Pergamon

Journal of Structural Geology, Vol. 17, No. 9, pp. 1207 to 1216, 1995
1995 Elsevier Science Ltd
Printed in Great Britain

0191–8141(95)00022–4

Finite strain heterogeneity and volume loss in slates of the Taconic Allochthon, Vermont, U.S.A.

ARTHUR GOLDSTEIN

Department of Geology, Colgate University, Hamilton, NY 13346, U.S.A.

JAMES PICKENS

Department of Geology and Geography, University of Massachusetts, Amherst, MA 01003, U.S.A.

KEITH KLEPEIS and FLENNER LINN

Department of Geology, Colgate University, Hamilton, NY 13346, U.S.A.

(*Received* 7 *March* 1994; *accepted in revised form* 8 *February* 1995)

Abstract—Slates of the Taconic Allochthon have ellipsoidal reduction spots which have been used to determine the finite state of strain at seven sites. The strain is highly heterogeneous at all scales, ranging from several centimeters to many kilometers. Variations in X/Y ratios is small but variations in Y/Z ratios is large and this pattern is seen at all scales. The heterogeneity can be used to determine a strain path, which is nearly horizontal on a Flinn diagram. We propose that uniaxial flattening associated with late stage cleavage development was accommodated by volume loss, and that the most highly strained sites have experienced an average 55% volume loss, at a minimum. Explaining our results without volume loss requires a subhorizontal extension and creates strain compatibility problems. Consideration of the strain history of these rocks suggests that folding-related strains have been modified by later cleavage-related events, the last of which was uniaxial flattening accommodated by volume loss. The finite strains are reflective almost exclusively of the latest, cleavage producing strains.

INTRODUCTION

The origin of slaty cleavage is a topic which has been debated since the earliest structural studies of cleavage. Early controversies focused on rotation vs recrystallization of platy minerals which define the cleavage and on whether cleavage is parallel to planes of high shear strain (see Wood 1974). Recently, debate has shifted to the role of volume loss during cleavage formation (e.g. Wright & Platt 1982, Beutner & Charles 1985, Waldron & Sandiford 1988, Henderson *et al.* 1986, Winstch *et al.* 1991) although this topic is by no means new (e.g. Sorby 1853). Volume loss models suggest that some minerals are preferentially dissolved and flushed from the system with pore fluids. Whereas there is widespread agreement that pressure solution is an important deformation mechanism in the formation of slaty cleavage, there is considerable disagreement about the distance of transport of dissolved constituents. Given that volume reduction is an expression of the complex interplay between inter- and intracrystalline strain accommodation mechanisms, phase changes, void space reduction and water removal, it is vital to understand its role during deformation. The topic of element mobility and fluid flow during deformation is also of considerable importance as it relates directly to the formation of mineral deposits, hydrocarbon migration and palaeomagnetism.

The amount of volume lost during slaty cleavage formation has been a subject of debate and controversy since Sorby (1853) first suggested that 60% of the volume of the Welsh slates had been lost. While it has been generally agreed that material redistribution does occur during slaty cleavage formation, the validity of true volume loss, either incremental (partial accommodation of strain through volume loss) or pure (total accommodation of strain through volume loss), during deformation has been widely debated. Specifically, finite strain studies evoking up to 60% volume loss during slaty cleavage formation (e.g. Sorby 1853, Wright & Platt 1982, Bell 1985, Beutner & Charles 1985, Henderson *et al.* 1986, Wright & Henderson 1992) have not been corroborated by geochemical studies (e.g. Waldron & Sandiford 1988, Ague 1991; Kanagawa 1991, Wintsch *et al.* 1991, Erslev & Ward 1994). Because difficulties commonly arise when attempting to factorize volume strain into pre-lithification compaction and tectonic strain (Ramsay & Wood 1973, Siddans *et al.* 1984) some workers have compared strain on limbs and hinges of folds to determine volume loss during cleavage formation (Wright & Platt 1982, Beutner & Charles 1985). In this study we show that finite strain heterogeneity, within single hand samples, within individual sites and between sites, can also be used to determine volume loss, regardless of the pre-slaty cleavage strain history.

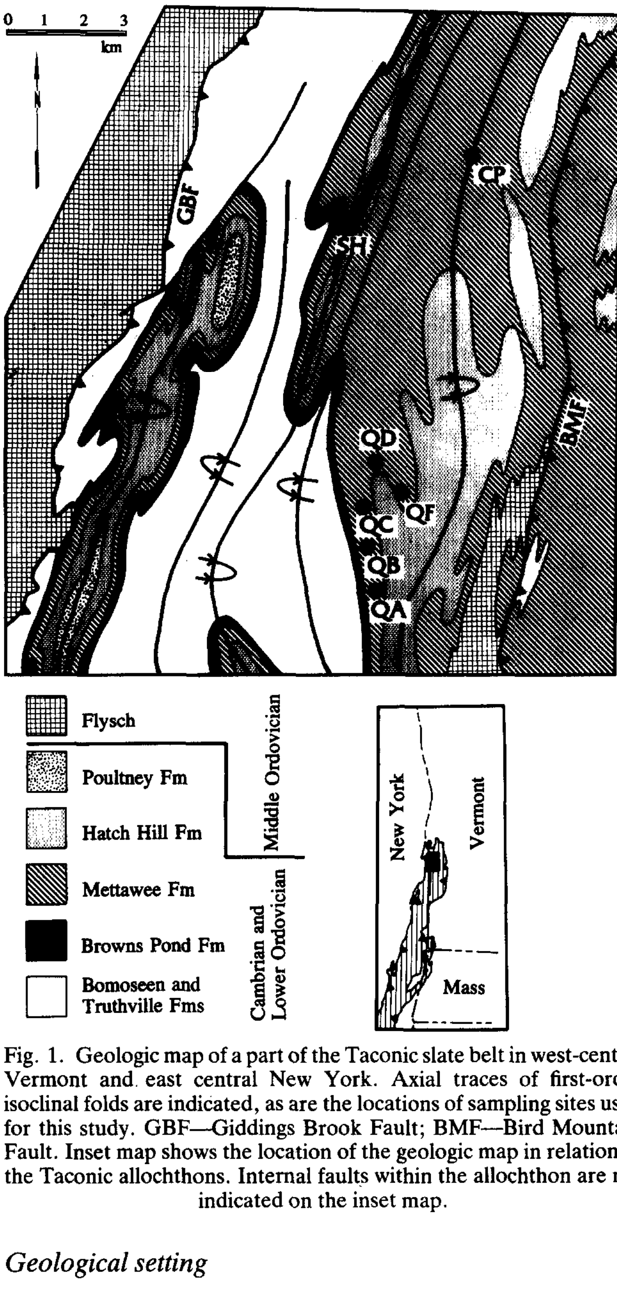

Fig. 1. Geologic map of a part of the Taconic slate belt in west-central Vermont and east central New York. Axial traces of first-order isoclinal folds are indicated, as are the locations of sampling sites used for this study. GBF—Giddings Brook Fault; BMF—Bird Mountain Fault. Inset map shows the location of the geologic map in relation to the Taconic allochthons. Internal faults within the allochthon are not indicated on the inset map.

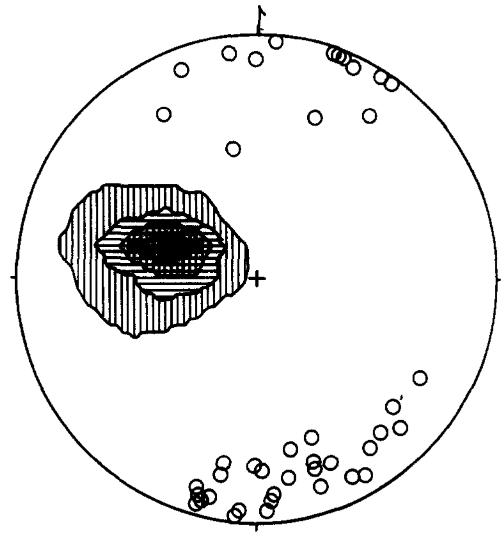

Fig. 2. Lower hemisphere, equal-area projection of 600 poles to slaty cleavage (contours) and 42 measured fold axes and bedding–cleavage intersections (circles). Data are taken from the area shown in Fig. 1. Contours are 1, 5, 10, 15 and 20% per 1% area.

Geological setting

The area from which our samples were collected is the Taconic slate belt of western Vermont and eastern New York (Fig. 1). The slates are of Cambrian and Ordovician age and were deposited on the paleo-passive margin of eastern North America as continental slope and rise deposits (Rowley & Kidd 1981, Stanley & Ratcliffe 1985). Lithologically, the sedimentary section consists predominantly of variously colored mudrocks interlayered with laterally discontinuous carbonates and arenites. The lowest part of the section consists of greywackes which lack distinct bedding and have been interpreted as rift clastics (Rowley & Kidd 1981). During the Taconic (middle Ordovician) orogeny, the continental slope and rise deposits were deformed and thrust westward onto the carbonate bank as the eastern margin of North America approached a west-facing subduction zone (Stanley & Ratcliffe 1985). The deformation involved both folding and thrusting, with the folds eventually assuming an isoclinal 'similar' geometry (Fig. 1) (Rowley *et al.* 1979, Crespi & Byrne 1987, Cushing & Goldstein 1990, Goldstein *et al.* 1991, Pickens 1993).

Structural relationships and incremental strain analysis in the lowest thrust sheet, the Giddings Brook Slice (GBS), indicate that Taconian slaty cleavage was superimposed on previously folded rocks. At the top of this thrust sheet, folds are transected by the next highest thrust fault, the Bird Mountain fault. Exposures of this fault are excellent and cleavage cuts smoothly across the fault without change in orientation or disruption, suggesting that the sequence of events was folding followed by thrusting and finally by cleavage formation. Cleavage is commonly parallel to the axial planes of these folds, but locally transects them, also suggestive of post-folding cleavage. The slaty cleavage displays none of the characteristics one might expect of syn-folding cleavage, such as refraction across beds of different competence. Rather, it cuts smoothly across all lithologies. Crespi & Byrne (1987) concluded that, at one locality, folds were produced by flexural flow mechanisms. However, the axial planar geometry of cleavage can not be explained by this mechanism. In thin section, one can see that the slaty cleavage is the second planar fabric to form in these rocks (Pickens 1993). A pre-slaty cleavage fabric can be observed in microlithons and low strain areas (i.e. adjacent to pyrite porphyroblasts) and consistently lies at a high angle (50–70°) to the dominant slaty cleavage and also transects bedding. Locally, a late crenulation cleavage is present, but is not ubiquitous. Fold axes plunge gently and reverse plunge about the horizontal, but only slightly (Fig. 2).

FINITE STRAIN MEASUREMENTS

Data

The Mettawee Formation is a maroon slate which, locally, displays green ellipsoidal reduction spots. Such spots have been widely used for finite strain measurements (Sorby 1853, Ramsay & Wood 1973, Wood 1974, Tullis & Wood 1975, Graham 1978, Siddans *et al.* 1984, Beutner & Charles 1985). Commonly, reduction spots in mudstones are ellipsoidal and slightly flattened in bedding, by compaction. In shales, the flattening in bedding is more extreme. As shales develop a slaty cleavage, the reduction spot *XY* planes depart from parallelism with bedding, assuming an orientation imtermediate between bedding and cleavage (Graham 1978). In highly cleaved slates which represent more advanced stages of deformation, including those studied here, reduction spots are aligned with their *XY* planes parallel (or as parallel as can be determined) to the cleavage.

We have followed the techniques for reduction spot measurement described by Tullis & Wood (1975). Blocks of slate were collected and were split along cleavage until an ellipsoidal spot was observed. That spot was then bisected along all three principal planes to assure that it was ellipsoidal and that the true half-lengths of the principal axes were measured. Approximately 50 spots were measured from each of seven localities (Fig. 1), commonly coming from 4 to 6 different blocks. Some quarries displayed so many spots as to allow data sets of nearly 200 spots although one locality was so nearly devoid of spots to allow only ten measurements. Two of our sites are at the hinges of folds and the remainder are on limbs (Fig. 1). Fold hinges are very tight in the Taconic slate bed and, for the most part, a single site would expose only one orientation of bedding either limb or hinge. Bedding and cleavage are parallel at sites from limbs of folds and are perpendicular at sites from hinges. At one site (CP), a first-order synclinal fold hinge is exposed, but the uneven distribution of reduction spots did not allow us to sample more than one bedding orientation, perpendicular to cleavage.

Two different kinds of reduction spots are present in the Mettawee formation. Some are nearly perfect ellipsoids, with their *XY* plane parallel to cleavage (or as close as parallel to cleavage as can be determined). Others are splotches, with shapes that span the range of imaginations. We assume that the ellipsoids resulted from deformation of spherical spots formed around a small, equant, fragments of organic matter. Unfortunately, the Mettawee formation can not be observed in an undeformed state, and this assumption can not be tested. Ellipsoidal reduction spots are oriented with their long axes (*X*) generally down dip, parallel to a weak grain elongation lineation on cleavage. *Y* is generally horizontal, subparallel to fold axes and *Z* is perpendicular to cleavage. The splotches, on the other hand, probably formed from reduction around an irregular piece of organic matter or along a crack, resulting in a pre-deformational shape which is indeterminate.

The shapes of reduction spots are highly heterogeneous within single blocks (Fig. 3), within different blocks from a single site (Fig. 4) and between sites (Fig. 5). Despite the scatter in values, virtually all the reduction spots measured fall within the field of apparent flattening on a Flinn deformation plot (Figs 3–5). Variance of *X*/*Y* ratios is a magnitude lower than *Y*/*Z* and *X*/*Z* ratios; standard deviations are different by a factor of two (Table 1). Viewed as a whole, the data follow an almost horizontal linear distribution across a Flinn diagram (Figs 3–5). As shown in the modified Flinn diagram in Fig. 6, *X*/*Z* and *Y*/*Z* ratios define a line with unit slope, showing that the variation of *X* with *Z* is identical to the variation of *Y* with *Z*. The very large scatter of the data from site to site results in considerable statistical overlap of the mean strain for all sites (Fig. 3). One of the more surprising aspects of these data is that there is not a clear distinction of strain states between fold hinges and limbs (Fig. 5).

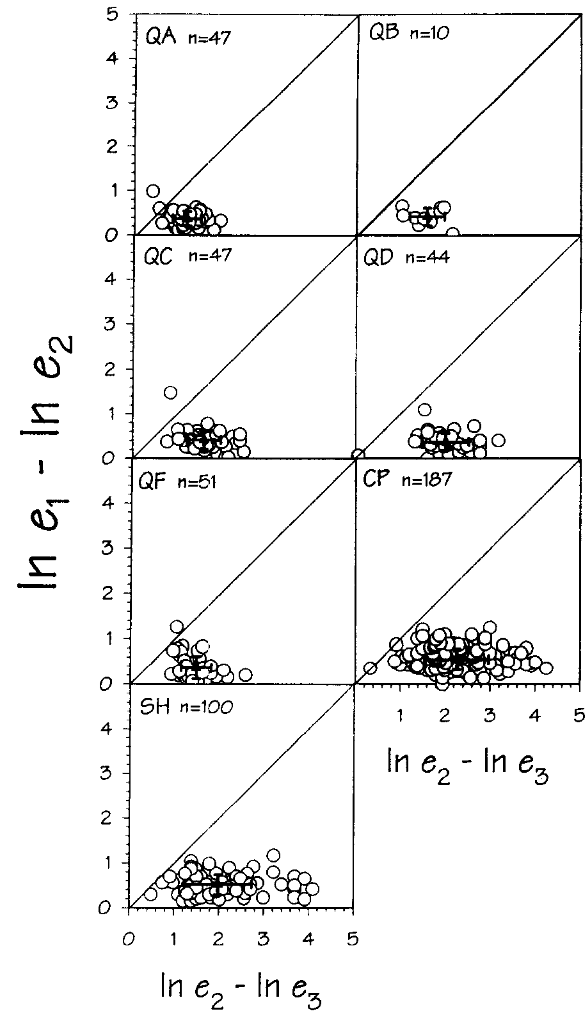

Fig. 3. Logarithmic Flinn diagrams of shapes of reduction spots measured at individual sites for this study. Each point represents one reduction spot bisected along all three principal planes. Triangles show arithmetic means and error bars are ±1 standard deviation.

Other workers have reported on the strain states of Taconic slates and some of our sites were also used by them (Wood 1974, Hoak 1992, Table 1). In total, ten sites have been measured by us and other workers, and there are essentially no differences between the various data sets. Wood (1974) measured strain at seven sites, five of which we have remeasured and his values are within ±1 standard deviation of ours (Table 1). Further, his site mean values are spread along the same horizontal trend as are ours (Fig. 5). In his compilation of slate strain values from the Taconics and Wales, Wood (1974)

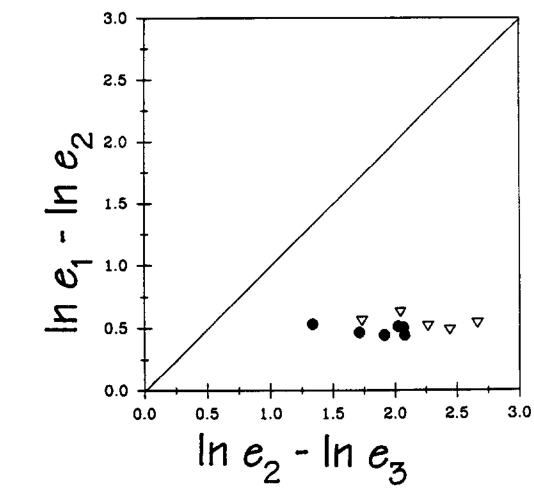

Fig. 4. Average reduction spot shapes in blocks from two different sites. Open symbols are average spot shapes from five separate blocks of slate from site CP. Closed symbols are average block shapes from six different blocks from site SH.

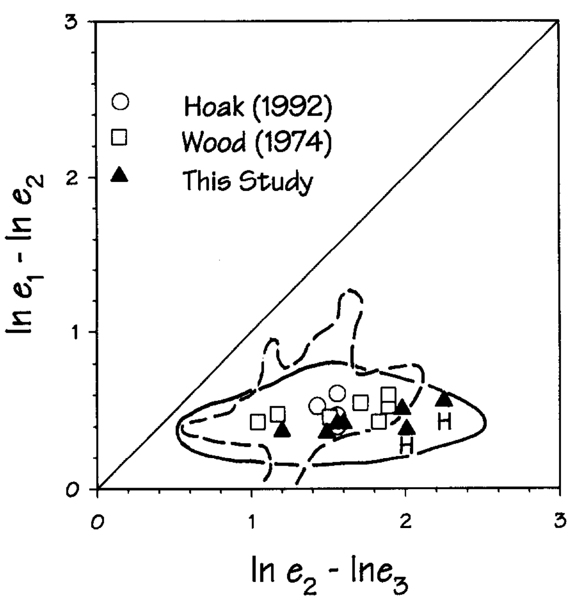

Fig. 5. Summary of all reduction spot data from the Taconic slate belt. Black triangles are site averages measured for this study; symbols with an H are from hinges of folds, all others are from limbs. Open symbols are from studies by Wood (1974) and Hoak (1992). The dashed line shows the field of reduction spot shapes from the Taconics and Welsh slate belts from Wood (1974) and the solid line shows the field of data measured by Hoak (1992).

shows a pattern which is composed of a horizontal trend and a trend with a positive slope. Although one can not know for sure, it is likely that the horizontal trend is representative of Taconic data and the other trend is defined by data from the Welsh slate belt. Hoak (1992) measured reduction spots at four sites, three of which we have also collected samples from. His values are also identical to ours, within statistical limits. Although Hoak's (1992) site mean values are clustered, his data are spread along the same horizontal trend as are ours and Wood's (Fig. 5). Thus, we believe that the horizontal spread seen in our data is not an artifact of our measurement technique or indicative of error. Rather, this trend is reflective of the true variability in strain states in slates of the Taconics.

Interpretations

The heterogeneity of finite strain states as indicated by reduction spots can be interpreted in several ways; as indicative of a strain path, as resulting from spatial variations in compaction, as resulting from temporal variations in spot formation or as an artifact of measurement error. The strain path interpretation assumes that the more highly strained parts of a block of slate achieved their finite state by passing through the lowest states. Such an assumption was also made by Wood (1974) and Kligfield *et al.* (1977) and is extensively discussed in those works. In addition, the deformation path concept was tested experimentally with positive results (Donath & Wood 1976). This assumption is considered to be a valid possibility for Taconic slates because the heterogeneity exists at the scale of a single block and it is unreasonable to assume that different parts of a single block experienced vastly different compactional or strain histories. Rather, it is reasonable to assume that certain areas of a rock mass progress further along a strain path than do other areas, even only centimeters away. Because the same heterogeneity that is present at the scale of a single block of slate is also seen at the scale of a single quarry and between quarries, we suggest that a regional strain path can be constructed by connecting the lowest site mean strain states with the highest. Wood (1974) considered such an analysis equally valid as deriving a strain path for a single sample. The strain path so derived is nearly horizontal on a Flinn diagram, rising off the horizontal only for the highest strain states measured. Thus, a strain path is suggested in which the X/Y ratio remains nearly constant while Y/Z and X/Z ratios increase.

The strain path delineated suggests a uniaxial flattening superimposed on previously strained rocks. Incremental strain results show that prior to the formation of slaty cleavage, the rocks experienced reasonably complex strain histories (Fig. 7, Crespi & Byrne 1987, Cushing & Goldstein 1990, Pickens 1993). The lowest strain states recorded by reduction spots will, of course, reflect this early part of the strain history as well as any compactional strain. However, even the lowest strain states measured are strongly overprinted by the effects of late stage cleavage formation. Therefore, it is not possible to determine the strain associated with the earliest stages of deformation. A minimum strain path, however, may be described by assuming that the lowest strain states measured reflect no cleavage-related strain.

The strain path discussed above could have been achieved through one of two end-member models; constant volume deformation or deformation accommodated exclusively by volume loss. Combinations of these two end members are also possible. A constant volume model would require that as Z shortened, both X and Y elongated at equal rates, maintaining a constant X/Y ratio (uniaxial flattening). The strain variation between

Table 1. Finite strain values from reduction spots from the Taconic slate belt of Vermont and New York. Values for this study are expressed as means plus or minus one standard deviation. Values from Wood (1974) and Hoak (1992) are taken from those works

	This study			Wood (1974)			Hoak (1992)		
Site	ln x/y	ln y/z	n	ln x/y	ln y/z	n	ln x/y	ln y/z	n
QA	0.37 ± 0.17	1.20 ± 0.33	47	0.48	1.17	28			
QB	0.42 ± 0.20	1.56 ± 0.41	10	0.55	1.71	74	0.53	1.43	15
QC	0.42 ± 0.21	1.60 ± 0.38	47	0.46	1.51	30			
QD	0.38 ± 0.19	2.01 ± 0.52	44				0.61	1.56	21
QF	0.36 ± 0.25	1.49 ± 0.35	51						
CP	0.56 ± 0.23	2.25 ± 0.71	187	0.43	1.83	52	0.47	1.56	19
SH	0.51 ± 0.22	1.98 ± 0.75	100	0.53	1.89	30			
Green dump							0.40	1.56	5
Wells				0.60	1.89	44			
Matthews				0.43	1.04	25			

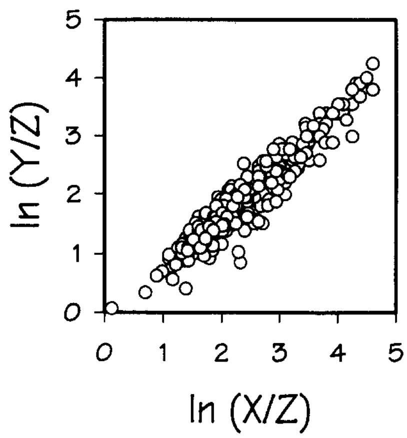

Fig. 6. Plot of all reduction spot shapes showing relationship between Y/Z and X/Z ratios.

lowest and highest site mean strains includes an increase in X from 90% to 200%, Y from 30% to 80% and Z from −60% to −82%, approximately (Fig. 8). Thus, a constant volume deformation would require a 38% elongation in Y for the most highly strained site, with other sites experiencing smaller average elongations in Y. This is the absolute minimum change in Y because it relies, as noted above, on the assumption that our lowest strain site experienced no cleavage-related strain. Fabric observations and incremental strain data (Crespi & Byrne 1987, Cushing & Goldstein 1990; Pickens 1993) both reflect extension in X and shortening in Z prior to the uniaxial flattening associated with final slaty cleavage development, but a lack of fibers parallel to Y shows clearly that deformation was plane strain. More significantly, the incremental strain data suggest that the majority of fiber growth that occurred defines a segment of the deformation path leading up to the uniaxial flattening phase outlined by the spot data. The only evidence of extension in X and Y parallel to cleavage is a small increment of fiber growth on pyrite porphyroblasts, marking the end of strain shadow development (Pickens 1993). The Y axis of the strain ellipsoid lies in the horizontal direction, subparallel to fold axes. As pointed out by Beutner & Charles (1985) elongation in such a direction presents strain compatibility problems unless fold hinges are highly curved or the region lies in a strongly curved orocline. Neither is the case for the Taconics. As shown in Fig. 2 and seen on the geologic map (Fig. 1) fold hinges do curve, but not my more than 10° in nearly all cases. A constant volume model, therefore, does not agree with the regional geology, the incremental strain data or fabric observations.

The alternative to a constant volume deformation is one in which shortening in Z is accommodated by loss of volume and no elongation in X or Y. We can evaluate the amount of volume lost by applying the methods discussed in Ramsay & Wood (1973). They show that:

$$\ln(1 + \Delta) = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$$

with Δ = volume change (negative for volume loss and positive for volume gain) and $\varepsilon_{1,2,3}$ = principal natural strains (ln 1 + e). Further, they showed that, for coaxial strain:

$$\varepsilon_i^{\mathrm{T}} = \varepsilon_i^1 + \varepsilon_i^2$$

for $i = 1, 2, 3$; with $\varepsilon_i^{\mathrm{T}}$ representing the total (finite) principal strain, ε_i^1 representing the first increment of strain and ε_i^2 the second increment. Because the volume loss model is coaxial, in which only the Z (ε_3) axis shortens while X and Y remain unchanged, the calculations are straightforward. The increment of strain in the Z direction involved in going from the lowest to the highest strain sites is $\varepsilon_3^{\mathrm{T}} - \varepsilon_3^1$. The lowest strain site has an average shortening in Z of 60% ($1 + e_3 = 0.4$, $\varepsilon_3^1 = -0.916$) and the highest has an average 82% shortening ($1 + e_3 = 0.18$, $\varepsilon_3^{\mathrm{T}} = -1.714$). Thus, we can say that:

$$\ln(1 + \Delta) = -0.798$$

because both ε_1 and $\varepsilon_2 = 0$. This equation yields the result that on average, for the pure volume loss model, the highest strain site was subjected to 55% volume reduction. The heterogeneity in strain states would indicate that areas of each site were subjected to both greater and lesser amounts of volume reduction. If we assume that the lowest strains are affected by no volume loss, 55% represents the average volume loss associated with slaty cleavage formation at the highest average strains. However, even the sites with the lowest average strains have very well developed slaty cleavage, suggesting that they too were affected by volume loss. In addition, individual reduction spots exist at the lowest strain site which have lower Y/Z ratios than the average for that site. If we assume that the pre-slaty cleavage strain included 40% shortening in Z, then the lowest mean strains are reflective of 20% volume reduction and the highest represent 64%. These figures represent only the volume loss associated with the last phase of cleavage formation and, therefore, are possible minima with respect to the overall volume changes experienced during sediment burial, diagenesis and total strain history.

The analysis discussed above is based on the assumption that, prior to the imposition of slaty cleavage, all sites, and all areas within a single site, had experienced nearly identical strain histories, resulting in nearly identical finite strain states. Such an assumption can not be tested in the study area, so it is prudent to consider other possible ways of explaining the observed strain heterogeneities. One other way of doing so would be to consider a two stage deformational history for the slates, in which some sites, or some areas within a single site, experience more compactional strain than others. Superposing a uniform plane strain on such a distribution would result in a pattern similar to that seen in the Taconic slates. If we consider such a model, for example, to explain the heterogeneity of strain seen in six different blocks of slate from the Scotch Hill quarry (site SH, Fig. 9), we can see that the block with the lowest strain would have experienced a compactional shortening of 55% whereas the block with the highest strain would have experienced a compactional shortening of 80%. Such values are significantly higher than observed for compactional shortening in argillaceous rocks, typically around 40% (Ramsay & Wood 1973, Graham 1978, Siddans *et al.* 1984). Further, it is unreasonable to assume that such extreme variations in compaction could have occurred within an area of a few hundred meters or within the 0.1 m^3 of an individual block. Furthermore, given the complete strain history experienced by the Taconic slates (Cushing & Goldstein 1990, Pickens 1993, Fig. 7) a simple two-stage history of inhomogeneous compaction followed by plane strain is inconsistent with the observation that folding and an early cleavage predate slaty cleavage formation.

Because we do not know that the reduction spots were spherical at any point in their history, it might be that they formed at different times during compaction, resulting in different initial ellipticities. One could suppose that, as fissility developed in the compacting shale, reduction spots formed with shapes which reflected the degree of fissility, such that later formed spots might initially have been more ellipsoidal than earlier formed spots. Such a mechanism might be referred to as temporal variation in spot formation. The validity of this mechanism is difficult to assess, because the slates are in such a highly deformed state. Graham (1978) showed that a lack of parallelism between cleavage and the XY plane of reduction spots in Permian red shales and slates of the Alpes Maritimes was an indication that the spots were initially ellipsoidal before strain, i.e. flattened in bedding. His analyses did not indicate a large range in initial ellipticity. For Taconic slates, ranges of pre-deformational reduction spot ellipticities sufficiently large to result in the observed strain heterogeneity is as improbable for temporal variation in spot formation as it is for spatial variation in compaction. Finally, as for spatial variation in compaction, the temporal variation model would only result in the observed strain heterogeneity if a fairly simple strain history has modified those shapes. This has been shown to be untrue.

DISCUSSION

The magnitudes of volume loss we have derived for the slates of the Giddings Brook Slice are comparable to those determined for other rocks. Henderson *et al.* (1986) and Wright & Henderson (1992) concluded that between 40% and 60% volume loss affected rocks of the Goldenville formation during cleavage formation. Wright & Platt (1982) found approximately 50% volume loss in the Martinsburg shale based on strain of graptolites and Beutner & Charles (1985) derived a 42% volume loss for slates of the Hamburg sequence in Pennsylvania. Thus, our minimum average volume loss for the most highly strained site of 55% is entirely in keeping with values for slaty cleavage formation from other areas.

Recently, Erslev & Ward (1994) concluded that samples of Mettawee, Goldenville, and Martinsburg formations, all of which are proposed candidates for large volume loss during cleavage formation, showed no geochemical evidence for loss of some elements with respect to others. This conclusion was based on XRF macroprobe mapping of compositions around buckled veins, beds and zones of coalesced slaty cleavage. For the sample of Mettawee formation, they found that areas adjacent to the outer arcs of a buckled quartz and calcite vein had compositions richer in silica and poorer in alumina, iron and magnesia than inner arcs. These differences decreased with distance from the vein. Erslev & Ward (1994) concluded that material dissolved from inner arcs was locally precipitated in outer arcs, that no loss of volume occurred and that the slate several millimeters away from the vein represents the original composition of the protolith. One of their arguments is that a protolith would have had to have been almost unbelievably siliceous to have lost sufficient silica to account for large volumes and still yield the observed compositions. Further, they contend that one can consider average shales (Gromet *et al.* 1984) to represent the composition of the protolith. However, Erslev and Ward (1994) show that the slate away from the vein contains approximately 55 wt% silica whereas average shales contain approximately 64 wt%. Close examination of the sample used by Erslev & Ward (1994) shows no textures indicative of material addition, such as fibrous overgrowths, in areas adjacent to outer arcs of the folded vein. Thus, we can not, at this time, accept the assumptions of Erslev & Ward (1994). Additional geochemical investigations of the Mettawee formation are

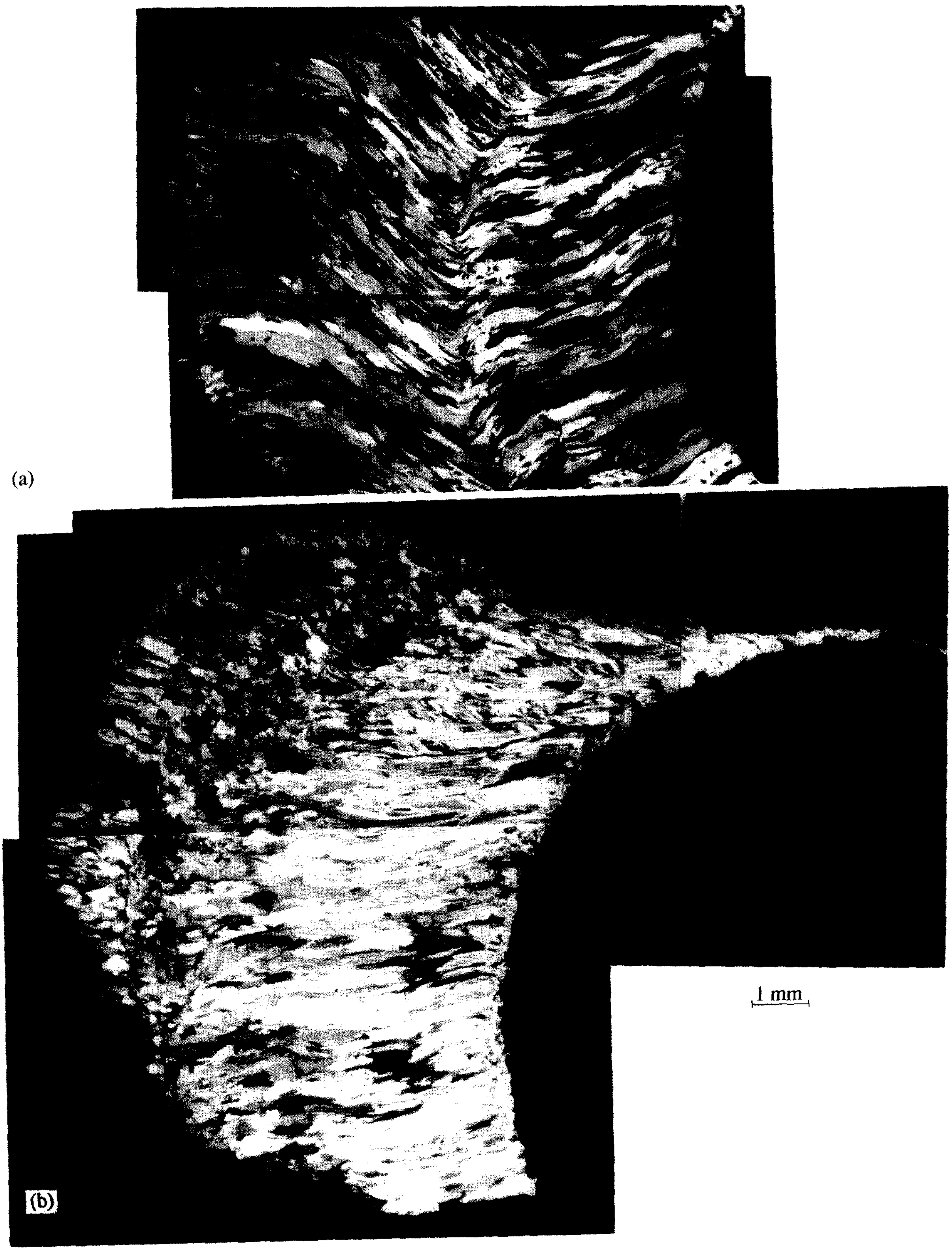

Fig. 7. Photomicrograph of quartz and calcilte pressure shadows on a pyrite framboids from the Hatch Hill Fm. (a) Section through pressure shadow cut perpendicular to both slaty cleavage and the fold axis in the XZ orientation. The photograph is 12 mm across and the margin of the 9 mm diameter spherical framboid is on the right. The slaty cleavage is horizontal. Note that the strain indicated by the pressure shadow is large, and is composed of increments of coaxial strain and increments of non-coaxial strain, some with a large component of coaxial strain and only a small component of non-coaxiality and others with the opposite. Note also that there is no increment of coaxial strain accumulation with extension parallel to the slaty cleavage orientation. (b) Section through pressure shadow cut parallel to cleavage in the XY orientation. Scale is the same as in (a). Note the lack of fiber growth parallel to Y.

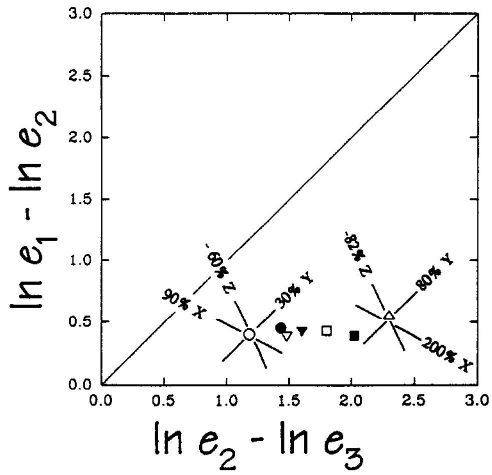

Fig. 8. Evaluation of principal strains needed to account for the observed site mean strains with a constant volume model.

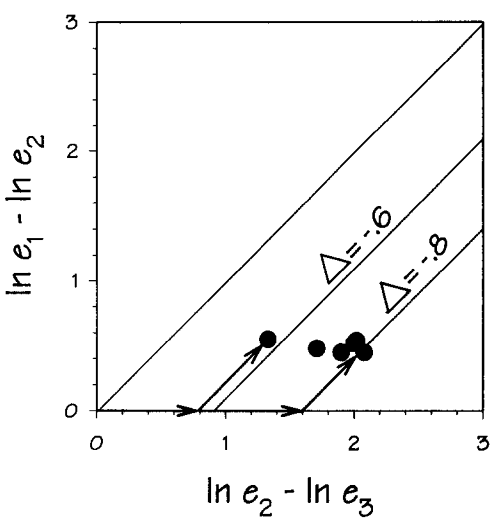

Fig. 9. Evaluation of a two stage model of strain accumulation for block average strains from site SH. Horizontal arrows show the paths which would have been followed for compactional strain, somewhat less than 60% shortening for the lowest block and 80% for the highest block. Lines pointing up from the x axis show paths which would be followed by superposing a uniform plane strain on a heterogeneous compaction, giving rise to the observed heterogeneity. This model does not validly account for the observed strain heterogeneity, see text for discussion.

required before we can make definitive statements about compositional changes, or lack of changes, during cleavage formation.

One of the more interesting aspects of the data set presented here is the lack of any obvious distinction in finite strain state between hinges and limbs of similar folds (Figs 3 and 5, sites QD and CP). Although the two sites from fold hinges have the highest average strains we have measured, the large scatter in the data makes these values statistically indistinguishable from strain magnitudes at other sites. Our interpretation that finite strains are reflective of late stage, uniaxial flattening accommodated by volume loss includes, necessarily, a conclusion that fold shapes have been heavily modified by this late stage flattening. This final strain increment has undoubtedly been largely responsible for the modification of folds to the isoclinal 'similar' geometry so common in the Giddings Brook Slice. The finite strains recorded at different sites will reflect all events which have affected these rocks, including compaction, pre-folding layer parallel shortening, folding-related strain and post-folding strain, including the late stage flattening discussed above. Beutner & Charles (1985) noted that superposing flattening and tectonic strains on limbs and hinges of folds will yield different strain paths for the two positions. Bell (1985) reached similar conclusions and showed that volume loss accompanying tectonic strain would have a major effect on the strain paths. Neither study considered the strains that would accompany the folding, only the effect of superposing compactional strains with tectonic strains having different orientations with respect to bedding.

Considering the multitude of possible fold mechanisms (e.g. Beutner & Diegel, 1985) and the paucity of data which bear on fold mechanisms in the Taconics, we do not believe that sufficient data exist to accurately model the complete strain history of these rocks, including strain accumulated during the folding. We can, however, speculate on the deformation history of the slates using fabric observations (Pickens 1993) and the incremental strain data which are available (Crespi & Byrne 1987, Cushing & Goldstein 1990, Pickens 1993). Crespi & Byrne (1987) suggested a flexural flow model for the development of one well exposed syncline in the Giddings Brook slice. Such a mechanism would produce clearly distinguishable finite strain states between hinge and limbs of folds, which we have not seen in our data. Fold formation through heterogeneous simple shear (Beutner & Diegel 1985; Mitra 1978) is an alternative model and may have been an active process in the Taconics (Cushing & Goldstein 1990). However, the very large finite strains which develop on the overturned limbs of folds thus formed argues against such a mechanism. Pickens (1993) suggested an alternative deformation history for the Taconics involving compactional flattening, layer parallel shortening, buckle folding and late stage flattening and slaty cleavage formation accommodated by volume loss. Layer parallel shortening superposed on compactional strains will produce constrictional strains. Subsequent folding would then produce strains which would be different on hinges and limbs but, we contend, that this distinction would be largely obscured by later flattening and cleavage formation. Obviously, additional detailed finite and incremental strain analyses are required before an unequivocal deformation can be deduced.

CONCLUSIONS

We have measured finite strain in slates of the taconic allochthon in Vermont and have found the strain to be highly heterogeneous at scales ranging from several centimeters to many kilometers. The nature of the heterogeneity is that small variation occurs in X/Y ratios but very large variation exists in Y/Z ratios. We believe that the heterogeneity can be used to construct a regional strain path, at least for the later stages of the strain history of these rock during which the slaty cleavage developed. This strain path is subhorizontal on a Flinn diagram, reflecting uniaxial flattening. Assuming constant volume deformation, this strain path would indicate considerable elongation in Y, subhorizontal and subparallel to fold axes. Because direct evidence exists that deformation was plane strain and because constant volume deformation creates strain compatibility problems, we favor a volume loss model. The most highly strained site would have lost an average 55% volume assuming that the lowest strain site has experienced no volume loss. Because even the low strain sites have very well developed slaty cleavage, the 55% figure is a minimum and actual volume loss is probably higher. The scales of heterogeneity suggest that even at sites which experienced relatively low average volume losses, areas would exist which had lost very large volumes.

Acknowledgements—This work was supported by grants from the Colgate University Research Council and Sigma Xi. Discussions with Mike Williams and Eric Erslev have been especially helpful. Reviews by Jean Crespi, Jane Gilotti and Jack Henderson have greatly improved the manuscript.

REFERENCES

Ague, J. J. 1991. Evidence for major mass transfer and volume strain during regional metamorphism of pelites; with supplemental data. *Geology* **19**, 855–858.

Bell, A. 1985. Strain paths during slaty cleavage formation—the role of volume loss. *J. Struct. Geol.* **7**, 563–568.

Beutner, E. & Charles, E. 1985. Large volume loss during cleavage formation, Hamburg sequence, Pennsylvania. *Geology* **13**, 803–805.

Beutner, E. & Diegel, F. 1985. Determination of fold kinematics from syntectonic fibers in pressure shadows, Martinsburg slate, New Jersey. *Am. J. Sci.* **285**, 16–50.

Crespi, J. M. & Byrne, T. 1987. Strain partitioning and fold kinematics in the Giddings Brook slice, Taconic allochthons, west central Vermont (abstr.). *Geol. Soc. Am. Abs. w Prog.* **19**, 9.

Cushing, J. & Goldstein, A. G. 1990. Strain history of a mesoscale similar fold in Taconic slates, western Vermont (abstr.). *Geol. Soc. Am. Abs. w Prog.* **22**, 10.

Donath, F. & Wood, D. 1976. Experimental evaluation of the deformation path concept. *Phil. Trans. R. Soc. Lond. A.* **283**, 187–201.

Erslev, E. & Ward, D. 1994. Non-volatile element and volume flux in coalesced slaty cleavage. *J. Struct. Geol.* **16**, 531–553.

Graham, R. H. 1978. Quantitative deformation studies in the Permian rocks of the Alpes-Maritimes. Sciences de la terre et Mesures, Bureau de Recherches Geologiques et Minieres Memoir **91**, 219–238.

Goldstein, A. G., Cushing, J. & Schott, R. 1991. History of folding and thrusting in the Taconic fold-thrust belt, western Vermont. *Geol. Soc. Am. Abs. w Prog.* **23**, 36.

Henderson, J. R., Wright, T. O. & Henderson, M. N. 1986. A history of cleavage and folding: an example from the Goldenville Formation, Nova Scotia. *Bull. geol. Soc. Am.* **97**, 1354–1366.

Hoak, T. 1992. Strain analysis, slaty cleavage and thrusting in the Taconic slate belt, west-central Vermont. *Northeastern Geology* **14**, 7–14.

Kanagawa, K. 1991. Change in dominant mechanisms for phyllosillicate preferred orientation during cleavage development in the Kitakami slates of NE Japan. *J. Struct. Geol.* **13**, 927–943.

Kligfield, R., Lowrie, W. & Dielzel, I. 1977. Magnetic susceptibility as a strain indicator in the Sudbury basin, Ontario. *Tectonophysics* **40**, 287–308.

Pickens, J. 1993. Strain partitioning and cleavage formation in the Mettawee Slates of the Taconic Allochthon. M.S. Thesis, University of Massachusetts.

Ramsay, J. G. & Wood, D. S. 1973. The geometric effects of volume change during deformation processes. *Tectonophysics* **16**, 263–277.

Rowley, D. B. & Kidd, W. S. F. 1981. Stratigraphic relationships and detrital composition of the Medial Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic orogeny. *Geology* **89**, 199–218.

Rowley, D. B., Kidd, W. S. F. & Delano, L. L. 1979. Detailed stratigraphic and structural features of the Giddings Brook slice of the Taconic Allochthon in the Granville area. In: *New York State Geological Association and NEIGC Guidebook of Field Trips* (edited by Friedman, G. M.). Rensselar Polytechnic Institute, Troy, New York, 186–242.

Siddans, A. W. B., Henry, B., Kligfield, R., Lowrie, W., Hirt, A. & Percevault, M. N. 1984. Finite strain patterns and their significance in Permian rocks of the Alpes Maritimes (France). *J. Struct. Geol.* **6**, 339–368.

Sorby, H. C. 1853. On the origin of slaty cleavage. *Edinburgh New Philos. J.* **55**, 137–148.

Stanley, R. S. & Ratcliffe, N. M. 1985. Tectonic Synthesis of the Taconian Orogeny in Western New England. *Bull. geol. Soc. Am.* **96**, 1227–1250.

Tullis, T. E. & Wood, D. S. 1975. Correlation of finite strain from both reduction bodies and preferred orientation of mica in slate from Wales. *Bull. geol. Soc. Am.* **86**, 632–638.

Waldron, H. M. & Sandiford, M. 1988. Deformation volume and cleavage development in the metasedimentary rocks from the Ballarat slate belt. *J. Struct. Geol.* **10**, 53–62.

Wintsch, R. P., Kvale, C. M. & Kisch, H. J. 1991. Open-system, constant-volume development of slaty cleavage, and strain-induced replacement reactions in the Martinsburg Formation, Lehigh Gap, Pennsylvania. *Bull. geol. Soc. Am.* **103**, 916–927.

Wood, D. S. 1974. Current views on the development of slaty cleavage. *Annu. Rev. Earth & Planet. Sci.* **2**, 369–401.

Wright, T. O. & Henderson, J. R. 1992. Volume loss during cleavage formation in the Meguma Group, Nova Scotia, Canada. *J. Struct. Geol.* **14**, 281–290.

Wright, T. O. & Platt, L. B. 1982. Pressure dissolution and cleavage in the Martinsburg shale. *Am. J. Sci.* **282**, 122–135.