight to irregular. Straight boundaries generally represent discontinuities commonly iron-enriched, which separate visibly undeformed, mismatched micas of different orientation. Where boundaries are irregular, bent micas can be traced from QM into M domains and irregularities are caused by projecting zones of mica (Fig. 2b). Quartz aggregates and even individual grains are continuous across domain boundaries; however, they are much narrower in M domains than in QM domains (Fig. 2b).

Figure 1(a) shows that in the section parallel to F_4, rock homogeneity is interrupted by the presence of 'sericite' aggregates developed from andalusite crystals, by the presence of biotite-rich pressure shadows fringing the aggregates (e.g. P in Fig. 1a), and by the presence of abnormally wide, quartz-rich domains (here called crenulated S_2 enclaves) aligned parallel to S_2 and S_4. Attention was focused on the obvious enclave on the right-hand side of Fig. 1(a). It is an area of quartz, muscovite and biotite in which the enveloping surface to S_2 makes a half interlimb angle of about 50° with the boundary of adjacent M domains and in which small open crenulations have interlimb angles of about 80–140°. A similar crenulated S_2 enclave occurs in a section perpendicular to F_4 (B in Fig. 1b), and this enclave passes at its ends into normal M and QM domains (Figs. 1b & c). The presence of open folds with interlimb angles of 75–150° in the centre of this enclave, compared with angles of 20–60° between M and QM domains suggests that the enclave has not undergone as much D_4 strain (as recorded by the degree of appression of microfolds) as the remainder of the rock. The same suggestion may also apply to the enclaves in the section parallel to F_4. Crenulated S_2 enclaves are richer in quartz and poorer in muscovite than QM or M domains (Table 1). The percentage of biotite in the crenulated S_2 enclave in

Table 1. Percentage mineralogical composition on an areal basis (modal analysis) of crenulated S_2 enclaves, QM and M domains. Muscovite data by difference

	Section parallel to F_4 axes			Section perpendicular to F_4 axes		
	Crenulated S_2	QM	M	Crenulated S_2	QM	M
Quartz	36.0	26.0	6.0	27–30	24.0	5.0
Biotite	8.7	6.1	3.7	4.0	6.0	5.0
Muscovite	55.3	67.9	90.3	69–66	70.0	90.0

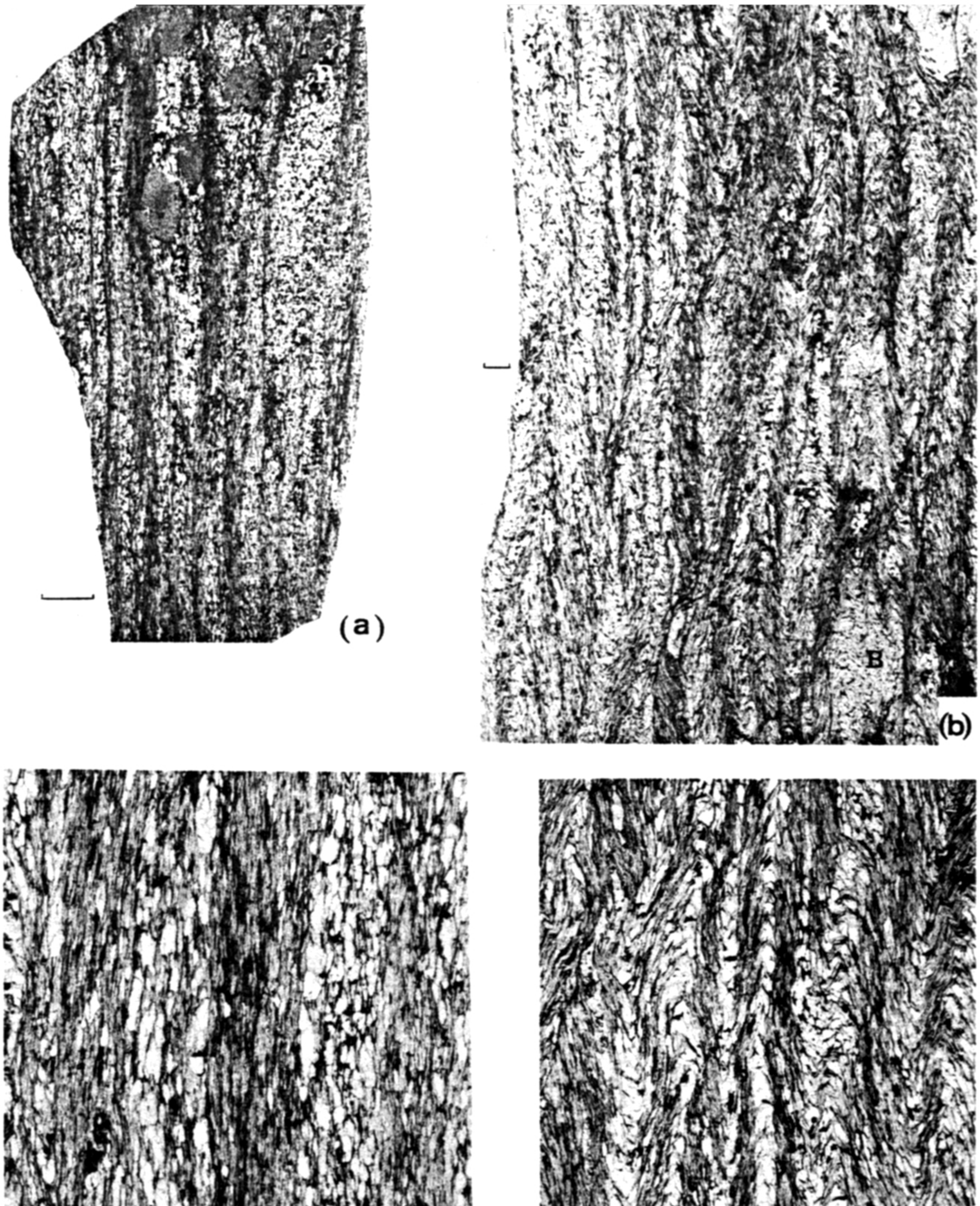

Fig. 1. (a) General view of layered S_4 schistosity in a section parallel to F_4, with dark-coloured M domains, light-coloured QM domains and light-coloured wide crenulated S_2 enclaves (e.g. right of figure). Note persistence of some domains and merging of others. Porphyroblasts at top of figure are 'sericite' pseudomorphous after early andalusite. Pressure shadows on relict andalusite crystals represented by biotite and quartz-rich zones (e.g. P). Plane polarized light. Bar scale, 2.4 mm. (b) General view of layered S_4 schistosity and F_4 microfolds in a section perpendicular to F_4. Note variable development of dark-coloured M and light-coloured QM domains, and the crenulated S_2 enclave at lower right. 'Sericite' aggregate after andalusite at upper right. Enclave B is shown in detail in Fig. 2(c). Plane polarized light. Bar scale, 0.85 mm. (c) Detail of M and QM domains from left side of Fig. 1(a). Note nature of domain boundaries and parallelism of S_2 and S_4. Dark grains are biotite; grey ones are muscovite; white is quartz. Plane polarized light. Bar scale, 0.32 mm. (d) Detail of a section perpendicular to F_4 taken from the left side of Fig. 1(b). S_4 is defined by an alternation of dark M domains and light-coloured QM domains. QM domains generally occupy F_4 hinges, whereas M domains generally occupy limb areas. As a result, micas in both domains lie oblique to S_4. Note, however, that part of the left-hand M domain occupies an F_4 hinge zone. Some QM domains (e.g. third from right) are narrower than M domains. Plane polarized light. Bar scale, 0.63 mm.

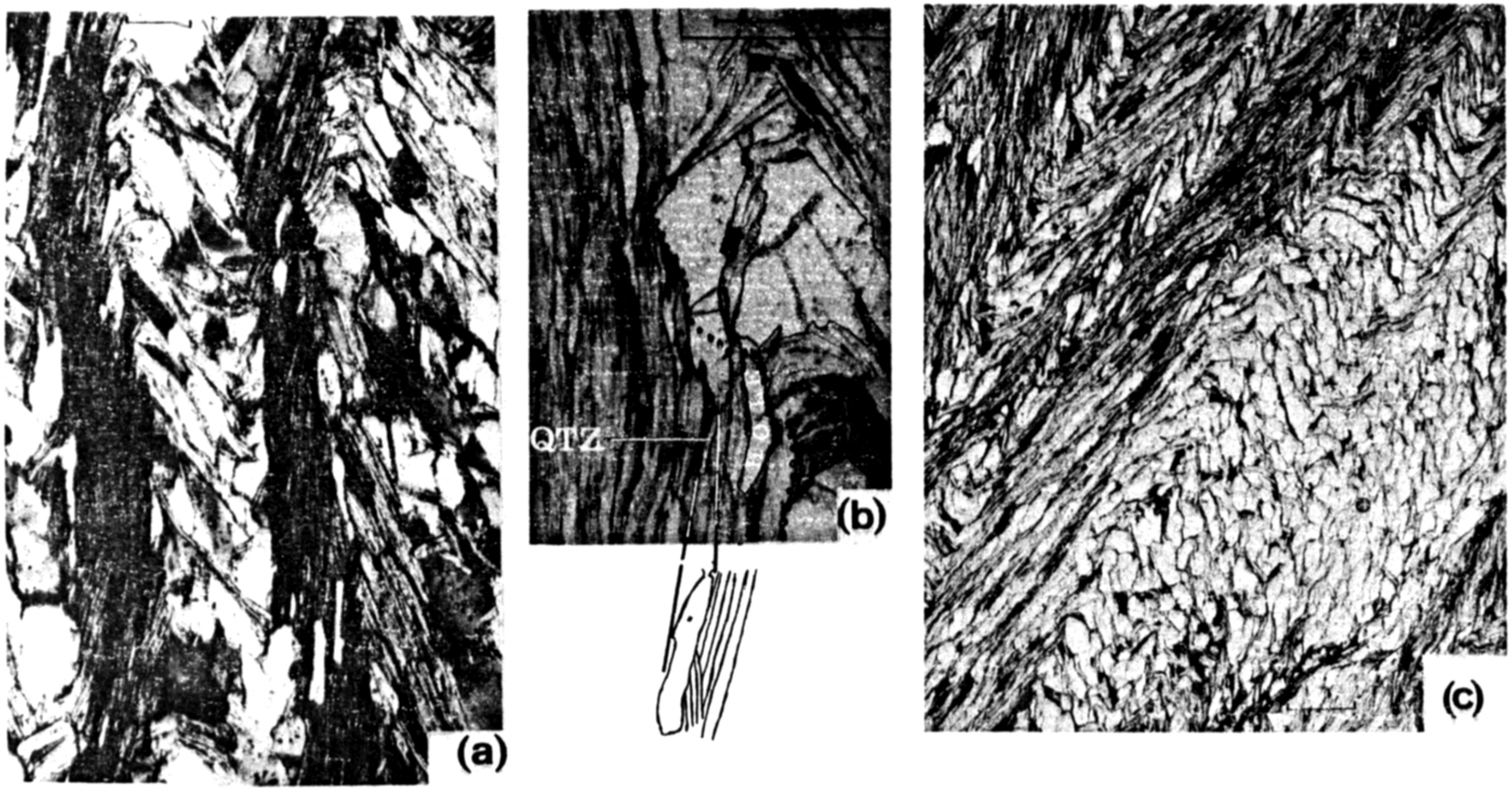

Fig 2. (a) Detail of M and QM domains, section perpendicular to F_4. Note change in size and number of quartz grains between domains, and oblique relations between S_2 muscovite and S_4. Right-hand M domain in part occupies an F_4 hinge zone. Continuity of muscovite between M and QM domains is visible at upper right. Crossed nicols. Bar scale, 0.2 mm. (b) Detail of boundary between QM and M domains showing reduction in size of quartz grains (QTZ) across domain boundary (shown by dots). Dashed line indicates boundary between muscovite grains continuous across domain boundary (r.h.s.) and those occurring only within the M domain (l.h.s.) See text. Large white 'grain' to the right of the dashed line is a hole in the section. Biotites and iron oxides black in colour. Plane polarized light. Bar scale, 0.25 mm. Detailed sketch shows obliquity between muscovite grains abutting narrow quartz grain on l.h.s. (c) Detail of a section perpendicular to F_4 showing detail of crenulated S_2 enclave B in Fig. 1(b). Note contrast in tightness of folds between this enclave and adjacent M and QM domains. Plane polarized light. Bar scale, 0.4 mm.

the section perpendicular to F_4 is lower than that in adjacent M and QM domains (Table 1 and Fig. 2c). This probably reflects its heterogeneous initial distribution rather than any growth in M and QM domains.

From the above, the assumption is made that grain shapes, sizes and proportions in crenulated S_2 enclaves have undergone less change than those in M or QM domains. Such an assumption is supported by Gray's (1979, p. 108) suggestion that the greatest changes in grain dimension occurred at interlimb angles of $\leq 90°$. (Note, however, his fig. 1 only records measurements made at one angle—160°—greater than 90°). The assumption made here has two consequences. Firstly, the shapes, sizes and proportions of grains in crenulated S_2 enclaves approximate more closely than those in QM or M domains, the shapes, sizes and proportions of grains in minimally or undeformed S_2. Secondly, comparisons of grain shapes, sizes and proportions between crenulated S_2 enclaves and QM and M domains provide minimum estimates of changes involved in the formation of S_4. The problem of comparing grain shapes, sizes and proportions between deformed and minimally or undeformed rocks affects all such crenulation studies because, in order to establish migration patterns, it is not sufficient to compare grain shapes, sizes and proportions between end-product M and QM domains, especially when they have been affected by different, unknown volume changes and solution histories. Perhaps the work of Marlow & Etheridge (1977) is most relevant because it examines, within one hand specimen, changes from uncrenulated S_1 to the newly developed layering, S_2.

DEFORMATION MECHANISMS

How have the various minerals reacted to the D_4 deformation? In addition to chemical breakdown as outlined above, biotite grains together with muscovite, have deformed by kinking. Where there is no continuity of (001) traces across axial surfaces, kinking was accompanied either by kink-boundary migration (Williams *et al.* 1977) and/or solution. The latter is especially likely to have occurred where kink surfaces are irregular and marked by an enrichment of iron-oxide minerals (Wilson 1979). Solution has probably occurred where micas are truncated by domain boundaries which may be iron-enriched. No new mica growth parallel to S_4 was found. Deformation in quartz grains has not led to formation of new grains, and evidence of intracrystalline deformation is restricted to undulosity, formation of some deformation bands and minor subgrain formation in the inner arcs of F_4 fold hinges. Quartz/quartz boundaries may be sutured. Because of the absence of stable quartz/quartz boundaries, and the difference in size between these quartz grains and new syn-S_4 grains found elsewhere in the Mt. Franks area (Glen 1978), there is no reason to suggest that changes in the shapes of quartz grains have been caused by more intense intracrystalline deformation leading to recrystallization, or that the observed strain effects in quartz grains reflect an additional event superimposed on this recrystallization. Rather, the appearance of very irregular quartz/quartz boundaries and the shapes of quartz grains such as in Fig. 2(b), suggest that changes in grain shapes may be due to solution of quartz.

QUANTITATIVE DATA

Method

Dimensions of quartz and biotite grains were measured in the following way. Transparent shadow-master sketches at 50 times enlargement were made from thin sections and overlain on millimetre graph paper. Lengths, widths and areas were then counted. Although this method did in some cases involve estimating fractions of grains, on a trial basis it was found to be more accurate for measuring areas than using a planimeter. Because of different domain sizes, the data were normalized to 100 grains in each domain and then divided by the original enlargement ($\times 50$) and mean and standard deviation were obtained using a programmable H.P. Calculator. Because of their ragged nature, lengths and widths of biotite grains were not measured. Nor was it possible to measure sizes of individual muscovite grains because of lateral and end-on amalgamation.

Results

Length, width and areal data for quartz grains, and areal data for biotite grains are shown in Table 2, along with calculated numbers of grains/unit area (mm^2), and total area of quartz and biotite/unit area (mm^2). Calculated percentage changes between domains (including crenulated S_2) are based on mean data. Statistical analysis of these changes, in terms of differences between means with their associated standard errors are shown in the Appendix. This analysis indicates that with the exceptions of the change in length of quartz grains from crenulated S_2 to QM domains (parallel to F_4) and area of quartz grains from crenulated S_2 to QM domains in the section perpendicular to F_4, all changes have statistical significance.

Reference diagrams for the section parallel to F_4 are Figs. 3(a) & (b), which, together with Table 2, allow the following inferences to be made:

(1) Quartz grains change in shape from irregular-equant (crenulated S_2) to equant or slightly elongate in S_2 (QM domains) to elongate (M domains). These changes are associated with decreases in all dimensions, from crenulated S_2 to QM domains (16% in length, not significant, 39% in width, 45% in area) and more drastically from crenulated S_2 to M domains (42% in length, 75% in width, 84% in area).

(2) The total area of quartz in each domain is reduced by 32% (from crenulated S_2 to QM domains) and by 86% (from crenulated S_2 to M domains).

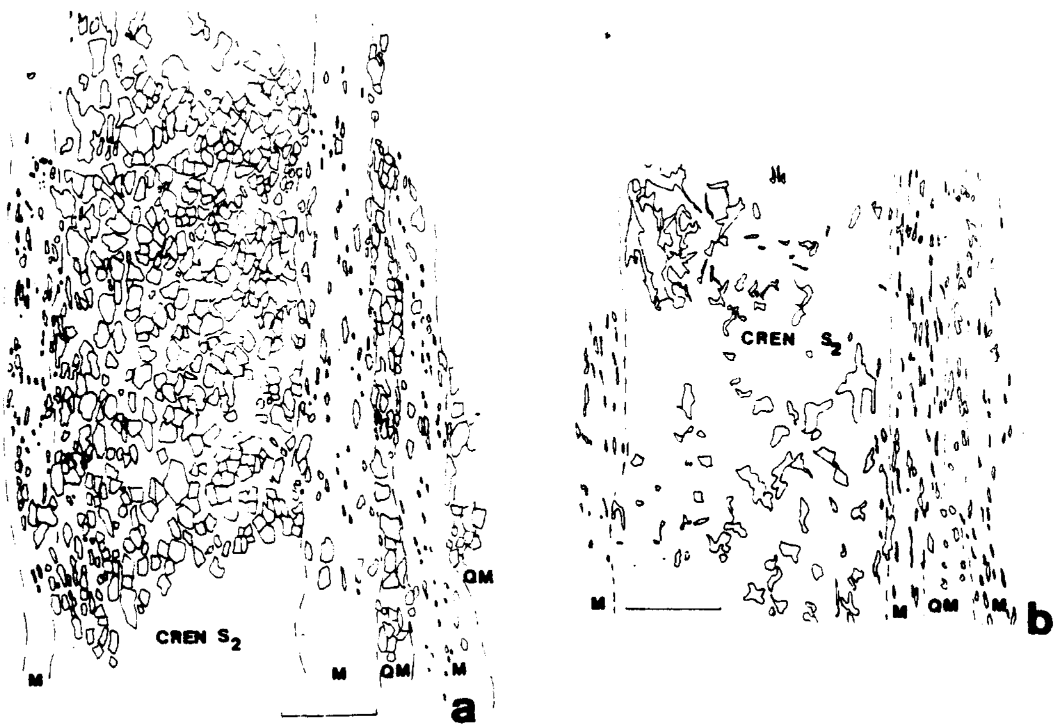

Fig. 3 (a) Shadowmaster sketch of section parallel to F_4 showing change in shape, size and proportion of quartz grains between a crenulated S_2 enclave and QM and M domains. Bar scale, 1 mm. (b) Shadowmaster sketch of section parallel to F_4 showing change in shape, size and proportion of biotite grains between a crenulated S_2 enclave and QM and M domains. Bar scale, 1 mm.

(3) Biotite grains change in shape from ragged and irregular or lying in S_2 (crenulated S_2) to less ragged and more elongate in S_2 (QM domains) to highly elongate in S_2 (M domains). These changes are associated with a decrease in the area of the mean biotite grain of 46% (crenulated S_2 to QM domains) and 77% (crenulated S_2 to M domains).

(4) The total area of biotite in each domain is basically unchanged from crenulated S_2 to QM domains, but decreases by 44% from crenulated S_2 to M domains.

Reference diagrams for the section perpendicular to F_4 are Figs. 4(a–d) which, together with Table 2, permit the following inferences to be made:

(1) Quartz grains change in shape from equant or slightly elongate to S_2 (crenulated S_2 and QM domains) to highly elongate in S_2 (M domains). From crenulated S_2 to QM domains, these changes are associated with a decrease in the width of grains (12%), an increase in length (29%) and no significant change in area. From crenulated S_2 to M domains these changes are associated with a decrease in all dimensions (21% in length, 75% in width, 78% in area).

(2) The total area of quartz in each domain is reduced by 29% (from crenulated S_2 to QM domains) and by 85% (from crenulated S_2 to M domains).

(3) Biotite grains change in shape from ragged and irregular or lying in S_2 (crenulated S_2) to less ragged and more elongate in S_2 (QM domains) to elongate in S_2 (M domains). These changes are associated with major changes in the area of the mean biotite grain which are difficult to explain (see below).

(4) The total area of biotite in each domain increases from crenulated S_2 to M domain and is also discussed below.

DISCUSSION

SiO_2 *migration patterns*

The mean grain-size data given in Table 2 suggests that in the section parallel to F_4, quartz grains in QM and M domains are smaller, shorter and narrower than those in crenulated S_2 enclaves. Shortening is, thus, suggested both along F_4 and especially perpendicular to S_4. Patterns between crenulated S_2 and QM domains in the section perpendicular to F_4 differ from those above. The suggested lengthening of quartz grains in S_2 is similar to results of Marlow & Etheridge (1977, table 2), and suggests that there was shortening perpendicular to S_2. From crenulated S_2 to M domains, mean grain-size data indicate a decrease in length, width (especially) and area of quartz grains (similar to data of Marlow & Etheridge 1977, table 2).

In summary, these data suggest a steady decrease in quartz size in sections parallel to F_4 and an eventual decrease in sections perpendicular to F_4. Extreme changes in volume of the mean quartz grain, obtained by multiplying the area in one section by the third dimension, range from decreases between 11 and 34%, from crenulated S_2 to QM domains, and decreases between 87 and 88% from crenulated S_2 to M domains. These data rule out significant transfer of SiO_2 from M domains

Table 2. Grain-size data for quartz and biotite in different domains and in different sections and changes in dimensions between crenulated S_2 enclave and QM and M domains

	Section parallel to F_4 axes					Section perpendicular to F_4 axes				
				Percentage changes					Percentage changes	
	C.S_2	M	QM	C.S_2→QM	C.S_2→M	C.S_2	QM	M	C.S_2→QM	C.S_2→M
QUARTZ										
Mean length (mm)	0.19(0.69)	0.16(0.082)	0.11(0.056)	−16%	−42%	0.14(0.056)	0.18(0.062)	0.11(0.062)	+29%	−21%
Mean width (mm)	0.12(0.046)	0.073(0.033)	0.030(0.017)	−39%	−75%	0.083(0.033)	0.073(0.036)	0.021(0.0096)	−12%	+75%
Area of mean grain (mm^2)	0.015(0.0093)	0.0082(0.0069)	0.0024(0.0024)	−45%	−84%	0.0094(0.0080)	0.0099(0.0076)	0.0021(0.0021)	+5%	−78%
No. quartz grains/ unit area (mm^2)	25	31.5	23	+26%	−8%	33	22	23	−33%	−30%
Total area of quartz/unit domain area (mm^2)	0.38	0.26	0.055	−32%	−86%	0.31	0.22	0.048	−29%	−85%
BIOTITE										
Area of mean grain (mm^2)	0.0074(0.011)	0.004(0.003)	0.0017(0.0014)	−46%	−77%	0.0018(0.0018)	0.0048(0.0042)	0.0038(0.0026)	+167%	+111%
No. biotite grains/ unit area (mm^2)	8	15.2	19.7	+90%	+146%	23.8	14.6	15.4	−39%	−35%
Total area of biotite/unit domain area (mm^2)	0.059	0.061	0.033	+3%	−44%	0.043	0.070	0.059	+63%	+37%

Notes

(1) Number of grains counted: Quartz—in section parallel to F_4, 93 (crenulated S_2); 48 (QM); 92 (M). In section perpendicular to F_4, 273 (crenulated S_2); 95 (QM); 72 (M). Biotite—in section parallel to F_4, 160 (crenulated S_2); 64 (QM); 47 (M). In section perpendicular to F_4, 52 (crenulated S_2); 11 (QM); 74 (M).

(2) Numbers in brackets are standard deviations.

(3) All grain data are given to two significant figures.

(4) Dimensions measured are apparent dimensions of grains as seen in two perpendicular surfaces.

(5) C.S_2, crenulated S_2.

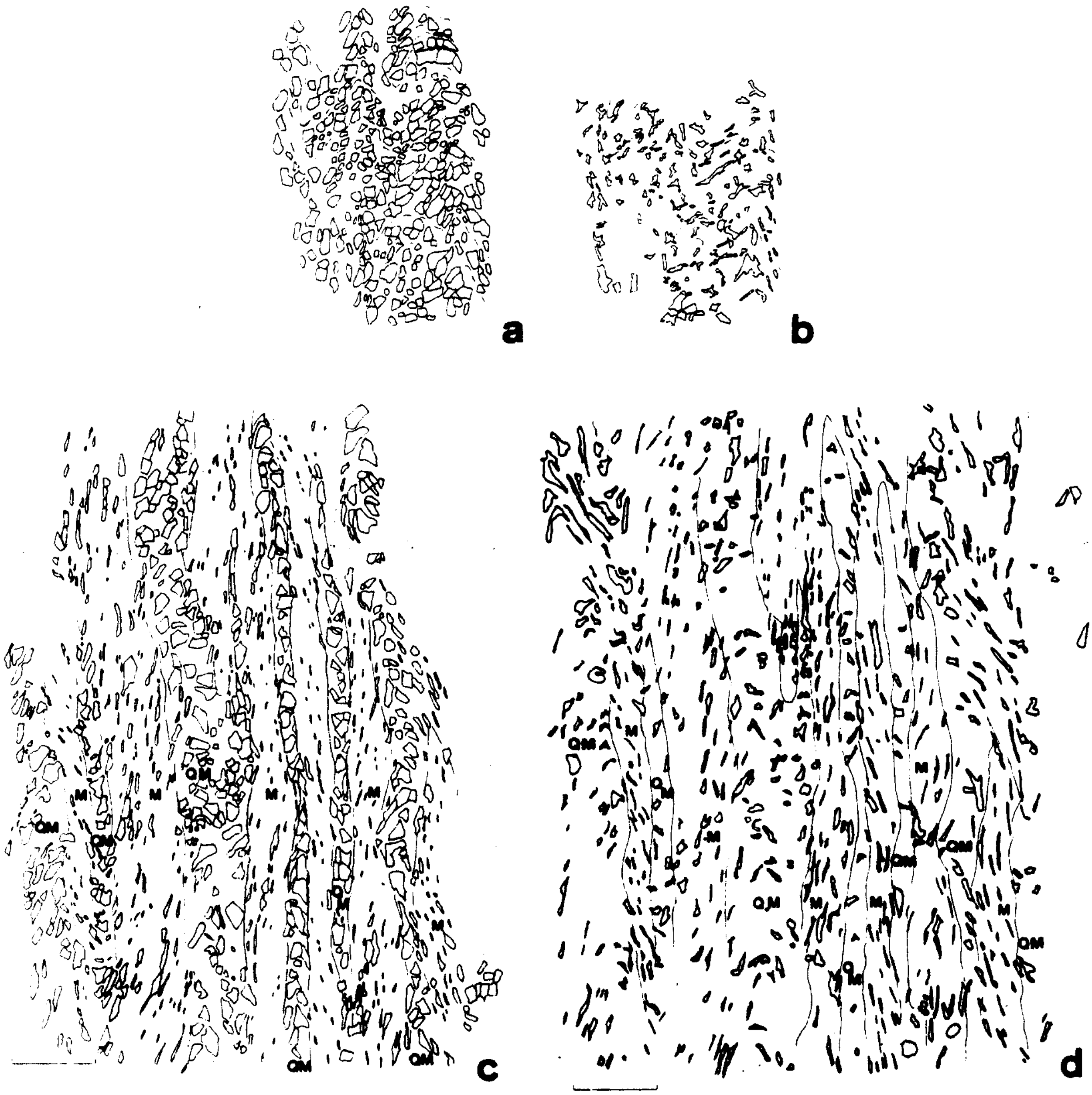

Fig. 4. (a) Shadowmaster sketch of crenulated S_2 enclave in a section perpendicular to F_4 showing shape, size and proportion of quartz grains. Trend lines of S_2 are also shown. Bar scale, 2.5 mm. (b) Shadowmaster sketch of a crenulated S_2 enclave in a section perpendicular to F_4 showing shape, size and proportion of biotite grains. Trend lines of S_2 are also shown. Bar scale, 2.5 mm. (c) Shadowmaster sketch of a section perpendicular to F_4 showing changes in shape, size and proportion of quartz grains between QM and M domains. Bar scale, 1 mm. (d) Shadowmaster sketch of a section perpendicular to F_4 showing changes in shape, size and proportion of biotite grains between QM and M domains. Bar scale, 1 mm.

onto quartz grains in QM domains. However, it is necessary to allow not only for an increase in grain size caused by overgrowths, but also for the possibility that transported SiO_2 is able to precipitate and grow as new grains. Thus, changes in the number of grains/unit area and the total area of quartz/unit area (Table 2) have to be taken into account. Decrease in the total area of quartz/unit area from crenulated S_2 enclaves to QM domains in the sections both parallel and perpendicular to F_4 precludes addition of material to QM domains. In this context, the increase in number of grains of quartz/unit area from crenulated S_2 to QM domains in section parallel to F_4 probably reflects large grains being split into smaller centres by solution.

I thus argue that the models of Cosgrove (1976, p. 170), Gray (1979 pp. 108–120) and others which favour transfer of SiO_2 out of M into QM domains are not applicable in any significant degree to the rocks studied here. If SiO_2 released from solution of quartz grains has not entered QM domains, it must either have left the system and/or been used up in formation of new minerals. This is discussed after the section on biotite.

Biotite component migration patterns

Because of their non-uniform size and distribution (e.g. Fig. 2c), biotite grains are more difficult to work with than quartz grains. Because of this heterogeneous distribution and because large grains at the edge of the crenulated S_2 enclave of Fig. 2(c) were not counted, and because there is no syn-S_4 growth of biotite which could cause the areal increases in grains in the section perpendicular to F_4, data from this section were not used. Areal data from the section parallel to F_4 are more reliable and indicate a reduction of 46 and 77%, respectively, between crenulated S_2 and QM and M domains. The total area of biotite/unit area of domain is roughly the same between crenulated S_2 and QM domains, but decreases between crenulated S_2 and M domains. The mineral composition data given in Table 1 also rule out any increase of biotite in QM domains. Thus the increase in number of grains/unit area probably reflects splitting of larger grains.

As with the quartz data, components of biotite have been lost from both M and QM domains. They have either left the system or been used in mineral forming reactions.

General mobility patterns

As indicated above, both quartz and biotite components have left the system and/or been used up in chemical reactions. Let us consider the implications of chemical reaction. The only new minerals optically identified in the groundmass are chlorite, pseudomorphous after biotite, muscovite, pseudomorphous after biotite, and unstrained muscovite cutting across deformed biotite grains in F_4 hinge zones. These new minerals are assumed to be syn-S_4 in age. Note that with the exception of 'sericite' grains in aggregates after andalusite crystals, there is no evidence in these rocks of new mineral growth controlled by the D_4 strain field. Although no biotite, chlorite or muscovite grains from the Mt. Franks area were analysed, analyses of similar minerals in similar settings from similar rocks are presented by Corbett & Phillips (1981, table 1). Their column 1 represents muscovite probably similar to that in S_2; their column 6 represents biotite grains and their columns 8 and 9 are chlorite after biotite.

1. *Biotite to chlorite*. This reaction is constrained by the major phases conserving volume. Molar volumes were obtained from the molecular weights (obtained from analytical data of Corbett & Phillips 1981) divided by mineral densities (obtained from Deer *et al.* 1962 and using an average of 3.2 gm cm^{-3} for biotite and 3 gm cm^{-3} for chlorite. The resultant unbalanced molecular equation is,

$$1 \text{ biotite} \rightarrow 0.7 \text{ chlorite}.$$

Such an equation involves production of silica, and can be rewritten as

$$1\,\text{cm}^3 \text{ biotite} \rightarrow 1\,\text{cm}^3 \text{ chlorite} + 0.214\,\text{cm}^3 \text{ quartz}.$$

2. *Biotite to muscovite (pseudomorphs)*. Using the analytical data of Corbett & Phillips (1981) and a density of 2.9 gm cm^{-3} (an average from Deer *et al.* 1962) the resultant unbalanced molecular equation is,

$$1 \text{ biotite} \rightarrow 1.06 \text{ muscovite}.$$

Small amounts of silica have to be introduced on the left-hand side of the reaction, and the equation can be rewritten as

$$1\,\text{cm}^3 \text{ biotite} + 0.18\,\text{cm}^3 \text{ quartz} \rightarrow 1\,\text{cm}^3 \text{ muscovite}.$$

3. *General reactions*. Other biotite to muscovite reactions are not constrained by constancy of volume, and silica is required for any reaction, for example:

$$1 \text{ biotite} \rightarrow \geq 0.87 \text{ muscovite}.$$

For biotite → muscovite, the amount of silica required is less than the amount liberated by the reaction biotite → chlorite. However, the capacity for this latter reaction to supply silica to the reaction biotite → muscovite is constrained by the small amount of chlorite in the rock. Once this supply has been exhausted, the most obvious source of silica is that released by the solution of quartz. Thus, depending on the amount of chlorite and identifiable syn—S_4 muscovite in the rock, not all biotite components need leave the system: some are used in the production of new minerals. In a similar way, depending upon the amount of biotite used up in reaction, small amounts of silica need not leave the system.

4. *Growth of muscovite*. Let us look simplistically at a hypothetical quartz grain bounded by continuous muscovite layers and extending from a QM domain into an M domain. The grain will be 71% smaller in the M domain than in the QM domain (see table 2). This reduction in area was caused by solution of quartz during the D_4 deformation. (Some reduction in area may have also been caused by the quartz grain being constrained to deform between micas acting as strong fibres (e.g. Hobbs *et al.* 1976, p. 251). However, this is unlikely because it assumes the quartz is bonded to the muscovite and no sliding has occurred). Solution of quartz would result in the formation of one or more 'holes' lying between the drastically reduced quartz grain and the bounding muscovites. These 'holes' could be removed by (i) a volume decrease, locally totalling 71% of the original mean quartz grain, (ii) growth of new mineral(s) or (iii) a combination of processes (i) and (ii). If there were no new mineral growth, one might expect to find either 'holes' between the reduced quartz grain and the bounding muscovite, or muscovite layers curved or deflected inwards as they maintain contact with the reduced grain. Curving of mica layers in such a way could result in the formation of other 'holes' further out in the rock matrix. As far as the author is aware, heterogeneities of this type have not been reported in the literature. Either they are not detectable or, following points (ii) and (iii) above, there has been some

mineral growth to take up some of the volume decrease. Marlow & Etheridge (1977) were the first to suggest that there had been new muscovite growth within crenulated schistosity during the formation of a new layered schistosity. Their suggestion (p. 880) was not based on optical evidence, but on a non-reconciliation between modal data with grain-size and number data.

In the rocks studied here, evidence for the formation of 'holes' or new minerals must be based on optical examination. This is because, unlike Marlow & Etheridge (1977), muscovite proportions were not measured directly. Direct evidence either way is hard to come by, not least for the reason that it is rare to find quartz grains or aggregates which are continuous across domain boundaries. One such aggregate, thinning from a QM into an M domain is shown in Fig. 2(b). Relations on the left side of the quartz grain are not diagnostic because this side of the grain lies along the domain boundary. Here, elongate biotite is present along the edge of the quartz grain in the M domain. Iron-oxide accumulations further up the grain may be partly after biotite. On the right side of the grain, muscovite layers adjacent to the grain in the QM domain are no longer adjacent to the grain in the M domain. Rather, they are separated from it by shorter muscovites which terminate at small angles against the quartz grain within the M domain. Detailed relations in this area (Fig. 2b) show that some of these short micas are oblique (*c.* 10°) to, and possibly cut across, muscovites parallel to the continuous bounding layer.

My preferred interpretation of these relationships is that the short muscovite grains grew within the crenulated S_2 schistosity during the D_4 deformation, and have grown to fill some of the area occupied by the quartz grain; that area having been previously removed by solution of SiO_2.

5. *Amount of silica lost to the system*. If no new minerals grew during the formation of S_4, the data given in Tables 1 and 2 suggest that the reduction in total area of quartz/unit area of domain of 85–86% in two orientations could be achieved by a total 'volume' decrease of the rock of 25–30%. The following points suggest that this decrease would not be drastically changed, given the small amounts of identifiable muscovite and chlorite, and even allowing for an unknown amount of muscovite growth in S_2 (see above). Based on the assumptions that muscovite growth took place at the expense of biotite + quartz, and that biotite components have not been introduced into the rock, the amount of biotite present constrains the amount of possible new muscovite growth. However, not only is the amount of biotite in the rock very much less than that of quartz, the amount used up is proportionately very much less than that of quartz. This may reflect differences in solubilities, (see e.g. Gray & Durney 1979). Furthermore, each amount of biotite used up in reaction, requires only 20% of that amount of quartz. Thus most of the silica dissolved in solution has probably left the system, and a 'volume' change of about 20–25% seems reasonable.

SUMMARY

An S_4 metamorphic layering from part of the Willyama Complex, New South Wales, Australia is defined by alternating M and QM domains which correspond to the limbs and hinges of symmetrical F_4 crenulations, and to the long limbs and hinges plus the short limbs of asymmetrical F_4 crenulations. M and QM domains are defined by different shapes, sizes and proportions of quartz and biotite and by different proportions of muscovite: M domains are richer in muscovite, and poorer in biotite and quartz than QM domains. Changes in the shapes, sizes and proportion of quartz and also biotite grains have been achieved by partial or complete solution of the grains, and by transfer of components in solution.

Attempts to ascertain migration patterns of soluble components during the formation of the S_4 layering are based on (1) examination of the rock in two (not just one) orientations, perpendicular and parallel to the axes of F_4 crenulations and (2) on a comparison of grain shapes, sizes and proportions in M and QM domains with those in enclaves of less-strongly crenulated S_2.

Measurement and comparison of grain sizes and proportions in crenulated S_2 enclaves with those in M and QM domains allow the following points to be made.

(1) SiO_2 has been lost from quartz grains in both M and QM domains. There is no sign that SiO_2, lost from M domains, has migrated into adjacent QM domains to form either overgrowths or new grains.

(2) Most of the SiO_2 dissolved from quartz grains has left the system although some has been used, together with biotite components, in the formation of syn-S_4 muscovite.

(3) Biotite grains have undergone less solution than quartz grains. Most of the biotite has probably undergone chemical reaction to muscovite or to chlorite. Insoluble components such as iron oxides have possibly been concentrated. Other components have probably left the system.

(4) Within M domains, some syn-S_4 growth of muscovite probably occurred within the crenulated S_2 schistosity. This growth took up some of the volume previously occupied by wholly or partly dissolved grains of biotite and quartz. However, the amount of muscovite formed in this way was limited, being restricted by the amount of biotite in the rock, according to the reaction biotite + quartz → muscovite.

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APPENDIX

In Table 2, there is, in some cases, considerable overlap between domains in grain dimensions within the range of one standard deviation. In order to assess the statisical significance of such data, the standard error in the mean,

$$\text{S.E.M.} = \text{S.D.}\ \frac{\text{standard deviation}}{\sqrt{\text{number of grains}}}$$

of each dimension was calculated and is listed below. Comparison of data between domains can now be made in terms of differences in mean dimension, with associated standard error:

$$M_1 - M_2 \pm \sqrt{(\text{S.E.M.}_1)^2 + (\text{S.E.M.}_2)^2}.$$

Significant changes are those where the difference in the means between domains is about five or six times greater than the associated standard error.

Section parallel to F_4

Mean ± S.E.M.

Quartz	Cren. S_2	QM	M
length	0.19 ± 0.0072	0.16 ± 0.012	0.11 ± 0.0058
width	0.12 ± 0.0048	0.073 ± 0.0033	0.03 ± 0.0018
area	0.015 ± 0.00097	0.0082 ± 0.0010	0.0024 ± 0.00025
Biotite	Cren. S_2	QM	
area	0.0074 ± 0.00087	0.0040 ± 0.0005	0.0017 ± 0.0025

$M_1 - M_2 \pm \sqrt{(\text{S.E.M.}_1)^2 + (\text{S.E.M.}_2)^2}$

Quartz	Cren. $S_2 \rightarrow$ QM	Cren. $S_2 \rightarrow$ M
length	0.03 ± 0.014	0.08 ± 0.0092
width	0.047 ± 0.0058	0.09 ± 0.0051
area	0.0068 ± 0.0014	0.0126 ± 0.0010
Biotite	Cren. $S_2 \rightarrow$ QM	Cren. $S_2 \rightarrow$ M
area	0.0034 ± 0.0000010	0.0057 ± 0.0000071

Section perpendicular to F_4

M ± S.E.M.

Quartz	Cren. S_2	QM	M
length	0.14 ± 0.0034	0.018 ± 0.0064	0.011 ± 0.0073
width	0.083 ± 0.0020	0.073 ± 0.0037	0.021 ± 0.0011
area	0.0094 ± 0.00048	0.0099 ± 0.00078	0.0021 ± 0.0025
Biotite	Cren. S_2	QM	M
area	0.0018 ± 0.00025	0.0048 ± 0.0014	0.0038 ± 0.00044

$M_1 - M_2 \pm \sqrt{(\text{S.E.M.}_1)^2 + (\text{S.E.M.}_2)^2}$

Quartz	Cren. $S_2 \rightarrow$ QM	Cren. $S_2 \rightarrow$ M
length	−0.04 ± 0.0073	+0.129 ± 0.0081
width	+0.10 ± 0.0042	+0.062 ± 0.0023
area	−0.0005 ± 0.00092	+0.0073 ± 0.0054
Biotite	Cren. $S_2 \rightarrow$ QM	Cren. $S_2 \rightarrow$ M
area	−0.003 ± 0.0000021	−0.002 ± 0.00000025