

Deformation volume and cleavage development in metasedimentary rocks from the Ballarat slate belt

HELEN M. WALDRON* and MICHAEL SANDIFORD†

Department of Geology, University of Melbourne, Parkville, Victoria 3052, Australia

(Received 24 April 1986; accepted in revised form 26 August 1987)

Abstract—Psammites from the Ballarat slate belt in SE Australia exhibit well-developed differentiated or spaced cleavage defined by alternating phyllosilicate- and quartz-rich domains (termed P- and Q-domains, respectively). Strain estimates derived from independent microstructural and chemical observations suggest that the P–Q fabrics developed in response to plane-strain deformation dominated by solution transfer with the principal finite shortening in the P-domains approximately twice that in the adjacent Q-domains. Significant finite extensions are indicated by ubiquitous quartz–albite–chlorite overgrowths in both P- and Q-domains, while pressure-shadow development around syntectonic pyrite porphyroblasts suggest finite extension of at least 100%. This estimate is comparable with the extension predicted for constant-volume deformation and consequently there appears to have been no significant bulk material loss or gain on the hand-specimen scale. These observations are consistent with solute transfer scales as little as a few centimetres via diffusion in a stationary fluid and do not require, although do not necessarily preclude, large-scale advective fluid transport through the slate belt during cleavage formation as suggested in previous studies.

INTRODUCTION

PARTITIONING of strain during cleavage formation in low-grade psammites commonly results in the development of spaced cleavage defined by alternating phyllosilicate- and quartz-rich domains, termed P- and Q-domains, respectively (Williams 1972, Stephens *et al.* 1979, Beach 1979). P–Q fabrics are believed to develop as a consequence of solution transfer in which dissolution has been strongly localized in the P-domains because (1) substantial chemical differentiation is associated with deformation and (2) detrital quartz grains show little evidence of plastic deformation but are strongly corroded, especially in P-layers.

The transfer distance of solute generated by dissolution in P-domains has been the subject of much speculation and is a problem which has considerable implications for the nature of fluid behaviour in low-grade metamorphic terrains (Marlow & Etheridge 1977, Alvarez *et al.* 1978, Beutner 1978, Gray 1978, Beach 1979, Stephens *et al.* 1979, Kreulen 1980, Knipe 1981, Pique 1982, Wright & Platt 1982, Etheridge *et al.* 1983, Bell 1985, Engelder & Marshak 1985). For small transfer distances, of the order of a few centimetres, the deformation may be considered as a closed system, and to a first approximation, as constant volume (ignoring the contribution to volume loss which may be due to collapse of porosity and phase changes). For larger transfer distances, the deformation on the hand-specimen scale is an open system and may involve large volume losses. Proponents of large volume loss or open system behaviour (e.g. Etheridge *et al.* 1983) have argued that

solute transfer distances are so large that metamorphic terrains exhibiting P–Q fabrics must have been flushed by a highly mobile advecting fluid possibly forming part of a large-scale convection system. This conclusion is not likely to apply to closed system behaviour. In view of the importance of such models for our understanding of the evolution of metamorphic terrains, we believe the evidence for closed system vs open system behaviour during the development of P–Q fabrics is in urgent need of evaluation.

Distinction between deformation involving constant volume and volume loss during the development of P–Q fabrics is only possible if the finite strain associated with cleavage formation is known, particularly the relative partitioning of strain between P- and Q-domains. In this paper we investigate this relationship between the finite strain, strain partitioning and the deformation volume in the development of P–Q fabrics using a combination of microstructural and chemical criteria to determine strain in natural samples from the Ballarat slate belt in Victoria, SE Australia (Fig. 1). We consider the implications of our findings in the light of speculation about the role of fluid and its behaviour in low-grade deformation dominated by solution transfer. The Ballarat slate belt provides an apt setting for this study because this region has provided the inspiration for much of the pioneering work relating to cleavage development (e.g. Hills & Thomas 1944, Stephens *et al.* 1979, White & Johnston 1981). Also, an example from this belt has been used in a recent controversial study by Etheridge *et al.* (1983) concerning the role of the fluid phase during regional metamorphism.

THEORETICAL CONSIDERATIONS

In order to investigate the nature of the deformation volume during cleavage development in P–Q fabrics, we

* Present address: Becquerel Laboratories Pty Ltd, P.O. Box 93, Menai, N.S.W. 2234, Australia.

† Present address: Department of Geology and Geophysics, University of Adelaide, G.P.O. Box 498, Adelaide, S.A. 5001, Australia.

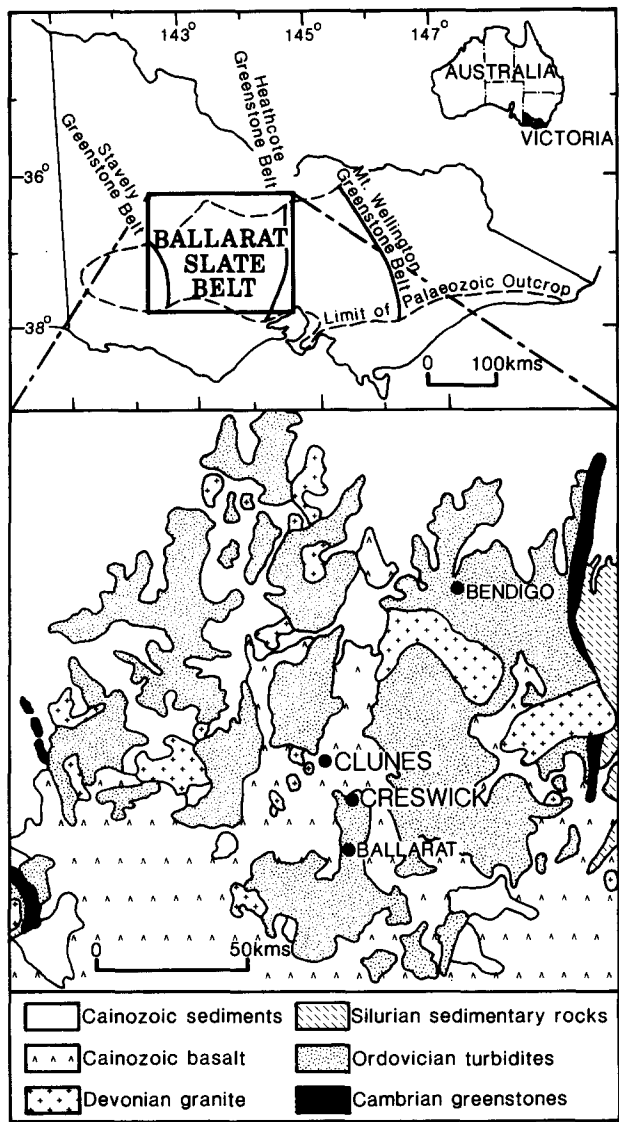


Fig. 1. Locality map showing the geological setting of the Ballarat slate belt.

begin by examining the theoretical relationships between finite strain, strain partitioning between P- and Q-domains and deformation volume. We consider the special case of constant-volume plane-strain deformation in which strain is accommodated by solution transfer. Justification for the treatment of the system in plane

strain and for the assumption that strain is accommodated by solution transfer is provided by consideration of fabrics in the natural samples from the Ballarat slate belt, described in the following sections (see also Gray & Durney 1979), and from many other examples described in the literature (Cloos 1947, Engelder 1979).

P-Q fabrics can be considered as a special case in which deformation is partitioned between two distinct domains, with the P-domains being high strain zones and the Q-domains being low strain zones (Fig. 2). In order to maintain strain compatibility both P- and Q-domains must undergo identical extensions in the plane of the cleavage (i.e. the plane containing the P-Q boundary). Strain partitioning therefore reflects different degrees of shortening across the domain boundary perpendicular to the cleavage plane (Fig. 2). We consider here the general case in which both incipient P- and Q-domains undergo shortening (Fig. 2). For constant-volume plane-strain deformation the strain partitioning ($\epsilon_{P,Q}$) between P- and Q-domains is defined as:

$$\epsilon_{P,Q} = P_0Q/PQ_0. \tag{1}$$

The ratios P_0/P and Q_0/Q have a special significance for plane-strain deformation accommodated by solution transfer, as they represent the ratio of the major and minor axes of the component of the finite-strain ellipse defined by dissolution alone in each domain. For instance, in a deformed psammite composed initially of spherical quartz grains, these ratios would be given by the length/width or aspect ratio of the corroded detrital quartz grains. We define the aspect ratios in the P- and Q-domains, respectively, $A_p = P_0/P$ and $A_q = Q_0/Q$. From (1) it follows that:

$$\epsilon_{P,Q} = A_p/A_q. \tag{2}$$

The principal extension in the cleavage plane (ϵ_x) is defined as

$$\epsilon_x = (L - L_0)/L_0. \tag{3}$$

For constant-volume deformation

$$RL_0 = (P + Q)/(L - L_0), \tag{4}$$

where

$$R = (P_0 + Q_0) - (P + Q).$$

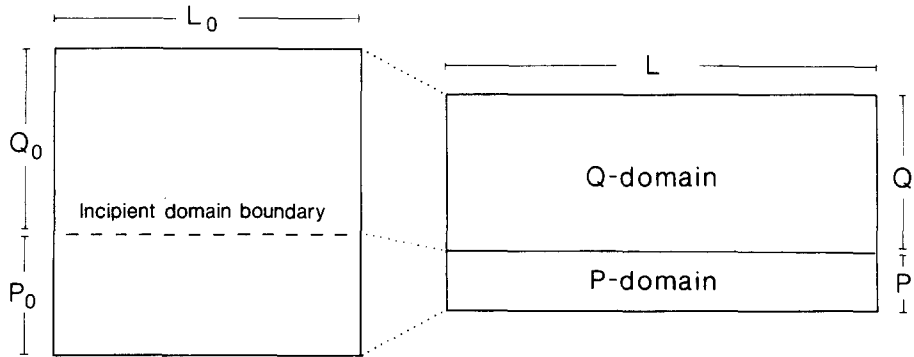


Fig. 2. Diagrammatic representation of the development of P-Q fabric, for constant-volume plane-strain deformation in which strain is preferentially partitioned into P-domains (see discussion in text). The P-Q fabric shown on the right is assumed to have been derived from an initially homogeneous body shown on the left. Constant extension in both P- and Q-domains is allowed by material transfer across the domain boundary via a solution-transfer deformation mechanism.

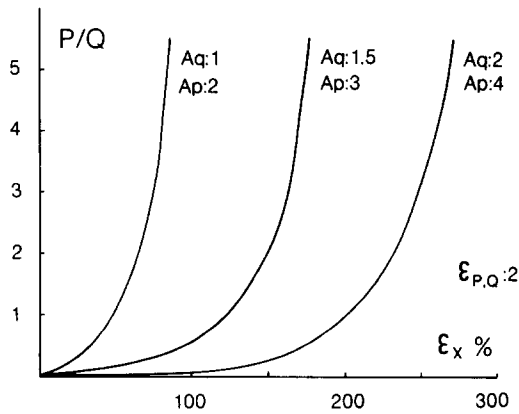


Fig. 3. Graphical representation of relations between ϵ_x , P, Q, Ap and Aq (see text) for constant-volume plane-strain deformation resulting in P-Q fabric development with the finite shortening in P-domains twice as much as in Q-domains.

Substituting for P_0 and Q_0 yields

$$R = PAp + QAq - (P + Q). \quad (5)$$

Combining equations (3) and (4) yields

$$R = \epsilon_x(P + Q). \quad (6)$$

Combining (5) and (6) yields

$$\epsilon_x = \frac{PAp + QAq}{P + Q} - 1. \quad (7a)$$

Substituting (2) in (7a) yields the equivalent expressions

$$\epsilon_x = \frac{Aq(P\epsilon_{P,Q} + Q)}{P + Q} - 1 \quad (7b)$$

and

$$\epsilon_x = \frac{Ap(P + Q/\epsilon_{P,Q})}{P + Q} - 1. \quad (7c)$$

The relationships among ϵ_x , Ap, Aq, $\epsilon_{P,Q}$, P and Q are shown graphically in Fig. 3.

Equations 7(a-c) are only strictly true for the special case where differentiation of P- and Q-domains occurs instantaneously at the beginning of the deformation. In the more general case where P-domains are initiated after deformation has already commenced, these equations will provide absolute minimum extensions for the constant-volume condition. The precise value of ϵ_x will then depend not only on the relative strain partitioning between, and the volumetric proportions of, P- and Q-domains, but also on the proportion of strain accom-

modated by deformation prior to the initiation of a P-domain.

P-Q FABRIC DEVELOPMENT IN PSAMMITES FROM THE BALLARAT SLATE BELT

The theoretical considerations presented in the previous section provide a basis for examining the volume changes during P-Q fabric development in natural samples. In this section we describe the microstructural and chemical characteristics of some samples in which the deformation is believed to closely approximate the conditions of plane strain, and in which the deformation mechanism was dominantly solution transfer. These samples are Lower Ordovician psammites from the Ballarat slate belt in Victoria, SE Australia. The slate belt consists of a turbidite sequence folded into a series of upright N-trending folds during the early-Middle Devonian Tabberabberan deformation (Thomas 1939, Sandiford & Keays 1986). This deformation has produced a well-developed spaced cleavage, or P-Q fabric, in some of the psammites as well as a slaty cleavage in the interbedded pelites. These fabrics are axial planar to the upright folds and clearly truncate sedimentary bedding. The samples described in this study are from drillholes at Clunes (sample Nos 21 and 24) and Creswick (sample Nos 28 and 42). The microstructural and chemical development of P-Q fabrics in Victorian Ordovician metasedimentary rocks has been described in a number of detailed studies (Hills & Thomas 1944, Glasson & Keays 1978, Stephens *et al.* 1979, White & Johnston 1981). In this contribution we present new petrographic descriptions and geochemical data as they relate to the aims of this paper. The reader is, however, referred to the previous work; in particular, the work of Stephens *et al.* (1979) for a more thorough discussion of the rocks hosting the P-Q fabrics from Clunes.

In hand specimen, the P-Q fabric is defined by the development of alternate light (Q) and dark (P) striping on a centimetre scale (Fig. 4a-d). The morphology of this striping varies considerably, with individual P-domains ranging in thickness from a few millimetres up to 1 cm. In some samples the boundary between domains is sharp (Fig. 4a, b & d), while in others it is gradational (Fig. 4c). Individual P-domains may be sub-parallel and separated by planar Q-domains, or form anastomosing

Table 1. Aspect ratios of detrital quartz grains in XY and YZ sections, concentration factors and measured and predicted extensions for four psammites

Sample	P/Q	Aq(XZ)	Aq(YZ)	Ap(XZ)	Aq(YZ)	Ap/Aq(XZ)	Ap/Aq(YZ)	C_I^*	Predicted ϵ_x	Measured ϵ_x
21	0.26	1.58	1.55	4.01	3.12	2.54	2.01	2.50	1.09	>1.25
24	0.29	1.59	1.46	3.29	2.95	2.07	2.01	1.69	0.97	—
28	0.25	1.81	1.74	3.44	2.95	1.90	1.70	2.01	1.14	—
42	0.20	1.55	1.52	2.71	2.69	1.75	1.77	2.66	0.74	—

* $C_I = \frac{\text{concentration of Zr in P-domains}}{\text{concentration of Zr in Q-domains}}$

networks isolating lenticular Q-domains. In all cases P-domains are volumetrically subordinate to Q-domains with typical ratios of P-domains to Q-domains (P/Q) of 0.2–0.3 (Table 1).

Petrography

In order to investigate the microstructural features of the P–Q fabrics, each sample has been sectioned along three planes: parallel to the cleavage (*XY*) within both P- and Q-domains; perpendicular to cleavage and parallel to the direction of the maximum finite extension (*XZ*); and perpendicular to both cleavage and to the direction of maximum finite extension (*YZ*).

In thin section, P- and Q-domains are distinguished by the relative proportions of constituent minerals, particularly phyllosilicates, albite and quartz (Table 2), and by the distinct microstructures in each domain (Figs. 4 and 5). This microstructural variation is well illustrated by the aspect ratio of relict detrital quartz grains (measured in *XZ* and *YZ* sections). In both domains relict detrital quartz grains are elongate within the plane of the cleavage, both in *XZ* and *YZ* sections, with the mean aspect ratio of grains in P-domains typically twice that for quartz grains in adjacent Q-domains (Fig. 6, Table 1). The mean aspect ratios of quartz grains in *XZ* sections are marginally, although probably not significantly, greater than the aspect ratios for grains in *YZ* sections from the same domain (Fig. 6).

Detrital quartz grains generally show only minor evidence of plastic deformation in the form of slight undulose extinction (Fig. 4f), and recrystallization textures, which are only rarely observed (Fig. 5d). Fibrous

quartz–chlorite overgrowths on detrital grains are elongated in the *X* direction and are abundant in both P- and Q-domains (Fig. 5b & d). No fibres have been observed elongated in the *Y*-direction. Detrital muscovite grains are variably oriented, with (100) frequently at a high angle to the rock cleavage in Q-domains, and at a low angle to the rock cleavage in P-domains, suggesting considerable mechanical rotation in the latter. In the Q-domains detrital muscovite is commonly disaggregated with secondary chlorite forming overgrowths between the pulled-apart fragments of muscovite (Fig. 5c). In such intergrowths the proportion of secondary chlorite is commonly equal to, or greater than the muscovite, implying large (>100%) extensions in *X*. Syntectonic pyrite porphyroblasts with large quartz pressure shadows elongated only in the *X* direction occur in some other samples from Clunes and Creswick but are present only in one of the samples (No. 21) described here (Fig. 5a).

The absence of pressure-shadow and fibrous overgrowth elongation in the *Y* direction in *XY* sections suggests that deformation occurred in the plane-strain or constrictional-strain fields, and together with the absence of evidence for dissolution of detrital quartz grains parallel to *X* in *XY* sections, suggests that the deformation was a plane strain. The pressure-shadow development about pyrite porphyroblasts implies extension in *X* of at least 120–130%. Because of the possibility that substantial strain accumulated prior to porphyroblast growth, this value is likely to be an absolute minimum for finite extension associated with cleavage formation. While it is not possible to quantify the amount of strain in the other samples described due to

Table 2. Chemical analyses and normative mineralogy of P- and Q-domains for four psammites

Sample	21			24			28			42		
Domain	Q	P	P/Q	Q	P	P/Q	Q	P	P/Q	Q	P	P/Q
Element												
SiO ₂ wt%	77.84	60.83	0.78	78.78	66.20	0.84	75.70	58.89	0.78	80.73	59.06	0.73
TiO ₂	0.39	1.02	2.62	0.40	0.78	1.95	0.52	1.11	2.13	0.49	1.18	2.41
Al ₂ O ₃	9.47	19.21	2.03	9.59	16.24	1.69	10.03	19.01	1.90	9.09	19.95	2.19
Fe ₂ O ₃	3.17	4.45	1.40	3.23	4.27	1.32	3.99	5.53	1.39	2.12	5.90	2.78
MgO	1.44	2.37	1.65	1.44	2.26	1.57	1.91	2.73	1.43	0.65	1.74	2.68
K ₂ O	1.78	5.68	3.19	1.70	4.47	2.63	2.07	5.25	2.54	1.66	5.50	3.31
Na ₂ O	1.86	1.46	0.78	1.98	1.59	0.80	1.28	0.98	0.77	1.44	0.49	0.34
Y ppm	34	74	2.18	34	56	1.65	35	69	1.97	31	77	2.48
Zr	130	325	2.50	135	228	1.69	184	370	2.01	158	420	2.66
Sr	75	64	0.85	46	47	1.02	97	81	0.84	74	78	1.05
Rb	91	270	2.97	85	215	2.53	97	247	2.55	78	265	3.40
V	38	96	2.53	37	82	2.22	45	105	2.23	35	110	3.14
Th	12.0	30.6	2.55	10.9	18.1	1.66	11.6	24.8	2.14	9.75	22.6	2.32
Hf	5.18	11.8	2.28	4.89	8.90	1.82	7.08	14.8	2.09	6.69	15.3	2.29
Σ REE	127.3	354.0	2.78	136.2	254.9	1.87	152.1	321.5	2.11	121.2	444.9	3.67
Normative mineralogy %												
Apatite	0.3	0.5	1.7	0.3	0.5	1.7	0.4	0.7	1.8	0.3	0.7	2.3
Rutile	0.4	1	2.5	0.4	0.8	2.0	0.5	1.1	2.2	0.5	1.2	2.4
Chlorite	9.4	11.8	1.3	9.5	12.5	1.3	12.8	15.3	1.2	3.1	6.9	2.2
Muscovite	17.8	56.8	3.2	17	44.7	2.6	20.7	52.5	2.5	16.6	55	3.3
Albite	12.7	1.7	0.1	14.3	4	0.3	7.8	3.6	0.5	10.8	0	0
Quartz	57.4	25.7	0.4	57.9	35.3	0.6	56.4	27	0.5	64.6	31	0.5
Pyrite	0.5	0.3	0.6	0.2	0.1	0.5	0.5	0.3	0.6	0.4	0.3	0.8
Zircon	0.03	0.07	2.3	0.03	0.05	1.7	0.04	0.07	1.8	0.03	0.08	2.7

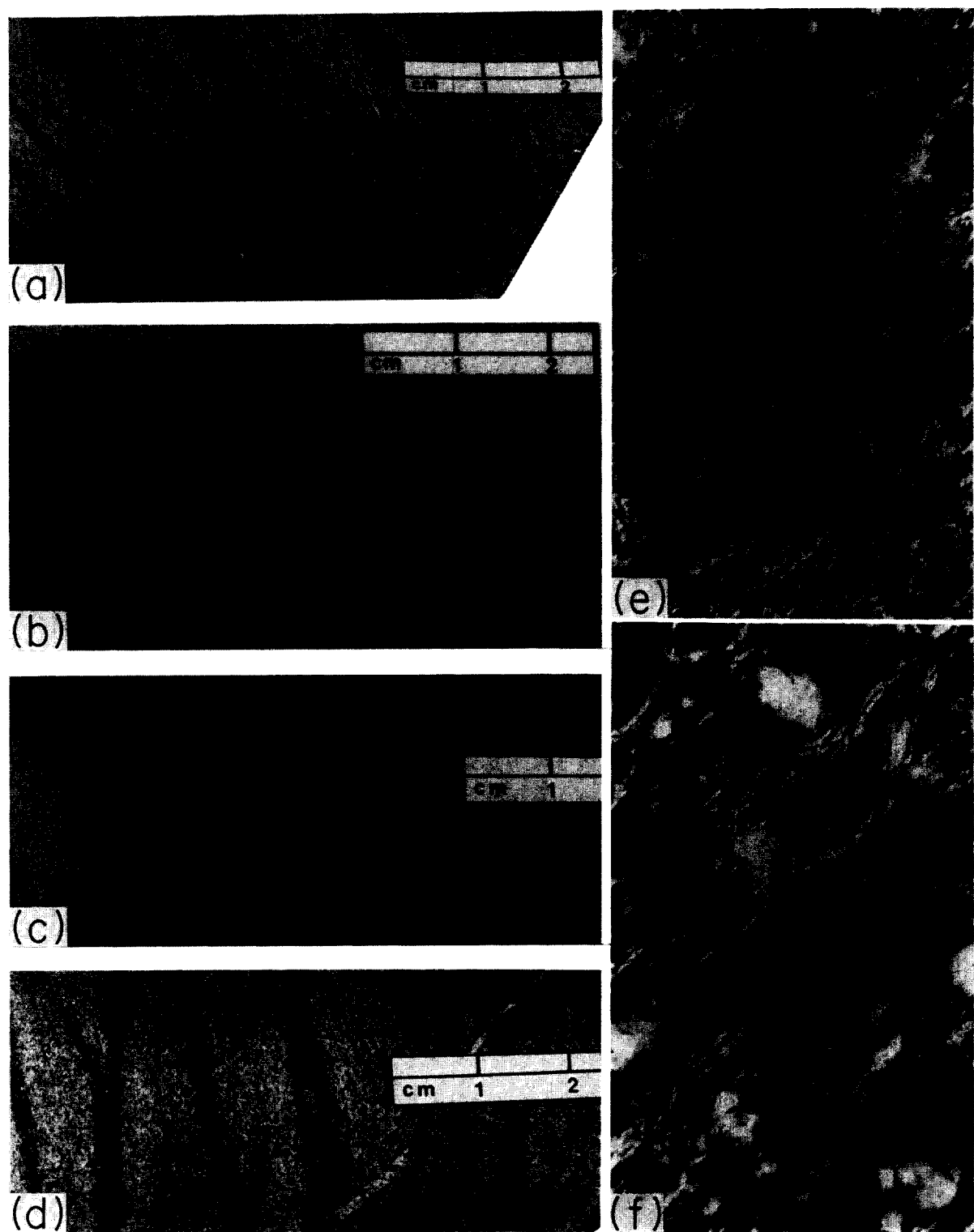


Fig. 4. (a)–(d) Drill core from Ballarat slate belt showing variable morphological development of P–Q fabrics. (a) Sample 21; (b) Sample 24; (c) Sample 28 and (d) Sample 42. (e) *XZ* section through P-domain in Sample 21. Field of view is approximately 1.3×2.0 mm. (f) *XZ* section through Q-domain in Sample 21. Field of view is approximately 1.3×2.0 mm.

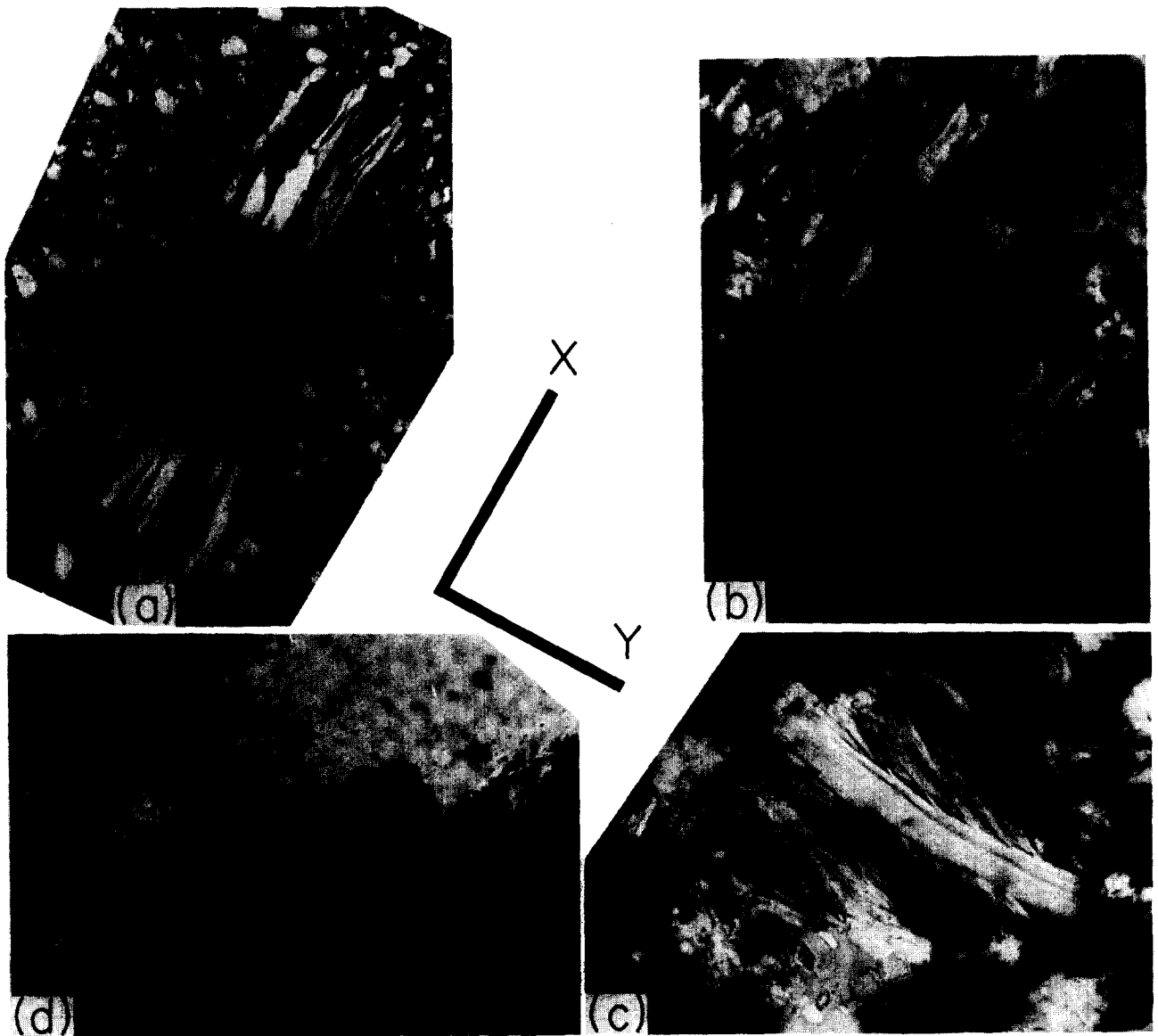


Fig. 5. Detailed microstructure in *XY* section of Q-domain in Sample 21. (a) Quartz fibre development in pressure shadow developed around pyrite porphyroblast. Field of view is approximately 2.0×3.5 mm. (b) Detail of (a) showing elongation of quartz-chlorite fibrous overgrowths on detrital quartz grains. Field of view is approximately 0.25×0.3 mm. (c) Pulled apart detrital muscovite flake. Individual pull apart zones are infilled with chlorite. Field of view is approximately 0.4×0.5 mm. (d) Marginal recrystallization of detrital quartz grain. Field of view is approximately 0.2×0.3 mm.

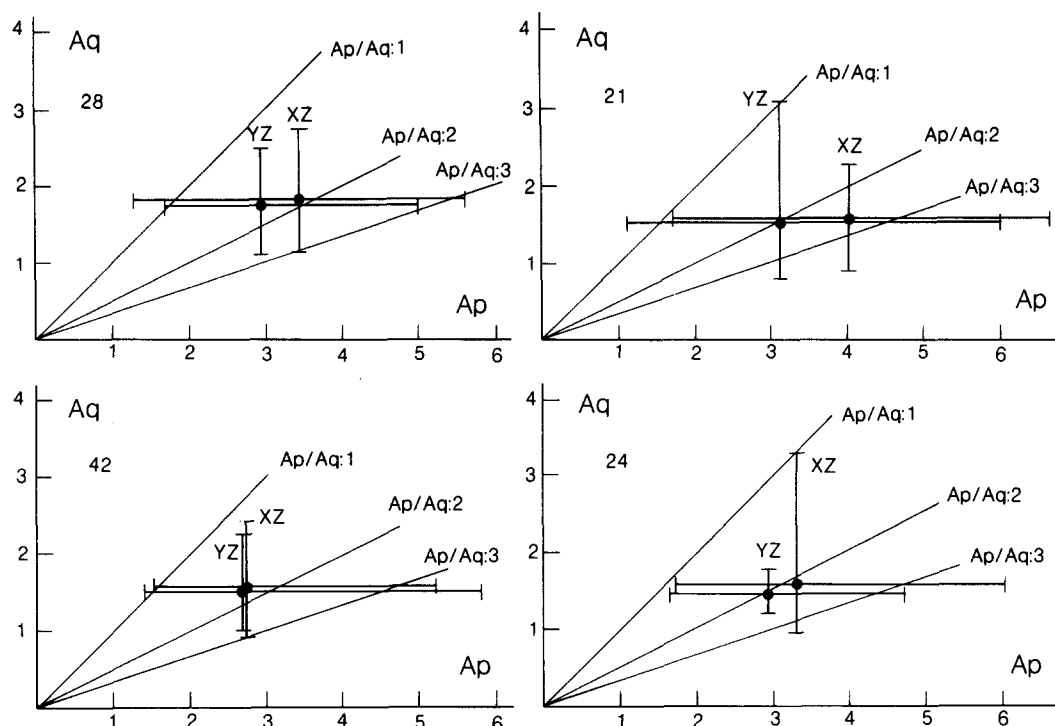


Fig. 6. Shape fabric of detrital quartz grains for Samples 28, 21, 42 and 24 plotted as the aspect ratio of quartz grains in Q-domains (Aq) vs the aspect ratio of quartz grains in P-domains (Ap). Filled circles represent the mean value of 20 or more quartz grains from an individual section (either an XZ or YZ section) and bars indicate the total range in aspect ratios for an individual section. The ratio of the mean value of Ap to the mean value of Aq lies in the range 1.7–2.5 for all samples (see Table 1). Note that in all cases the aspect ratios of quartz grains in XZ sections are greater than the aspect ratios of quartz grains in YZ sections from the same sample.

the absence of syntectonic pyrite, similarities in the morphological and modal development of quartz–chlorite intergrowths and in shape fabrics of detrital quartz grains in both P- and Q-domains in all samples suggests that they have all undergone similarly large extensions. In particular, the development of chlorite overgrowths on detrital muscovite as illustrated in Fig. 5(c) occurs in all samples and points to large extensions in X.

In summary, microstructures show evidence of significant plane strain in both P- and Q-domains, with the bulk shortening in the P-domains estimated from microstructures to be approximately twice the bulk shortening in adjacent Q-domains. Finite extensions associated with cleavage development are estimated to be in excess of 100%. This point is particularly significant because in previous studies, finite extension associated with P–Q fabric development in the Ballarat slate belt has been considered negligible (Stephens *et al.* 1979, Etheridge *et al.* 1983). The abundance of overgrowths and corrosion surfaces, particularly on detrital quartz grains, implies that the dominant deformation mechanism was solution transfer (Durney 1972), with only a small proportion of the finite strain accommodated by plastic deformation processes.

Chemistry

Glasson & Keays (1978) and Stephens *et al.* (1979) have proposed that some elements, notably Ti and Zr, were chemically inert during cleavage development at

Clunes. If indeed this is the case, then the relative concentration of these elements in P- and Q-domains provides an independent estimate of solution-transfer strain partitioning. In the following section we provide evidence supporting the idea that some elements, which have behaved coherently during deformation, were probably inert during P–Q fabric development and may therefore be used to estimate strain partitioning.

The differentiated layering is sufficiently well developed in the psammites for individual P- and Q-domains from one rock to be isolated and analysed. Major and trace elements have been determined as part of a detailed study of the chemical changes associated with P–Q fabric development in a variety of cleaved and non-cleaved samples from Clunes and Creswick (Waldron & Keays work in preparation). The results of chemical analyses and the normative mineralogy of the P- and Q-domains for the four samples described in the present study are given in Table 2. The analyses were done by X-ray fluorescence (Haukka & Thomas 1977, Thomas & Haukka 1978) and instrumental neutron activation (Jacobs *et al.* 1977) methods. The normative mineralogy was calculated using a program by Fenton (work in preparation) which apportions selected major and trace element concentrations according to the average composition of component minerals (determined by electron microprobe from Victorian Ordovician meta-sedimentary rocks). The normative mineralogy has been used, in preference to modal mineralogy, because of difficulties in estimating modes for fine-grained inter-

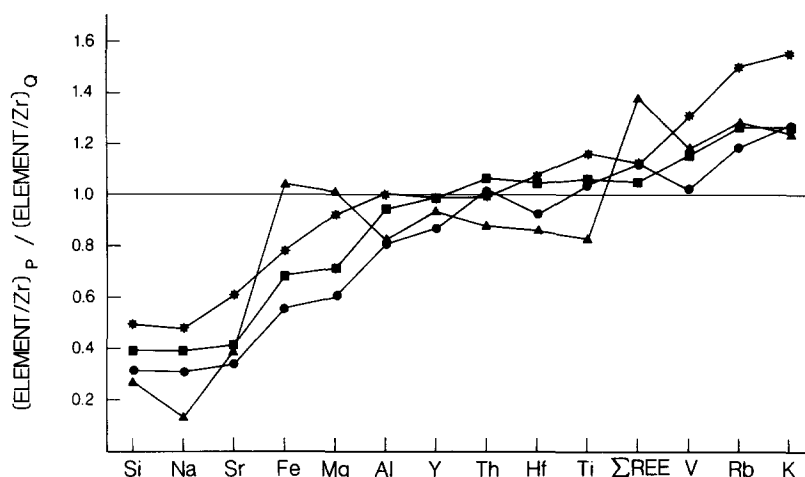


Fig. 7. Ratio plot for various elements (normalized to the immobile element Zr) in the P-domain relative to the Q-domain. Samples are: dots No. 21; stars No. 24; squares No. 28; triangles No. 42.

growths of quartz, albite, chlorite and mica. Only the minerals accounting for the bulk of the chemistry of the P- and Q-domains have been included in the norms (Table 2).

It can be seen from Table 2 that for each of the P-Q pairs, the P-domains are richer in most elements except Si, Na and Sr. Several elements, notably Ti, Y, Hf, Th, Zr and REE, are concentrated in the P-domains relative to the Q-domains (P/Q) by a factor of approximately 2, while K, Rb and V are enriched to a greater extent, and Fe and Mg are enriched in the P-domains to a lesser degree. These chemical differences between the P- and Q-domains can be accounted for in terms of the mineralogy of the layers. The dominant control of Si concentration is quartz, while Na and Sr are accommodated in albite and the enrichment of Q-domains in these elements reflects the relatively high proportion of quartz and albite in these domains. Potassium, Rb and V are mainly contained in muscovite, and chlorite accounts for most of the Fe and Mg. The main hosts of Zr, Y, Th, Hf and REE are zircon and apatite, although REE also occur in muscovite. Rutile is the dominant host for Ti with lesser amounts incorporated in muscovite and chlorite.

Coherent behaviour of elements can be demonstrated by a value of one for the ratio of pairs of elements in the P-domain divided by the same elements in the Q-domain, i.e.

$$(\text{element } a/\text{element } b)_P / (\text{element } a/\text{element } b)_Q = 1.$$

In contrast, non-coherent behaviour of elements will be indicated by ratios other than one. Coherency between Ti, REE, Zr, Y, Hf and Th can be demonstrated in this way for the samples described (Fig. 7). In previous studies of various rocks, these elements have been considered to be inert and not susceptible to mobilization during low-grade metamorphism (Coish 1977, Floyd & Winchester 1978, Humphris *et al.* 1978, Wood 1980, Petersen 1983, Zielinski 1985) and in the psammites considered here they are mainly hosted by the resistant minerals apatite, zircon and rutile which show little

evidence for dissolution, recrystallization or precipitation during cleavage formation. We suggest that their coherent behaviour in these rocks provides strong circumstantial evidence that they have been immobile, passively concentrating in the P-domains during development of the P-Q fabric. In contrast, the other elements showing non-coherent behaviour with respect to Zr (Fig. 7) are interpreted as having been mobile during cleavage development. Silicon, Sr, Na, Fe, Mg and possibly Al have been partitioned into the Q-domains relative to the inert elements, while K, Rb and V have been partitioned into the P-domains.

The concentration of inert elements during deformation by solution transfer provides an independent strain gauge between domains strained to different extents. The concentration factor of approximately 2 (C_f in Table 1) in these samples is consistent with the microstructural evidence for P-domain shortening approximately twice that of adjacent Q-domains.

Discussion of results

The results of chemical and microstructural analysis of P-Q fabrics in psammites from the Ballarat slate belt are shown in Tables 1 and 2. Table 1 also shows predicted extensions in X (ϵ_x) for constant volume, plane-strain deformation dominated by solution transfer calculated using equation (7). All rocks described show microstructural evidence for significant extension (i.e. quartz-albite-chlorite overgrowths). However, only in one of these samples (No. 21) has it been possible to quantify the state of strain by the use of pressure shadows around syntectonic pyrite porphyroblasts. In this sample, plane-strain deformation with a minimum extension of 120–130% is indicated. This measured extension is similar to, although somewhat greater than, the predicted value of 110% calculated using equation (7) (Table 1). This disparity between the predicted strain and the recorded strain estimate in Sample 21 (with the latter being larger) could conceivably represent a bulk volume gain on the hand-specimen scale. However, it could equally be due

to the initiation of P-domains after a significant proportion of strain had been accommodated by deformation. Moreover, as the predicted strain refers only to strain accommodated by solution transfer, any contribution to the finite strain by other deformation mechanisms would result in a disparity between the natural and predicted strains. Such disparities are likely to be small because solution transfer is believed to account for the bulk of the strain in the samples. Clearly the similarity of the measured and predicted strains in Sample 21 is difficult to reconcile with the interpretation that P–Q fabric development in psammites is associated with substantial volume loss on the hand-specimen scale. Rather we believe the data are more consistent with approximately constant volume deformation. In view of the similar development of overgrowth microstructures and geochemical characteristics of P–Q fabrics in the other samples described we conclude the deformation was approximately constant volume on the hand-specimen scale, with the P–Q fabric developing due to strain partitioning between adjacent domains on a centimetre scale.

DISCUSSION AND CONCLUSIONS

We have argued that cleavage development in psammites from the Ballarat slate belt occurred by deformation which was to a first approximation constant volume on the hand-specimen scale. This conclusion differs considerably from previous studies of samples from the same area (Stephens *et al.* 1979, Etheridge *et al.* 1983). The differences between the previous studies, which argued for considerable volume loss, and our own study stem largely from our recognition that the psammites have undergone considerable bulk extensions in *X*, in both the P- and Q-domains, and that this extension has been accommodated largely by the formation of quartz–albite–chlorite overgrowths on pre-existing detrital grains, due to solution-transfer dominated deformation.

We have argued that the development of P–Q fabrics may be viewed as a consequence of partitioning of solution-transfer strain between two domains. In the P-domain dissolution proceeded more rapidly than precipitation, leading to a net volume loss, while in the Q-domain precipitation proceeded more rapidly than dissolution leading to a net volume gain. The chemical data for individual P- and Q-domains suggest that this deformation partitioning was facilitated by the migration of Si, Na, Sr, Fe, Mg and possibly Al from P-domains to Q-domains, and the migration of K, Rb and V from Q-domains to P-domains. These changes are reflected in the differences in mineralogy and microstructure of the two domains. The predominance of corroded detrital and diagenetic quartz, albite and chlorite in P-domains indicates dissolution of these minerals and their probable redeposition as the quartz–albite–chlorite overgrowths observed in Q-domains. The abundance of muscovite in the P-domains clearly hosts the additional K, Rb and V. Titanium, Zr, Hf, Y and REE appear to

have been little affected by the solution-transfer process and differences in their concentrations in adjacent domains reflects the passive accumulation in the P-domains of their host minerals zircon, rutile and apatite.

In order to balance volume loss in P-domains with volume gain in Q-domains, as is required by a constant-volume deformation on the hand-specimen scale, the minimum distance for solute transfer is half the width of an individual P–Q domain couple. This distance is in the order of 0.5–1.0 cm in the samples described here, and similar spacing has been documented for other localities (Williams 1972) and thus seems characteristic of P–Q fabrics in general. The regularity of the P–Q fabric spacing, despite significant morphological variations (Fig. 4a–d) suggests an intrinsic control on the spacing of the P–Q domains. It is possible that the spacing is dictated by the distance over which solution transfer is capable of maintaining strain compatibility within the deforming rock.

A central question in cleavage development is whether solute transport occurs within an advecting fluid or by diffusion in a stationary fluid. According to Fletcher & Hofmann (1974) the characteristic transport distance for diffusion is given by the relation

$$(Dt)^{1/2},$$

where *t* is time, and *D*, the effective diffusivity, is given by

$$D = \tau\beta D_i.$$

D_i is the intrinsic diffusivity, *τ* is a parameter related to the tortuosity of the diffusion path and *β* is the fraction of cross-sectional area occupied by fluid. After Walther & Wood (1984) and Rubie (1986) we assume the following values of 10^{−8} m² s^{−1} for the intrinsic diffusivity of SiO₂ in an aqueous fluid, 0.7 for the tortuosity parameter and 10^{−3} for the fluid fraction. The characteristic diffusion distance for a 10⁷ year deformation is therefore in the order of 10 m. This is likely to be a maximum value as there is some evidence that the intrinsic diffusivity in grain-boundary fluids is significantly lower than the diffusivity in a bulk fluid, possibly by several orders of magnitude (Rutter 1976, Rubie 1986). The observed cleavage spacing in the P–Q fabrics is therefore consistent with the possibility that P–Q fabric development within the Ballarat slate belt occurred by diffusion in a stationary fluid. This contrasts with the interpretation of Etheridge *et al.* (1983, 1984) who argued that such fabrics develop as a consequence of pervasive flushing by a fluid which formed part of convection cell on the scale of 10⁴ m within the upper crust.

Clearly the existence of syntectonic vein networks within deformed turbidite terrains such as the Ballarat slate belt points to local solute transfer paths on a scale significantly larger than P–Q spacing. Such vein systems may therefore require the advection of fluid during metamorphism. The scale of this solute transfer and the fluid/rock ratio required for it remains one of the critical concerns in our studies of low-grade metamorphic terrains. The existence of interconnected porosity defined

by vein networks would greatly facilitate advection of large volumes of fluid but does not necessarily require large fluid/rock ratios. One of our principal aims here has been to evaluate the necessity of large fluid/rock ratios in the formation of one of the most common deformation fabrics in low grade metasedimentary terrains, viz, P–Q fabrics in psammities. Large fluid rock ratios would be demanded if there was significant volume change during P–Q fabric development. However, unlike earlier workers, we find no evidence for such volume changes and we therefore question the necessity of large convective circulation systems during low grade metamorphism, as proposed in previous studies.

Acknowledgements—We thank C. B. Douthitt and R. R. Keays for their comments and suggestions on early versions of the manuscript and D. W. Durney for initial discussion on the topic. Reviews by R. Knipe and T. Engelder improved the paper significantly. M. W. Fenton is thanked for the use of his normative mineralogy program. The co-operation and assistance given by Western Mining Corporation Ltd, especially Bob Sloane, who allowed access to diamond drill core from Clunes and Creswick, is gratefully acknowledged. This work was supported by the Department of Geology, University of Melbourne, while HMW held a Commonwealth Postgraduate Research Award. MS acknowledges the receipt of a C.S.I.R.O. Postdoctoral Fellowship. Finally, but by no means least, Isabel Munro is thanked for typing the manuscript.

REFERENCES

- Alvarez, W., Engelder, T. & Geiser, P. A. 1978. Classification of solution cleavage in pelagic limestones. *Geology* **6**, 263–266.
- Beach, A. 1979. Pressure solution as a metamorphic process in deformed terrigenous sedimentary rocks. *Lithos* **12**, 51–58.
- Bell, A. 1985. Strain paths during slaty cleavage formation—the role of volume loss. *J. Struct. Geol.* **7**, 563–568.
- Beutner, E. C. 1978. Slaty cleavage and related strain in Martinsburg Slate, Delaware Water Gap, New Jersey. *Am. J. Sci.* **278**, 1–23.
- Cloos, E. 1947. Oolite deformation in the South Mountain fold, Maryland. *Bull. geol. Soc. Am.* **58**, 843–918.
- Coish, R. A. 1977. Ocean floor metamorphism in the Betts Cove ophiolite. *Contr. Miner. Petrol.* **60**, 255–270.
- Durney, D. W. 1972. Solution-transfer, an important geological deformation mechanism. *Nature, Lond.* **235**, 315–317.
- Engelder, T. 1979. Mechanisms for strain within the upper Devonian clastic sequence of the Appalachian plateau, Western New York. *Am. J. Sci.* **279**, 527–542.
- Engelder, T. & Marshak, S. 1985. Disjunctive cleavage formed at shallow depths in sedimentary rocks. *J. Struct. Geol.* **7**, 327–343.
- Etheridge, M. A., Wall, V. J., Cox, S. F. & Vernon, R. H. 1984. High fluid pressures during regional metamorphism and deformation: implications for mass transport and deformation mechanisms. *J. geophys. Res.* **89**, 4344–4358.
- Etheridge, M. A., Wall, V. J. & Vernon, R. H. 1983. The role of the fluid phase during regional metamorphism and deformation. *J. metamorphic Geol.* **1**, 205–226.
- Fletcher, R. C. & Hofmann, A. W. 1974. Simple models of diffusion and combined diffusion infiltration metasomatism. In: *Geochemical Transport and Kinetics* (edited by Hofmann, A. W., Gilletti, B. J., Yoder, Jr, H. S. & Yund, R. A.). *Carnegie Inst. Washington Pub.* **634**, 243–259.
- Floyd, P. A. & Winchester, J. A. 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chem. Geol.* **21**, 291–306.
- Glasson, M. G. & Keays, R. R. 1978. Gold mobilisation during cleavage development in sedimentary rocks from the auriferous slate belt of central Victoria, Australia: some important boundary conditions. *Econ. Geol.* **73**, 496–511.
- Gray, D. R. 1978. Cleavages in deformed psammitic rocks from southeastern Australia: their nature and origin. *Bull. geol. Soc. Am.* **89**, 577–590.
- Gray, D. R. & Durney, D. W. 1979. Investigations on the mechanical significance of crenulation cleavage. *Tectonophysics* **58**, 35–79.
- Haukka, M. T. & Thomas, I. L. 1977. Total X-ray fluorescence analysis of geological samples using a low dilution lithium metaborate fusion method. Matrix corrections for major elements. *X-ray Spectrom.* **6**, 204–211.
- Hills, E. S. & Thomas, D. E. 1944. Deformation of graptolites and sandstones in slates from Victoria, Australia. *Geol. Mag.* **81**, 216–222.
- Humphris, S. E., Morrison, M. A. & Thompson, R. N. 1978. Influence of rock crystallisation history upon subsequent lanthanide mobility during hydrothermal alteration of basalts. *Chem. Geol.* **23**, 125–137.
- Jacobs, J. W., Koroter, R. L., Blanchard, D. P. & Haskin, L. A. 1977. A well-tested procedure for instrumental neutron activation analysis of silicate rocks and minerals. *J. Radioanalyt. Chem.* **40**, 93–114.
- Knipe, R. J. 1981. The interaction of deformation and metamorphism in slates. *Tectonophysics* **78**, 249–272.
- Kreulen, R. 1980. CO₂-rich fluids during regional metamorphism on Naxos (Greece): carbon isotopes and fluid inclusions. *Am. J. Sci.* **280**, 745–771.
- Marlow, P. C. & Etheridge, M. A. 1977. Development of a layered crenulation cleavage in mica schists of the Kanmantoo Group near Macclesfield, South Australia. *Bull. geol. Soc. Am.* **88**, 873–882.
- Petersen, M. D. 1983. The use of the 'immobile' elements Zr and Ti in lithogeochemical exploration for massive sulphide deposits in the Precambrian Pecos greenstone belt of northern New Mexico. *J. Geochem. Explor.* **19**, 615–617.
- Pique, A. 1982. Relations between stages of diagenetic and metamorphic evolution and the development of a primary cleavage in the northwestern Moroccan Meseta. *J. Struct. Geol.* **4**, 491–500.
- Rubie, D. C. 1986. The catalysis of mineral reactions by water and restrictions on the presence of aqueous fluid during metamorphism. *Mineralog. Mag.* **50**, 399–415.
- Rutter, E. H. 1976. The kinetics of rock deformation by pressure solution. *Phil. Trans. R. Soc. A* **283**, 203–219.
- Sandiford, M. & Keays, R. R. 1986. Structural and tectonic constraints on the origin of gold deposits in the Ballarat slate belt, Victoria. In: *Turbidite-hosted Gold Deposits* (edited by Kleppie, J. D., Boyle, R. W. & Haynes, S. J.). *Geol. Ass. Can. Spec. Paper* **32**, 15–24.
- Stephens, M. B., Glasson, M. G. & Keays, R. R. 1979. Structural and chemical aspects of metamorphic layering development in metasediments from Clunes, Australia. *Am. J. Sci.* **279**, 129–160.
- Thomas, D. E. 1939. The structure of Victoria with respect to the Lower Palaeozoic rocks. *Min. geol. J.* **1**, 59–64.
- Thomas, I. L. & Haukka, M. T. 1978. XRF determinations of trace and major elements using a single-fused disc. *Chem. Geol.* **21**, 39–50.
- Walther, J. V. & Wood, B. J. 1984. Rate and mechanism in prograde metamorphism. *Contr. Miner. Petrol.* **88**, 246–259.
- White, S. H. & Johnston, D. C. 1981. A microstructural and microchemical study of cleavage lamellae in a slate. *J. Struct. Geol.* **3**, 279–290.
- Williams, P. F. 1972. Development of metamorphic layering and cleavages in low grade metamorphic rocks at Bermagui, Australia. *Am. J. Sci.* **272**, 1–47.
- Wood, D. A. 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth Planet. Sci. Lett.* **50**, 11–30.
- Wright, T. O. & Platt, L. B. 1982. Pressure dissolution and cleavage in the Martinsburg Shale. *Am. J. Sci.* **282**, 122–135.
- Zielinski, R. A. 1985. Element mobility during alteration of silicic ash to kaolinite—a study of tonsein. *Sedimentology* **32**, 567–579.