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# Deformed graptolites, finite strain and volume loss during cleavage formation in rocks of the taconic slate belt, New York and Vermont, U.S.A.

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**Abstract**—An analysis of graptolites in the Taconic slate belt of eastern New York and western Vermont (U.S.A.) shows that they are nearly ideal strain markers. For the three species used in this study, *Orthograptus whitfieldii*, *Orthograptus calcaratus* and *Climacograptus bicornis*, the spacing of thecae is constant except for the first five or so thecae in the proximal part of the fossil rhabdosome. Further, the thecal apertures are perpendicular to the long axis of the stipe. Observations of the thecal spacing in deformed rocks leads to a determination of extension ($e = (l_f–l_0)/l_0$) and a measure of the angle between thecal aperture and stipe axis yields a direct determination of angular shear strain. In practice, we find it is most straightforward to use length changes to determine the magnitude of principal strains. In Taconic slates, $e_1$ ranges from 1.0 to 0.24, $e_2$ ranges from 0.23 to –0.43 and $e_3$ ranges from –0.56 to –0.74. Thus, we find that the absolute finite strain in these slates is constrictional at three sites, plane strain at another and a true flattening at only one site. An examination of volume changes based on strain results in determinations of between 81% volume loss and 7% volume gain, with volume losses between 28% and 81% in 9 out of 10 calculations. These conclusions are in accord with previous determinations of volume loss based on reduction spot analyses and are consistent with the observation that pressure dissolution was a common grain scale deformation process in cleavage formation but that these slates lack abundant veins, fibrous overgrowths or other identifiable sites of reprecipitation.

## INTRODUCTION

The determination of finite strain is one of the principal goals of structural geology. The magnitude and orientation of the finite strain ellipsoid is critical for constraining, for example, fold mechanisms, displacement across ductile shear zones and volume changes during deformation. Most strain measurement techniques (reduction spots, $R_f$-$\phi$, center-to-center, Fry, etc.) return finite strain ratios which are useful for many applications. However, there are some applications for which absolute finite strains are required. Measurement of absolute finite strains requires objects of known pre-deformation size whereas strain ratios may be determined if rocks contain objects of known shape or distribution. In this regard, the use of deformed graptolites has been under-utilized as a strain measurement technique.

Determination of volume changes is one case for which absolute finite strains are preferable to strain ratios. The amount of volume change which may or may not accompany slaty cleavage formation is a topic which has been debated for nearly 150 years. Sorby (1853) suggested nearly 60% loss of material based on study of reduction spots in Welsh slates. Although he later refined that estimate downward to approximately 20% (Sorby, 1908), numerous other workers have concluded that large volume losses (approximately 50–60%) have accompanied cleavage formation (e.g. Goldstein *et al.*, 1995; Wright and Platt, 1982; Beutner and Charles, 1985; Henderson *et al.*, 1986; Wright and Henderson, 1992; Jenkins, 1987). Others have found little evidence for volume loss (e.g. Wintsch *et al.*, 1991; Erslev and Ward, 1994; Kanagawa, 1991; Waldron and Sandiford, 1988; Tan *et al.*, 1995). Considering the lack of agreement between workers and the potential magnitude of mass transfer implied by up to 60% volume loss, the subject of volume changes during deformation is one which needs additional study. Interestingly, of the small number of papers which have utilized graptolites to determine strain, several have made contributions to the volume loss issue. Wright and Platt (1982) used samples of *Orthograptus* in the Martinsburg shale to conclude that approximately 50% volume loss had accompanied slaty cleavage formation. Jenkins (1987), using samples of a species of the graptolite *Didymograptus*, showed that the strain in rocks of the Llanvirn series of Abereiddi Bay (Wales) had experienced 56% reduction in volume during deformation. Tan *et al.* (1995) combined measurements of deformed *Oncograptids* from shales in Gisborne, Victoria (Australia) with measurements of pyrite framboid pressure shadows to conclude that no change in volume had affected those rocks during cleavage formation. Other work on graptolite deformation has been done by Hills and Thomas (1944) and Cooper (1970, 1990) although those workers have not made reference to volume changes.

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Goldstein *et al.* (1995) relied on strain ratios in Taconic slates to conclude that large heterogeneous volume loss had accompanied the deformation of those rocks, but they were unable to determine absolute strains. The reliance on strain ratios rather than absolute strains resulted in uncertainties about volume loss and Goldstein *et al.* (1995) based their conclusions, in part, on reasoning. In this paper we present absolute finite strains based on graptolite deformation as well as textural evidence both of which are indicative of large mass loss during cleavage formation. We show that calculated volume changes range from +7% to –81% and that most of the observed strains demand significant volume reductions. We also compare finite strains determined by analysis of deformed graptolites with other finite strain deter-

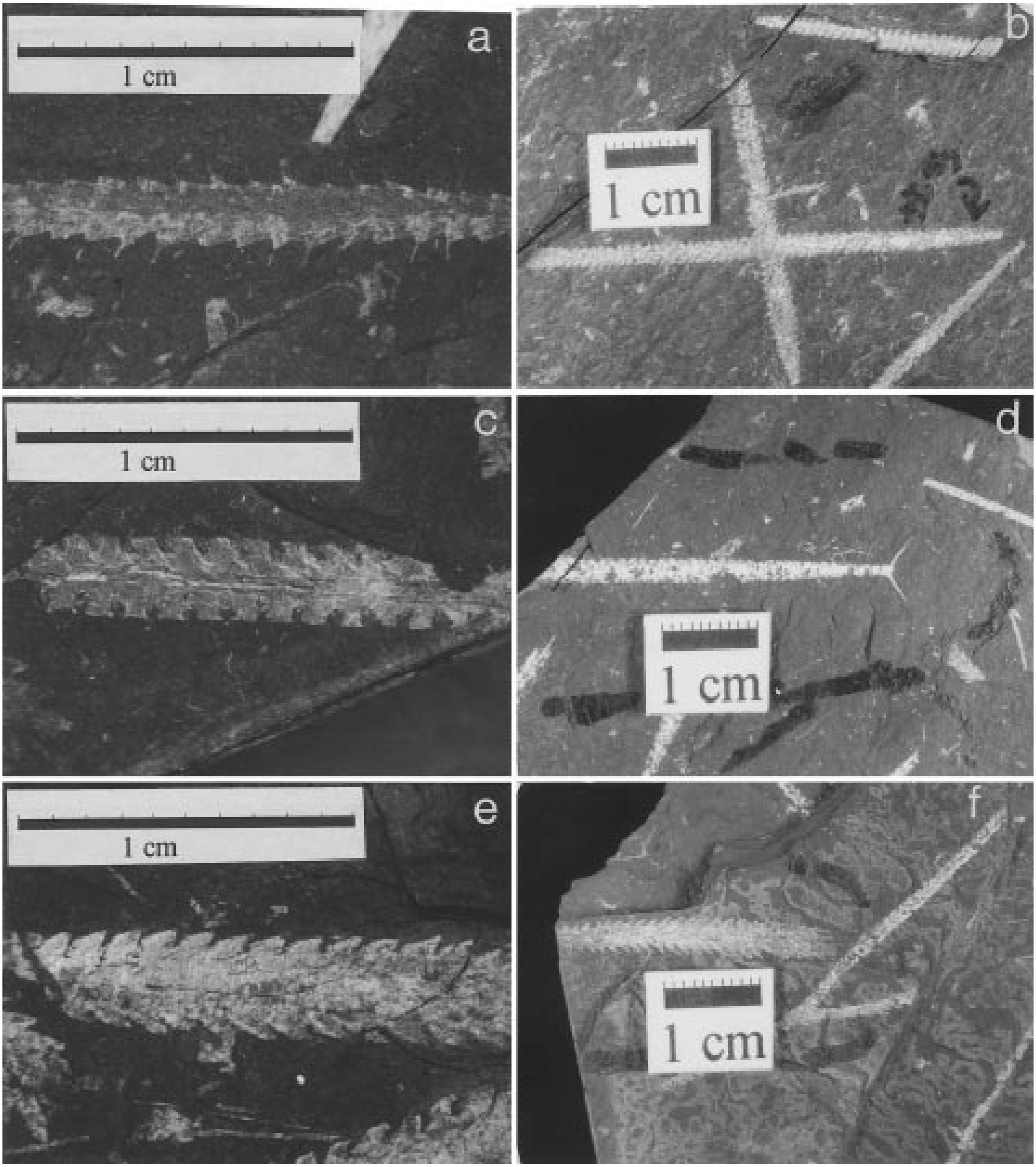


Fig. 1. Photographs of graptolites used in this study. (a), (c) and (e) are all undeformed specimens used to determine undeformed thecal spacings and (b), (d) and (f) are deformed specimens. (a) and (b): *Orthograptus whitfieldii*; (c) and (d): *Climacograptus bicornis*; (e) and (f): *Orthograptus calcaratus*.

minations, especially those from measurement of pressure shadows, and speculate on some of the factors which might control whether volume loss accompanies deformation or not.

## STRAIN MEASUREMENT FROM GRAPTOLITE DEFORMATION

Graptolites are two-dimensional impressions of three dimensional colonial organisms which lived during the Lower Paleozoic Era. They are commonly preserved as either carbon films in black shale and slate or as a white or pale green film (Fig. 1) which may be associated with pyritization of the fossil. Despite some reservations (Underwood, 1992), most workers have considered graptolites to be almost ideal strain indicators (Wright and Platt, 1982; Jenkins, 1987; Tan *et al.*, 1995; Cooper, 1970, 1990) because they have regular morphological characteristics which are different in deformed and undeformed states. Graptolites are preserved as long, thin stipes which may bear small, saw-tooth-shaped thecae on either or both sides (Figs 1 & 2). Using fossils preserved in early lithified, uncompacted rocks, paleontologists have determined that the thecae were the sites at which individuals in the colony lived. In life, the animals grew by adding thecae at the distal end of the stipe (Fig. 2) and these thecae were added with a regular spacing. Thus, observations of the thecal spacing in the deformed state yield the extension parallel to the stipe:

$$e = (l_f - l_0)/l_0 \tag{1}$$

with $l_0$ represented by the undeformed thecal spacing and $l_f$ represented by thecal spacing in the deformed state (Fig. 3).

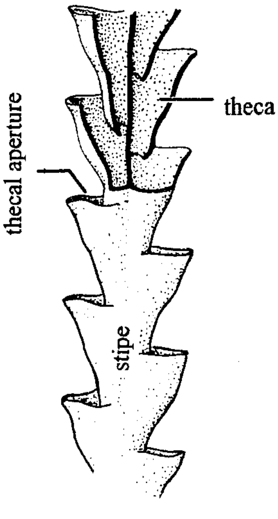


Fig. 2. Sketch of graptolite showing morphological elements referred to in this paper.

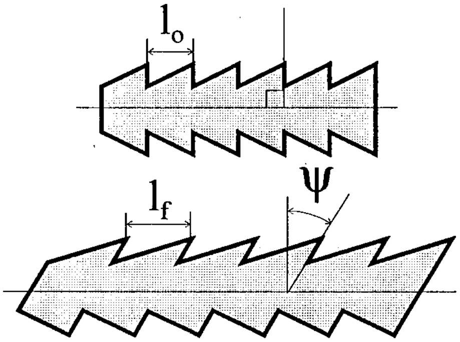


Fig. 3. Deformation of graptolites results in a change in the spacing of thecae as well as a change in angle of the thecal aperture. For samples of the three species used in this study the undeformed thecal apertures are perpendicular to the stipe so that measurement of the angle in the deformed state leads to a determination of angular shear strain parallel to that graptolite.

The geometry of two-dimensional finite strain is such that extension and shear strain are functions of the angle that a line makes with the directions of principal finite strains (Ramsay and Huber, 1983; pp. 127–149). The relationship between orientation and extension is especially useful for working with graptolites. Ramsay and Huber (1983) show that the relationship can be defined by the following equation in which change in length of a single graptolite is expressed as quadratic extension ($\lambda = (1 + e)^2$):

$$\lambda' = \lambda_1'(\cos^2 \theta') + \lambda_2'(\sin^2 \theta') \tag{2}$$

in which $\lambda_1'$ and $\lambda_2'$ are the reciprocal principal quadratic elongations and $\theta'$ is the angle between the maximum principal extension direction and the graptolite. This equation can be rewritten in the following form:

$$\lambda' = \lambda_1' + (\lambda_2' - \lambda_1') \sin^2 \theta'. \tag{3}$$

This formulation can be graphed with $\lambda'$ as the abscissa and with $\sin^2\theta'$ as the ordinate producing a linear arrangement of strain states (Fig. 4). Two advantages arise from such a formulation of the equations of strain. First, the statistics of linear regression are more accessible than are those for curve fitting and these statistics are, in general, more robust. These include not only the ability to fit lines to data arrays but also the ability to determine statistical variability. Such statistics are available on most general use data analysis software packages. The second advantage is that the principal strains plot at $\sin^2\theta'$ of 1.0 and 0.0, making it fairly simple to determine them from the graphs. Because some species of graptolites have thecal apertures which are perpendicular to the stipe, the angle between thecal aperture and the stipe in the deformed state yields a direct measurement of angular shear strain (Figs 1b, 2 & 3). Thus, one could examine graptolite strain in Mohr circle space although, in practice, determination of principal strains

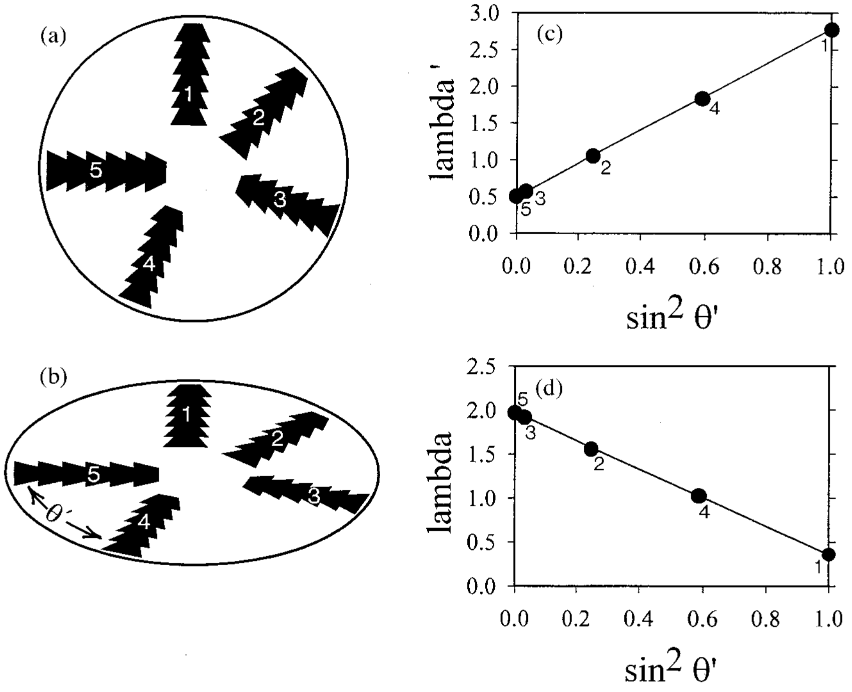


Fig. 4. Illustration of the method used for determining principal strains from deformed graptolites. (a) five graptolites in the undeformed state; (b) five graptolites from (a) deformed with one principal shortening and one principal elongation; (c) strain recorded by the five graptolites in (b) plotted according to equation (3); (d) strain recorded by five graptolites in (b) graphed according to equation (3) but with the reciprocal quadratic elongation ($\lambda'$) converted to quadratic elongations.

is more straightforward if one uses only length changes.

## THE TACONIC SLATE BELT

The area used for this study is the slate belt of the northern Taconic allochthon (Fig. 6). The Taconic allochthons are large slices of Cambrian through middle Ordovician fine-grained rocks originally deposited on the paleo-eastern passive margin of north America. During the middle Ordovician Taconic orogeny these rocks, along with slices of crystalline basement, were thrust westward on top of shelf carbonates of equivalent age. It is widely accepted that this deformation occurred during the collision of the early Paleozoic North American passive margin with the west-facing Taconian subduction zone (e.g. Stanley and Ratcliffe, 1985). In addition to thrusting, the rocks within the thrust sheets were isoclinally folded and a pervasive slaty cleavage formed parallel to the axial planes of the folds. The region has been used extensively for commercial slate quarrying and the slates have been the subject of a number of structural investigations (Goldstein *et al.*, 1995; Wood, 1974; Hoak, 1992; Pickens, 1993; Cushing and Goldstein, 1990; Crespi and Byrne, 1987; Bosworth and Vollmer, 1981; Bosworth and Rowley, 1984) as well as serving as a model for interpreting the origin of mountain belts in the context of plate tectonics (e.g. Bird and Dewey, 1970; Jacobi, 1981; Rodgers, 1970; Rowley and Kidd, 1982; Stanley and Ratcliffe, 1985).

Graptolites have been found in two formations of the Taconics, both black, rusty-weathering slates. In the Hatch Hill Formation the graptolites are neither abundant nor useful for strain analysis. However, they are reasonably widespread in the Mount Merino Formation and are almost ideal for strain studies. The Mount Merino is the youngest stratigraphic member of the Taconic sequence and is only locally overlain by middle Ordovician flysch, which was deposited over a regional angular unconformity. Within the Mount Merino Formation, the graptolite-bearing unit is the stratigraphically highest (Rowley *et al.*, 1979) resulting in its preservation only in the deepest synclines.

## ABSOLUTE FINITE STRAINS

Three species of graptolites which are abundant in the Mount Merino Formation have been utilized for this study: *Orthograptus whitfieldii* (Fig. 1a & b), *Orthograptus calcaratus* (Fig. 1c & d) and *Climacograptus bicornis* (Fig. 1e & f). For these three species, early formed thecae are slightly more closely spaced than are later formed thecae and the stipe widens progressively for the first few thecae (Fig. 1b & d). We note that once the stipe has achieved its 'mature' width the thecae maintain a constant spacing. Further, the thecal aperture is perpendicular to the long axis of the stipe in the undeformed state (Figs 1

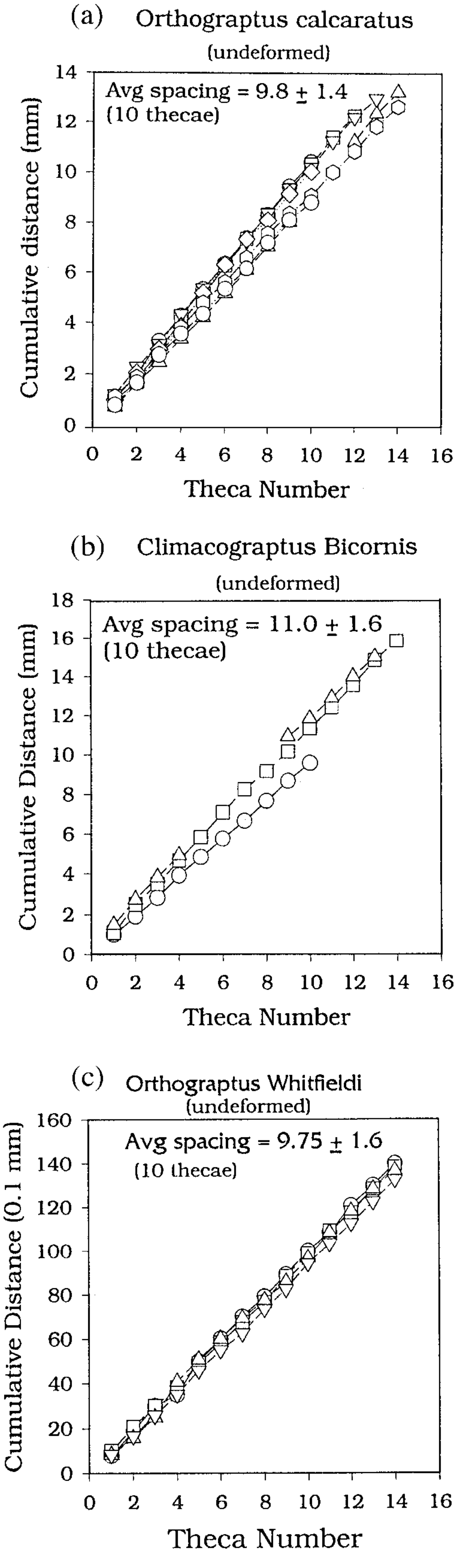


Fig. 5. Determination of undeformed thecal spacings. Theca number, plotted along the $x$-axis, is an arbitrary designation and does not refer to theca number in the paleontological sense. Data were all derived from measurement of thecal spacings far from the proximal end of the stipe. Average spacings between 10 thecae along with standard deviation are shown for each species. (a) *Orthograptus calcaratus*, (b) *Climacograptus Bicornis* and (c) *Orthograptus Whitfieldi*.

& 2) and the change in angle of the thecal aperture yields the angular shear strain (Fig. 3). Undeformed thecal spacings for the three species were obtained by measuring the dimensions of graptolites in samples borrowed from the Smithsonian Institution (Figs 1a, c, e & 5). These samples (Fig. 1), collected by James Hall, are from exposures of middle Ordovician rocks near Albany, N.Y. and were deposited closely in space and time with the graptolites of the Taconics. Undeformed thecal spacings were obtained by measuring the spacing between thecae for 10–15 thecae on each of between 3 and 6 individual graptolites. These spacings were used to determine a mean and standard deviation spacing between thecae (Fig. 5). We report these spacings as the distance between 10 thecae and these values are in good agreement with measurements by other workers (e.g. Elles and Wood, 1918).

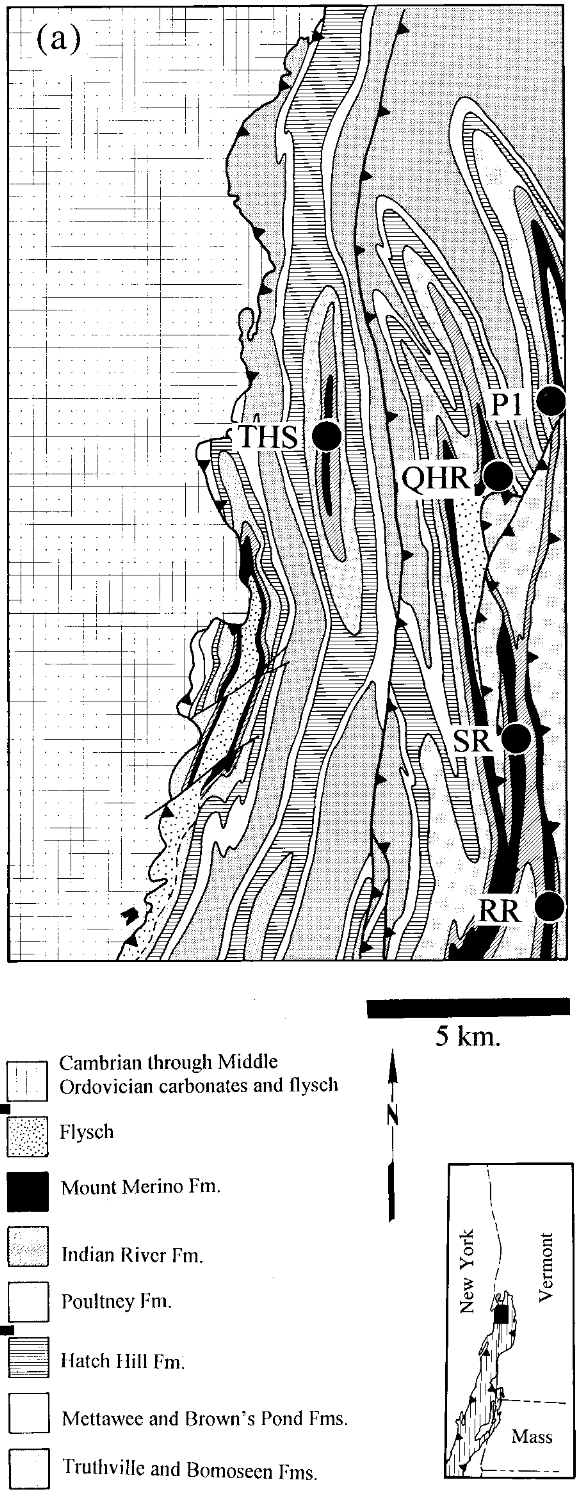
Graptolites were found at eight localities in the northern Taconic allochthon in sufficient numbers and with sufficiently good preservation to be measured (Fig. 6). The fossils are found on bedding planes as white, two-dimensional replacements of the original animal remains. Rocks of the Taconics have been isoclinally folded so that on limbs of folds bedding and cleavage are parallel. Because graptolites lie parallel to bedding, when they lie on cleavage surfaces one can see that bedding is exactly parallel to cleavage. The hinges of the folds are very sharp and the limbs are long so that most exposures in the Taconics display parallel bedding and cleavage. Of the eight sites we located, five are on limbs of folds, two are at hinges and one is intermediate between the two (Table 1). At each site, oriented blocks were collected and were split along bedding until well preserved graptolites were found. The spacing of between 5 and 10 thecae for each graptolite was measured either by photographing and measuring from the photographic print or by direct measurement under the microscope. Thecal spacings were converted to quadratic elongations and were plotted as a function of orientation (Fig. 7). The data were statistically analyzed by linear regression and the variability of that regression was also determined to the 95% level of confidence (Fig. 7). All errors reported in strains are at that statistical level. We believe that most of the variation in graptolite strains determined by using this method reflect the variation in original, undeformed thecal spacing (Fig. 5).

The data in Table 1 summarize the results of strain measurements and the data are shown in Fig. 7. The graphs (Fig. 7) display strains as quadratic elongation $(1 + e)^2$ whereas the principal strains in Table 1 are shown as extensions ($e$) because such values are more easily interpreted. Five sites located on limbs have parallel bedding and cleavage and, thus, yield determinations of the $X$–$Y$ principal strains. At hinges, where bedding is perpendicular to cleavage, the $Z$ principal strain is determined and the strain perpendicular to that, parallel to the bedding-cleavage intersection, is a non-principal strain. This is because the *X* direction of strain is not perpendicular to fold hinges but rakes from 40° to 90° southward on the cleavage plane and is marked by a prominent mineral elongation lineation. The final site does not record principal strains but is helpful in constraining the values of principal strain, especially *Z*.

An examination of Table 1 reveals considerable heterogeneity in the principal strains. $X$ ($e_1$) varies from 100% $\pm$ 8% elongation to 22% $\pm$ 4% elongation (note: all errors are $\pm$95% confidence limits). $Y$ ($e_2$) values range from 1% $\pm$ 8% elongation to 43% $\pm$ 10% shortening. One of our cleavage-parallel sites yields a *Y* value of near zero (plane strain) whereas the other four all record shortenings. Statistically, the *Y* value for site THS could also be a shortening but none of the variability in principal strain determination for the other sites allows for *Y* being an elongation. Our two hinge sites both record large amounts of shortening, 56% $\pm$ 13% and 74% $\pm$ 26%. The remaining site, intermediate between hinge and limb, also records large amounts of shortening, 52% $\pm$ 10%. Although this is not a principal strain, the minimum principal elongation (*Z*) must be smaller (more shortening) than this value suggesting that the large amounts of shortening recorded at the hinges are reasonable.

## COMPARISONS OF GRAPTOLITE STRAINS WITH OTHER STRAIN RESULTS

It is of interest to compare our strain results with other strain measurements made in the Taconics. Previous workers have determined strain in slates of the northern Taconics using reduction spots (Fig. 8) and pyrite framboid and porphyroblast pressure sha-



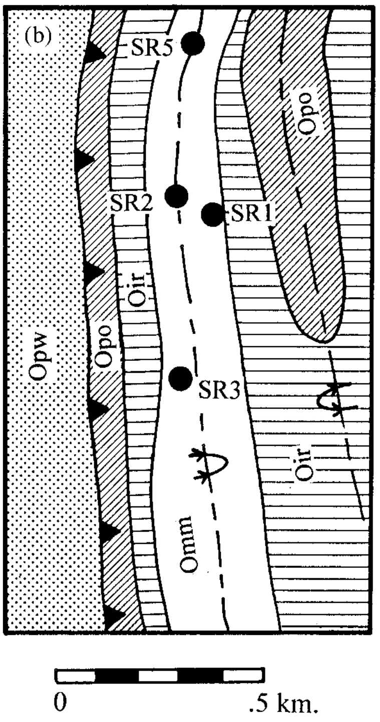


Fig. 6. Geologic maps of the study area. (a) Geologic map of the Whitehall, N.Y. region, modified from Fisher (1984). SR refers to a small region in which five sites are located, shown on (b). Sample localities QHR, P1, RR and THS are shown. (b) Geologic map of the Stoddard Road area showing location of sampling sites.

Table 1. Summary of principal strain values determined from graptolite deformation. $n$ is the number of graptolites measured at each site; $e_{1,2,3}$ are principal strains determined using the average thecal spacing for undeformed graptolites; $e_{\mathrm{fax}}$ is the strain recorded parallel to the fold axis; and $e_*$ is a non-principal strain which lies within bedding and perpendicular to the fold axis. BXC is the angle between bedding and cleavage. All errors are reported at the 95% confidence level

| Site | $n$ | $e_1$ | $e_2$ | $e_3$ | $e_{\mathrm{fax}}$ | $e_*$ | B × C |
|---|---|---|---|---|---|---|---|
| SR1 | 39 | 0.24 ± 0.06 | 0.43 ± 0.10 | | | | 0° |
| QHR | 23 | 0.32 ± 0.08 | 0.38 ± 0.16 | | | | 0° |
| THS | 25 | 0.62 ± 0.07 | 0.01 ± 0.08 | | | | 0° |
| RR | 10 | 1.0 ± 0.08 | 0.23 ± 0.07 | | | | 0° |
| P1 | 39 | 0.22 ± 0.04 | −0.11 ± 0.07 | | | | 0° |
| SR2 | 9 | | | −0.56 ± 0.13 | 0.06 ± 0.07 | | 90° |
| SR5 | 23 | | | −0.74 ± 0.26 | −0.03 ± 0.03 | | 90° |
| SR3 | 38 | | | | −0.03 ± 0.06 | −0.52 ± 0.10 | 65° |

dows (Fig. 9). Goldstein *et al.* (1995), Hoak (1992) and Wood (1974) all reported strains recorded by reduction spots in the same region from which graptolites were obtained, although the reduction spots are found lower in the stratigraphy in a different formation than are the graptolites. All three studies reported similar results, strains which lie in the field of apparent flattening (Fig. 8). It is difficult to compare these results directly with the data reported here because reduction spots record sedimentary compaction whereas graptolites do not. Further, reduction spots yield only strain ratios and one must assume either constant volume or some specific volume change in order to derive absolute strains (Goldstein *et al.*, 1995). The shape of reduction spots, highly flattened, is suggestive of a strain state with two principal finite elongations and one shortening. However, the graptolites clearly show that strain is a finite flattening at one site, is plane strain at another and is a finite constriction at the remaining three. Despite this, strain states displayed on a Flinn diagram (Fig. 10) show only two sites which plot as apparent constrictions (close to plane strain) whereas the other three all plot within the field of apparent flattening. These plots have been made by using the average $Z$ from sites SR2 and SR5 combined with $X$ and $Y$ from the five sites on limbs of folds. The error bars record the variation in strain ratios at the 95% confidence limit. The error in the $Y/Z$ ratio is large because we used the statistical variation in both of the hinge sites yielding an average $Z$ which ranges from 43% to 99% shortening. Two factors account for the lack of correspondence between absolute principal strains and the positions on the Flinn diagram (Fig. 8). The first is that we believe that a significant volume change has affected these rocks (see below) so that the strain state is best described as a finite constriction plus a volume loss. The other factor is that reduction spots record burial compaction whereas graptolites do not. Graptolites exist as three dimensional tubes (e.g. *Climacograptus*) or boxes (e.g. *Orthograptus*) which are compressed during burial. This vertical shortening does not alter the original thecal spacing so that graptolites record only the tectonic components of strain. If one adds an additional component of compaction (volume loss through porosity reduction) to graptolite strains, they plot well into the field of reduction spot strains so that we believe that the reduction spots record the true strains. Goldstein *et al.* (1995) noted that reduction spot strain was highly heterogeneous at a variety of scales and they used this observation to suggest large volume losses. We do not see the heterogeneity which those workers found. This is because reduction spots are only a few millimeters to a few centimeters in size and each spot can be considered independently whereas many graptolites must be used at a single site to determine an average site strain, thus obscuring any site-scale heterogeneity. Site-to-site heterogeneity (Fig. 8) indicates greater variability in $Y/Z$ values than in $X/Y$ values, similar to that seen in reduction spots.

Comparing graptolite strains to other strain determinations from Taconic slates is also possible (Fig. 9). The magnitude of elongation in $X$ may be derived from pyrite framboid and porphyroblast pressure shadows. Cushing and Goldstein (1990), Pickens (1993) and Chan and Crespi (personal communication, 1996) have all investigated this phenomenon in the northern Giddings Brook slice with comparable results. Cushing and Goldstein (1990) reported an average elongation of 101% from 24 framboid pressure shadows at one site; Chan and Crespi (personal communication, 1996) noted framboid pressure shadow elongation values of from 110% to 140% at five sites and Pickens (1993) found an average of 95% elongation from porphyroblast pressure shadows at seven sites. Despite the good agreement between these studies, none of them agrees with the lower strains determined from graptolites (Fig. 9 and Table 1). Pressure shadow strains have not yet been determined for the same sites used for graptolite strain measurements and we have only a single site which records an extension as high as those indicated by pressure shadows. At this time it appears that pressure shadow strains may be overestimating the true elongation.

One may determine the $Z$ component of strain in the Taconics by observing buckled beds at hinges of folds, where bedding and cleavage are perpendicular or with rare findings of buckled veins. We have found

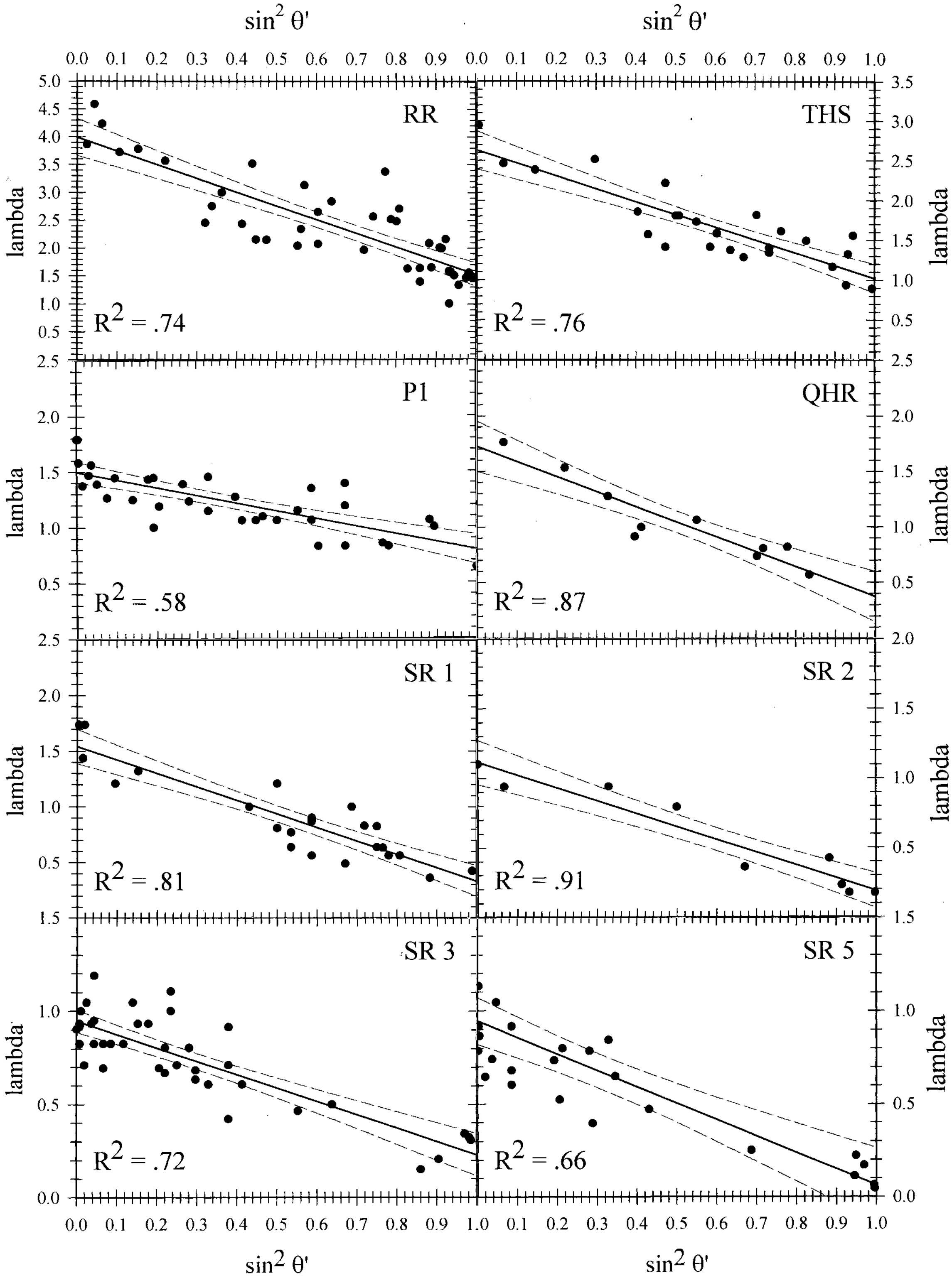


Fig. 7. Data derived from measurement of graptolites at each site. Data are shown as dots, the solid line is the linear regression fit to the data with $R^2$ noted; dotted lines are the 95% confidence limits for each regression determination.

four examples of these phenomena and the amounts of shortening average approximately 50% (Fig. 9). This is somewhat lower than the 56% and 75% shortening determined from graptolite measurement, but is much closer than the difference in *X* values.

Finally, we note that graptolites provide the only accurate method of determining *Y* in these, and most other, slates. Reduction spots, so common in red slates, are of little use in this regard because, as discussed above, they yield only strain ratios. We observe

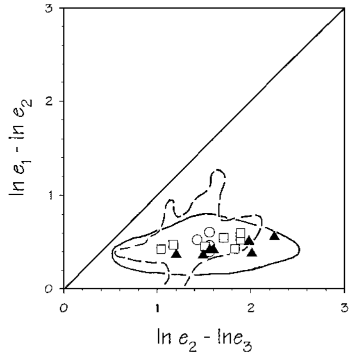


Fig. 8. Flinn diagram of strains derived from reduction spot measurements (from Goldstein *et al.*, 1995). Site average strains from Goldstein *et al.* (1995) are shown as triangles, data from Hoak (1992) are shown as open circles and data from Wood (1974) are shown as open squares. The range of data collected by Wood (1974) for slates from Wales and the Taconics is shown with a dashed line and the range of data collected by Hoak (1992) is shown with a solid line.

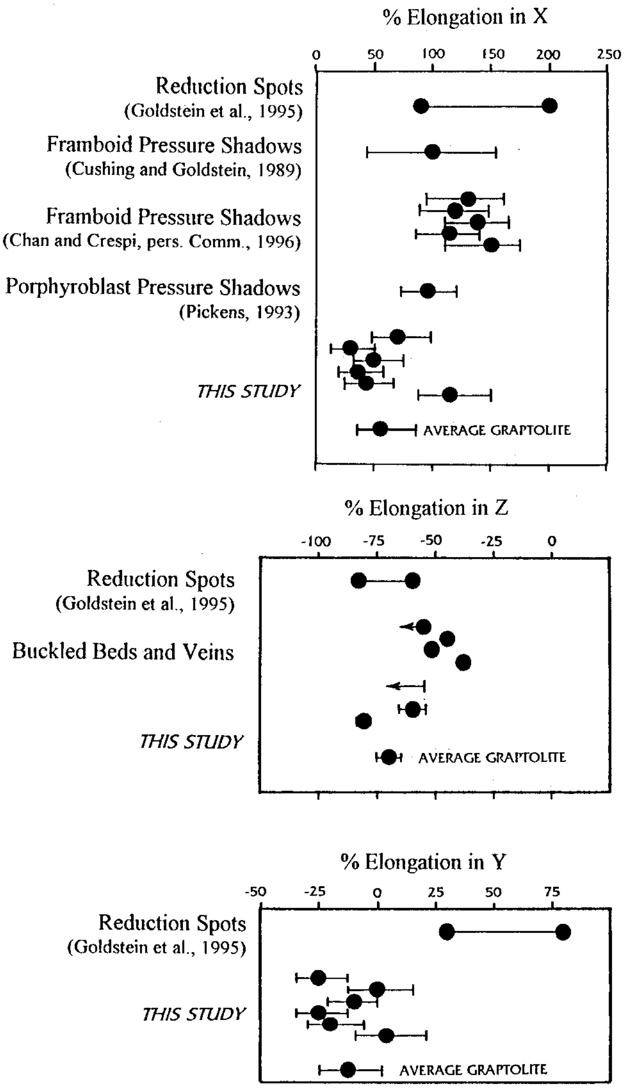


Fig. 9. Comparison of principal strain from this study with strain determinations from Taconic slates derived using other methods. Strains from reduction spots have been calculated assuming no volume loss. These values would change if one were to assume a volume change.

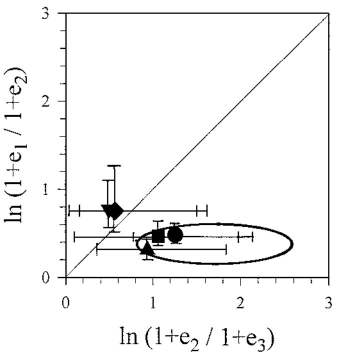


Fig. 10. Flinn diagram of strains from each site with parallel bedding and cleavage combined with an average shortening of 65%. Error bars show the variation in strain ratios if the 95% confidence limits are used. The ellipse shows the general region of reduction spot strain measurements.

that there is no indication in any of the other strain measurements made of Taconic rocks that $Y$ is a shortening (Fig. 9).

## VOLUME CHANGE CALCULATIONS

If the graptolite data are accepted as providing good measurements of principal finite strains, then these values can be used to constrain volume changes which may have affected these rocks. Such a determination relies on the mathematical relationship determined by Ramsay and Wood (1973):

$$\ln(1+\Delta) = \ln(1+e_1) + \ln(1+e_2) + \ln(1+e_3) \tag{4}$$

in which $\Delta$ is the volume change (positive for gains and negative for losses) and $e_1$, $e_2$ and $e_3$ are principal finite extensions. Because we have not been able to determine all three principal strains at one locality, it is necessary to combine principal strains from different localities. We have five sites which yield $XY$ principal strains and two which yield $Z$. For each site there is some variability in the principal strains derived which we interpret to be due to natural variability in undeformed thecal spacings. This is expressed, we believe, in the 95% confidence limits for the linear regressions (Fig. 7 and Table 1). We have combined strains such that the volume change for each site (Table 2) is based on the strains at that site ($XY$) and the $Z$ value at the two hinge sites, SR2 and SR5. The error in these site-level determinations is expressed by showing the volume change which would be derived by using the 95% confidence limits for the strains at that site.

The volume changes using this method are listed in Table 2. Using the best-fit linear regression to the strain data (Table 1 and Fig. 7) we note that volume losses are indicated for all sites with the sole exception of site RR which yields a slight increase in volume when the $XY$ values for this site are combined with the $Z$ value for site SR2. If the $Z$ value for site SR5 is

Table 2. Volume changes calculated from equation (4). Principal strains from sites with parallel bedding and cleavage have been combined with $Z$ values from the two sites at which bedding and cleavage are perpendicular. The value of the strains determined from linear regression are listed as 'Mean' and the statistical ranges using the 95% confidence limits around the regression are listed as 'Min' and 'Max'. Volume losses are shown as negative numbers and volume gains are listed as positive numbers

| | | SR2 | | | SR5 | |
|---|---|---|---|---|---|---|
| Site | Mean | Min | Max | Mean | Min | Max |
| SR1 | –68% | –83% | –50% | –81% | –99% | –54% |
| QHR | –65% | –83% | –39% | –78% | –99% | –43% |
| THS | –28% | –56% | +5% | –56% | –98% | –4% |
| RR | +7% | –31% | +26% | –35% | –98% | +40% |
| P1 | –52% | –70% | –31% | –71% | –99% | –36% |

used, the calculations yield volume losses for all sites with value ranging from 35 to 81% volume loss. If one considers the statistical ranges of the principal strains (Min and Max in Table 2) two of the five limb sites suggest volume gains using the $Z$ value for site SR2 but only site RR yields volume gains for $Z$ from SR5. Thus, we interpret these results as strongly suggestive of large volume losses for most of the sites within the Taconic slate belt.

A question of some significance is to what extent the statistical ranges of volume change are a reflection of reality. In other words, exactly how much of the volume loss or gain which has been calculated is reasonable? The extremes go from 40% volume gain to 99% volume loss. The very large volume losses calculated using the 95% confidence limits for site SR5 derive from the inability to define an appropriate minimum for $e_3$ at that site (Fig. 7). The linear regression is strongly affected by a range of strains parallel to or at a low angle to the bedding-cleavage intersection ($\sin^2\theta' \approx 0$). Thus, the lower intercept for the 95% confidence envelope is negative, a result which has no significance in the context of strain. Thus, we do not consider the very large volume losses to be accurate. Similarly, we have some concern about the determinations of volume gain in these rocks. We note below a number of observations which are consistent with volume losses for Taconic slates but we know of no observations which are in any way indicative of volume gains. If a rock has experienced true volume gain one should be able to see abundant veining or other evidence of precipitation of mineral matter. We do not find these features in the slates of the Taconics. Thus, we contend that the volume changes derived by using the linear regression $y$-intercepts are more reliable than those derived by using the statistical ranges of possibilities. This yields determinations of volume change which range from near 80% for some sites to near zero for others, with an average of approximately 44% for the region studied.

In order to use this method we must accept that the least principal strain ($Z$) value determined at fold hinges is close to that on fold limbs, where $XY$ values have been determined. Because cleavage does not appear to vary in intensity from limb to hinge we believe that the shortening measured at hinges is close, if not identical, to shortening which would be measured on limbs, if appropriate strain markers were present. In one site located on a fold limb we have found an early vein which is buckled and intersects cleavage at 55°. The shortening measured from that vein is 56% and the principal shortening must be greater than that (i.e. more shortening). We do not believe that strain would be homogeneous on the scale of a fold and the degree of heterogeneity would be controlled, for the most part, by the folding mechanism and the post-folding strain history. Several workers have determined that folding in the Taconics was a reasonably early structural event and that the slaty cleavage was superimposed on already folded rocks (Rowley *et al.*, 1979; Goldstein *et al.*, 1991; Crespi and Byrne, 1987). Such conclusions are based, in part, on the observation that cleavage cuts uniformly across the folds without displaying cleavage refraction or a fanning geometry. We assume that over a scale of several meters (the distance from hinge to limb) cleavage-related (post-folding) strain was fairly homogeneous. What may not be homogeneous is the strain related to folding. Different fold mechanisms will result in different strain patterns (e.g. Ramsay and Huber, 1987, pp. 445–473) and given only two dimensional strain markers, such as graptolites, it is not possible to uniquely determine this pattern. It is likely, however, that using two dimensional, bedding-parallel strain markers may make the problem more tractable than otherwise. The rocks of the Taconics are dominantly clay-rich with very few beds of other lithologies which could have acted as rigid, stress-bearing plates. Thus, buckling fold mechanisms may not generally apply to the Taconics. Crespi and Byrne (1987) suggested that folding was accomplished by flexural flow and that hinges were pinned. In this case, one would expect fold-related strain to be zero at the hinge and that strain on the limbs would approximate the strain in a shear zone with bedding acting as shear zone boundaries (Ramsay and Huber, 1987). In such a case the bedding will be a plane of no finite strain, as would any shear zone parallel plane in a homogeneous shear zone. Thus, graptolites may well not record any of the folding-related strain. For all these reasons we feel confident in using strain values from hinges as an approximation of shortening on fold limbs.

## DISCUSSION

The volume loss determined from graptolite strain values is in good agreement with other volume change determinations from the Taconics and other slate belts. It has been common for volume losses of between 40% and 60% to be proposed for slates (e.g. Goldstein *et al*., 1995; Wright and Platt, 1982; Beutner and Charles, 1985; Henderson *et al*., 1986; Wright and Henderson, 1992; Jenkins, 1988). In particular, Goldstein *et al*. (1995) suggested that volume loss for the Taconic slates was heterogeneous varying, at a minimum, from 0% up to 55%. Because these conclusions were based on reduction spots they had all the problems and uncertainties of strain studies based on strain ratios. In particular, Goldstein *et al*. (1995) had to assume that the site which had the lowest strain state had experienced zero volume change and the volume change for other sites was calculated from that. Considering that even the lowest strain site is highly strained and probably had experienced some volume loss, Goldstein *et al*. (1995) suggested that an average of between 50% and 60% loss of volume was reasonable for the Taconic slate belt. Erslev and Ward (1994) studied a single thin section from the Taconics and concluded that no volume change had affected that sample. They based that conclusion on the assumption that their sample had started with a composition similar to an average shale and, since it still had that composition, no significant volume changes had affected that sample. We do not agree with the assumption of initial composition and, rather, choose to interpret the data presented by Erslev and Ward (1994) as reflective of considerable elemental mobility and loss of approximately 50% volume.

Other observations suggest that volume loss has affected the slates of the Taconics. The slaty cleavage is marked by concentrations of illite separating domains rich in quartz, chlorite and minor amounts of calcite and albite (Fig. 11). The concentrations of illite have formed by dissolution of the other minerals leaving an insoluble residue of clays. We find little evidence of reprecipitation of any of these dissolved minerals. Fibrous overgrowths are exceptionally uncommon, although very small volumes surround pyrite framboids and porphyroblasts. Crespi and Chan (1996) have observed syn-tectonic fringes of mineralization on the edges of pre-tectonic veins, but these fringes are small compared to the volume of early vein material. No quartz-mica beards on quartz grains have been observed as they have been in many other slates. Similarly, veins are very uncommon in the Taconics. Even when veins are present, they can be shown to have formed either pre-cleavage or post-cleavage. Very little syn-tectonic mineralization can be found in these rocks and considering the evidence for pressure dissolution we feel that it is entirely consistent that we derive large volume losses from our strain analyses.

For large volume losses to be possible there must have been an appropriate hydrologic system. Fluids must have moved through the rock in such a way that the elements that are being dissolved do not reach saturation or dissolution will cease. The tectonic setting of the Taconic orogeny provides an appropriate paleohydrological scenario. During the middle Ordovician the paleo-eastern margin of North America contacted the west-facing Taconic subduction zone and it was probably this collision which stopped subduction. During the collision the rocks deposited on the passive margin of North America were imbricated and incorporated with the Taconic accretionary complex (Stanley and Ratcliffe, 1985). An examination of modern accretionary complexes shows that they are environments in which large volumes of water are passing through rock (e.g. Elderfield *et al*., 1990; Moore and Vrolijk, 1992; Kastner *et al*., 1991). This is seen in the common occurrence of submarine springs and mud volcanoes on the surface of accretionary complexes. Some workers have estimated the annual fluid discharge from accretionary complexes at 10 s to 100 s of $m^3$ per year for each meter of length of subduction zone (Kastner *et al*., 1991). The scale of this fluid flow system is sufficient to entirely recycle the world's oceans in approximately 500 Ma (Kastner *et al*., 1991). Apparently, loss of pore water occurs at shallow depths after incorporation into the prism but structural water held in smectite and opal-A is not released until much deeper (Moore and Vrolijk, 1992). This water passes upward through the accretionary complex and, at shallow depths, is focused along faults and fracture zones. At greater depths, fluid pressures are probably quite high (Moore and Vrolijk, 1992), perhaps equal to or greater than lithostatic stress, making it possible for pervasive, diffuse fluid flow necessary to accomplish the widespread dissolution suggested here. It is exactly this kind of hydrologic setting at which we might expect large volumes of dissolution and volume reduction. Thus, we can imagine that some slates were deformed in settings where the paleohydrology allowed major dissolution without much reprecipitation whereas others may have been deformed in setting which lacked the proper hydrogeochemical setting. From this perspective, we believe that it is entirely reasonable to find that some slates have lost volumes of 50–60% whereas others have lost essentially no volume at all.

An examination of modern accretionary prisms suggests an answer to the question invariably asked of those proposing large volume losses: "Where has it gone?". In modern accretionary prisms material dissolved at depth is transported upward with advecting water and discharged into the oceans. A similar situation might well have existed during the Taconic Orogeny. As long as a sufficiently vigorous flow system is operating it is possible that fluids never reached saturation, explaining the general lack of widespread syn-

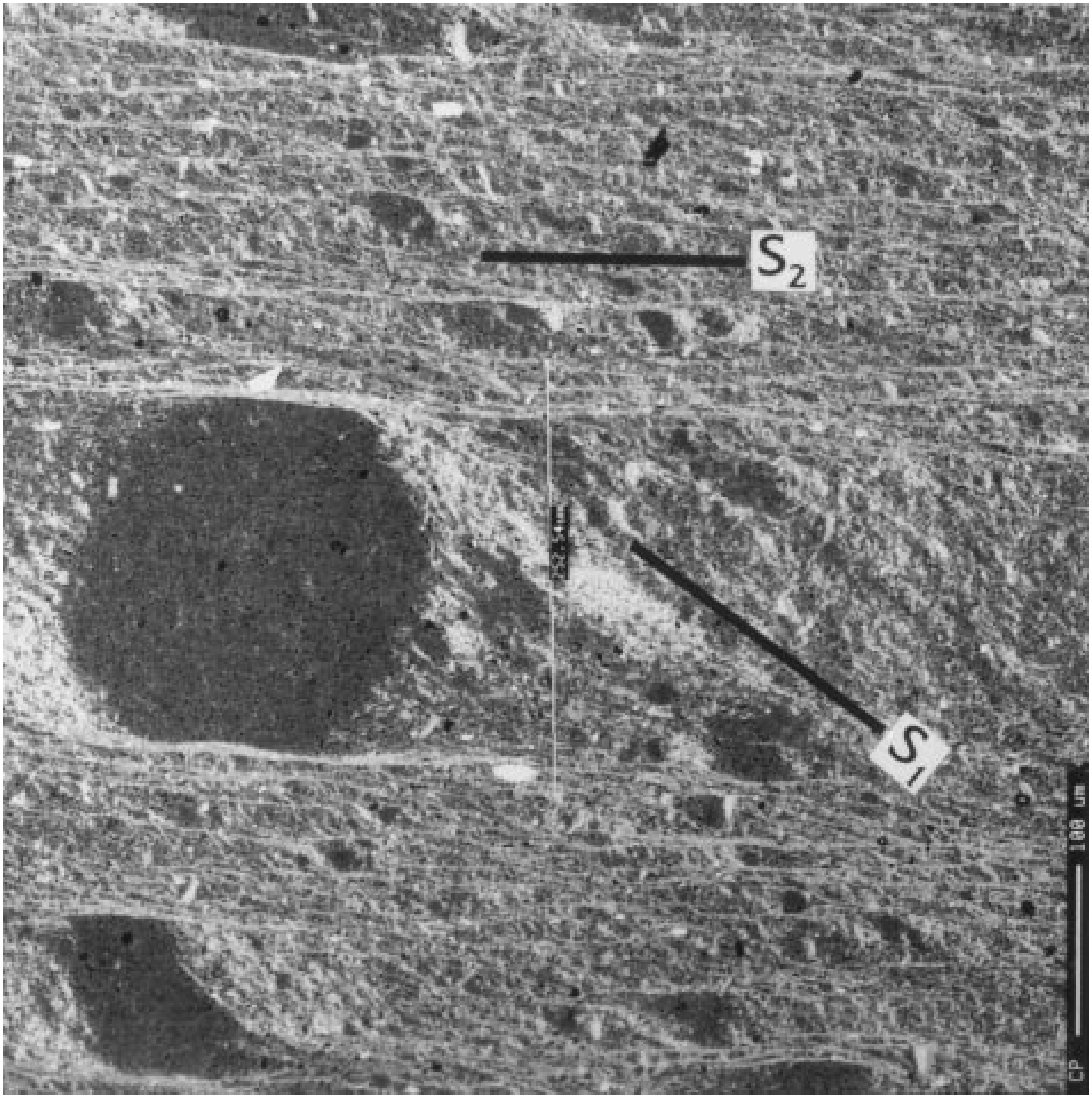


Fig. 11. Backscattered image of slaty cleavage and a ball of volcanic ash from the Indian River Formation in the Taconic slate belt. Slaty cleavage ($S_2$) cuts horizontally across the image and the pre-cleavage fabric ($S_1$) is seen in the strain shadow around the ash ball. Note the evidence for pressure dissolution as well as the general lack of fibrous overgrowths. Note scale bar in lower right of photo.

tectonic mineralization in the Taconics and helping to explain the large volume losses derived from strain analysis.

## CONCLUSIONS

1. The three species used for this study are nearly ideal strain indicators as they have regular thecal spacings and angles between the stipe and thecal apertures which are 90° in the undeformed state. Determination of principal strains is most straightforward if one uses length changes only.
2. The absolute finite strain for the Taconic slate belt is best described as a finite constriction plus a volume loss. Three out of five sites which define $e_2$ show it to be a shortening which varies from $\sim$10% to $\sim$40% shortening, one site defines near plane strain and only one site shows $e_2$ to have been an elongation. If one considers the effect of sedimentary compaction, strains determined from graptolites agree well with those from reduction spots. Graptolite strains, however, record lower extensions in $X$ than do measurements of pyrite framboid and porphyroblast pressure shadows, suggesting that

perhaps these values are overestimating true strain magnitudes.

3. Volume changes calculated from graptolite strain vary from 7% volume gain to 81% volume loss. Most combinations of strains result in large volume losses. Whereas some sites may have experienced no volume loss or even very slight volume gain, we find the calculations of large volume gain or very large volume loss to be at odds with observations of rock texture. The determinations of volume loss are in agreement with previous suggestions based on reduction spot measurement, textural observations and the general lack of syntectonic mineralization.

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