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Volume change accompanying cleavage development in graptolitic shales from Gisborne, Victoria, Australia

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Abstract—Studies on shape changes in deformed *Oncograptus upsilon* combined with strain analysis of pressure shadows around framboidal pyrite revealed that a small volume change of the order of 5 percent accompanied the cleavage development in the shales from Gisborne, Victoria. Starting from the proximal end, *Oncograptus upsilon* exhibits progressive increase in the spacing between successive thecae along the stipes. A new technique utilizing the distance between a specific number of thecae is used for computing the change in length along stipes of *Oncograptus upsilon*. The low volume change, accompanying a more than 70 percent shortening deformation, indicates that there is a less significant mass loss during cleavage development than has been inferred from some studies on volume change from thecal spacing in deformed graptolites.

INTRODUCTION

The possibility of large volume changes taking place in shaly rocks during cleavage-forming deformation has been a subject of considerable speculation since Sorby (1853) suggested that a volume loss of almost 60 percent had accompanied the formation of cleavage in the Cambrian rocks of North Wales. The difficulty of accounting for the disposal of such large quantities of material and the low compressibility of various rock materials later led Sorby (1908) and other workers (see Ramsay & Wood 1973, Wood 1974) to suggest lower volume losses of up to 20 percent. Although the amount of volume change during deformation is one of the most interesting unknown parameters and is of great relevance in explaining some of the structures found in deformed rocks (Ramsay 1967, p. 186), it is only rarely that the exact original dimensions of objects such as fossils and other strain markers are known and most studies of finite or total strains have not been able to compute the volume change.

Hills & Thomas (1944) pointed out that the spacing of thecae is a specific characteristic for each graptolite species and by measuring the number of thecae per cm in deformed graptolites whose original dimensions are known, they were able to compute the percentage shortening and lengthening on the bedding planes containing the graptolites. Their studies did not find any evidence that the formation of cleavage has involved any volume reduction of the rock mass, since the shortening normal to the cleavage is accompanied by an equivalent elongation parallel to the cleavage.

More recently, studies on the extent of volume changes during tectonic deformation, determined from changes in thecal spacing in deformed graptolites and other strain indicators, have suggested that very large volume reduction of the order initially suggested by Sorby (1853) accompanied the formation of cleavage (Wright & Platt 1982, Beutner & Charles 1985, Jenkins 1987, Wright & Henderson 1992). Wright & Platt (1982) favour pressure dissolution as the mechanism for the removal of the large amounts of material accompanying the suggested 50 percent volume loss in the Martinsburg shale. Other studies on volume changes in cleaved rocks based on density changes (Wood 1974) and chemical microstructural analysis (e.g. Cox & Etheridge 1989, Waldron & Sandiford 1989, Winstch *et al.* 1991, Erslev & Ward 1994) have generally given lower values ranging from 0 to 20 percent.

The Lower Palaeozoic rocks of Southeast Australia are richly endowed with graptolites, many of which have suffered tectonic deformation. Good specimens of deformed fossils from various localities in Victoria have been systematically collected over the past 50 years or more, studied and stored in the Museum of Victoria and in other collections. These graptolites provide an ideal collection for a study on the techniques of strain ellipse determination and volume changes accompanying the deformation. For this study, deformed *Oncograptus upsilon* from Gisborn (Fig. 1) have been analysed. The black graptolitic shales also contain small framboidal pyrites with straight to slightly curved quartz fibres in their pressure shadows and these strain markers can be utilized to determine the principal extension along the cleavage plane.

One of the major constraints in determining volume changes from shape changes in graptolites is that most deformed graptolites occur as two-dimensinal impressions on the bedding surfaces. For computation of the volume, the dimensions of the three principal axes of the strain ellipsoid are required and certain assumptions have been made in previous studies (e.g. Wright & Platt 1982, Jenkins 1987) to derive the three principal axes from the strain ellipse on the bedding surface. The validity or otherwise of such assumptions is crucial to the volume computation as large errors may be introduced by utilizing erroneous values for the principal axes. In this study, the additional data on the principal extension along the cleavage plane, obtained from an analysis of pressure shadows in the same specimen from which the strain ellipse on the bedding plane has been computed, allows for the three principal axes to be computed solely from the strain data.

GEOLOGICAL BACKGROUND

The Gisborne locality where the studied graptolite specimen was collected, is part of a 110 km wide zone of chevron-folded, cleaved and faulted Ordovician quartz-rich turbidites (Fig. 1). Interbedded quartz-wacke turbidites, siltstone and mudstone are tightly folded and show horizontal shortening in the order of 60–70% (Gray & Willman 1991a,b, Yang & Gray 1994). The graptolite sample studied (Fig. 2) comes from within cleaved, homoclinally dipping black shale containing minor thin sandstone and siltstone layers. Both cleavage (S_1) and bedding (S_0) dip steeply to the west with $S_0 \wedge S_1 < 10°$. Vergence relationships indicate that the sample came from the western limb of a tight to almost isoclinal anticline.

Cleavage in the Gisborne slate is dominated by a strong dimensional preferred orientation of both quartz and layer silicates, beard structures and pressure shadows on pyrite grains. Slate containing the graptolites shows a strong domainal slaty cleavage fabric with alternating layer silicate and quartz-rich domains spaced at approximately 50–80 μm (Fig. 2b). Within this domainal fabric there is pronounced alignment of thin, elongate white micas, where both long axes and (001) traces of the micas are subparallel to the cleavage domain boundaries (Fig. 2c). Elongate quartz grains within quartz-rich domains show strong development of beard structures defined by intergrowths of quartz and white mica. Rare coarse-grained mica augen, largely within quartz-rich domains, have (001) traces misoriented with respect to the cleavage traces (Fig. 2c). Bedding within the slate is preserved as thin (generally <50 μm width), discontinuous spindle-shaped (approximately 200 μm length) segments at a low angle (<10°) to, and cut by the intense slaty cleavage fabric.

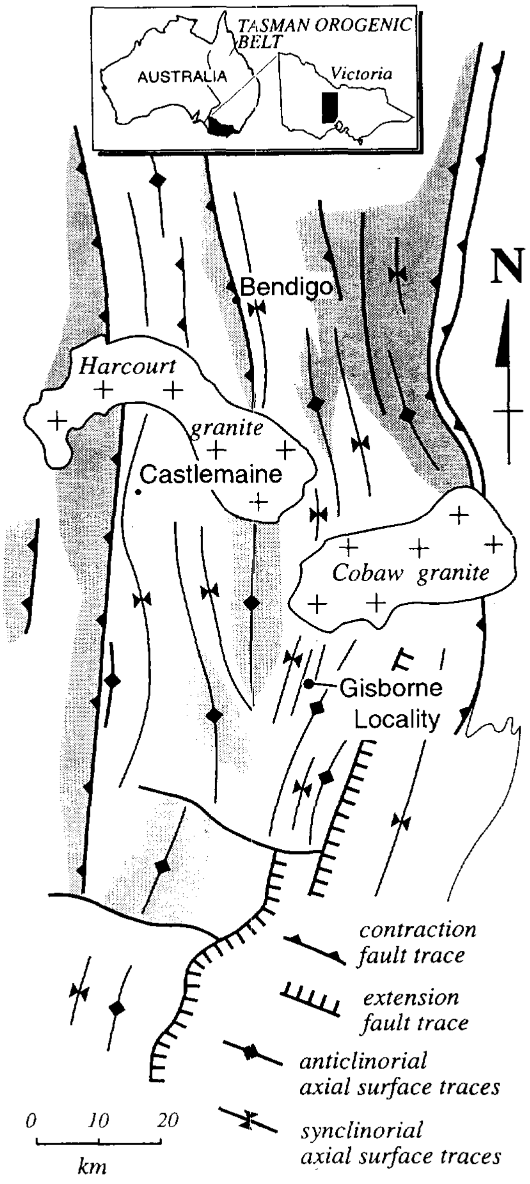


Fig. 1. Regional map of part of the Bendigo–Ballarat structural zone showing the major geological elements including Late Devonian post-tectonic granitoids (crosses) and the outcrop pattern of Lancefieldian (lowermost Lower Ordovician) quartz-rich turbidites (shaded). Outcrop of traces of major faults and anticlinorial and synclinorial axial surface traces are also shown. (Modified from Gray & Willman 1991b, fig. 1.) Location of the Gisborne slate locality is shown.

Small (20–50 μm) approximately spherical pyrite grains within both layer silicate and quartz-rich domains (Fig. 2d) contain pressure shadows of straight, thin, interlocking fibrous quartz and white mica. Shadows have tapered form but the fibres are all subparallel to the strong cleavage fabric in the slate. Absence of pressure shadow growth and fibrous overgrowths in sections cut parallel to the bedding cleavage intersection [i.e. the intermediate principal strain direction (Y) which lies

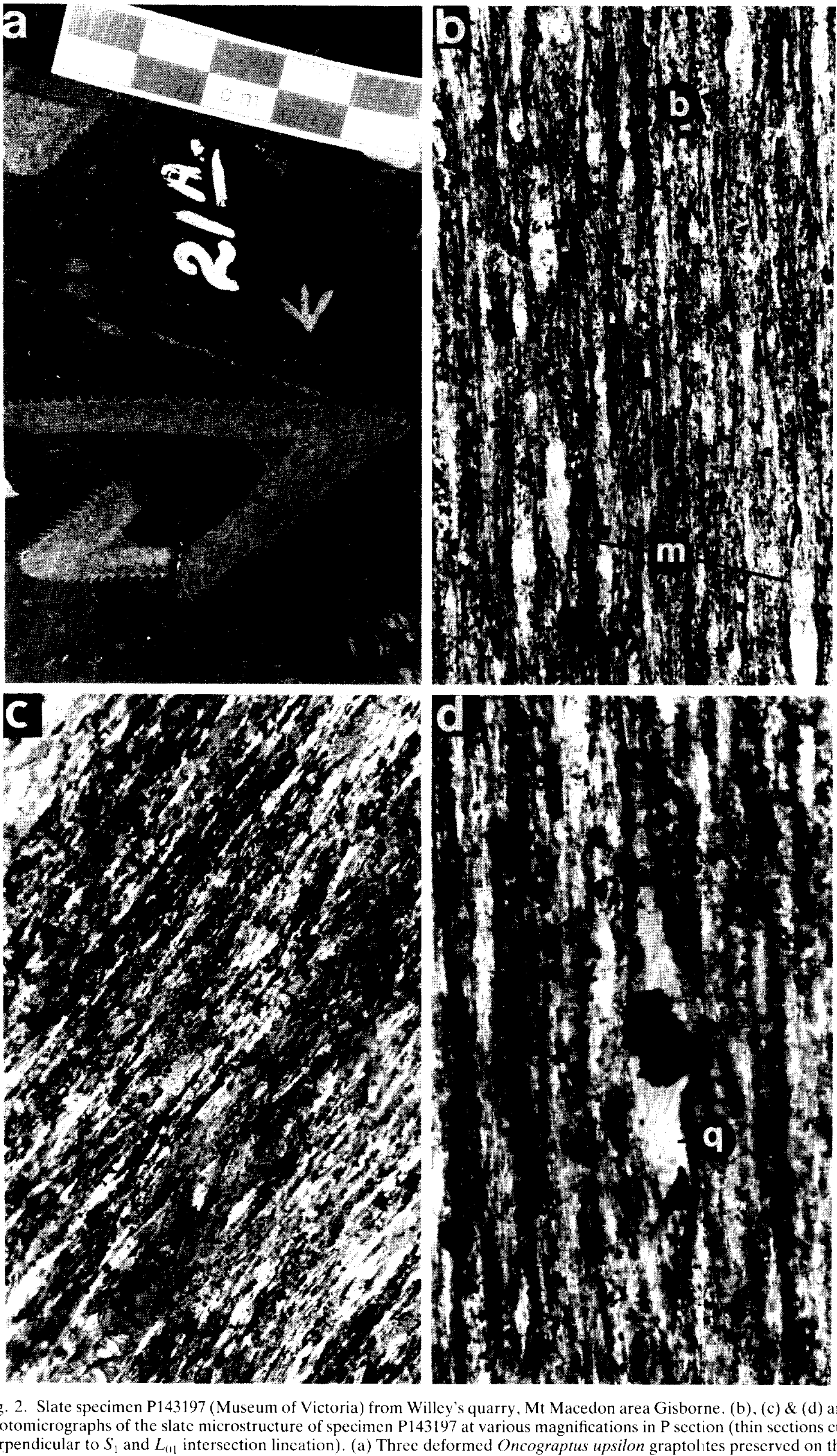


Fig. 2. Slate specimen P143197 (Museum of Victoria) from Willey's quarry, Mt Macedon area Gisborne. (b), (c) & (d) are photomicrographs of the slate microstructure of specimen P143197 at various magnifications in P section (thin sections cut perpendicular to S_1 and L_{01} intersection lineation). (a) Three deformed *Oncograptus upsilon* graptolites preserved on the bedding plane. (b) Strongly domainal slaty cleavage fabric showing beard structures on digital quartz grains ('b'), mica augen ('m') with (001) traces oblique to S_1 and a strong layer silicate preferred orientation in both quartz-rich and layer silicate domains. Base of photo is 300 μm. (c) Strong layer silicate preferred orientation. Note the corroded, splinter-like forms of the quartz and larger layer silicate grains. Base of photo is 170 μm. (d) Typical pressure shadow of quartz/layer silicate intergrowth on framboidal pyrite grain. Part of the pressure shadow phyllosilicates are deformed adjacent to a matrix detrital quartz grain ('q'). Note once again the strong layer silicate preferred orientation in the matrix.

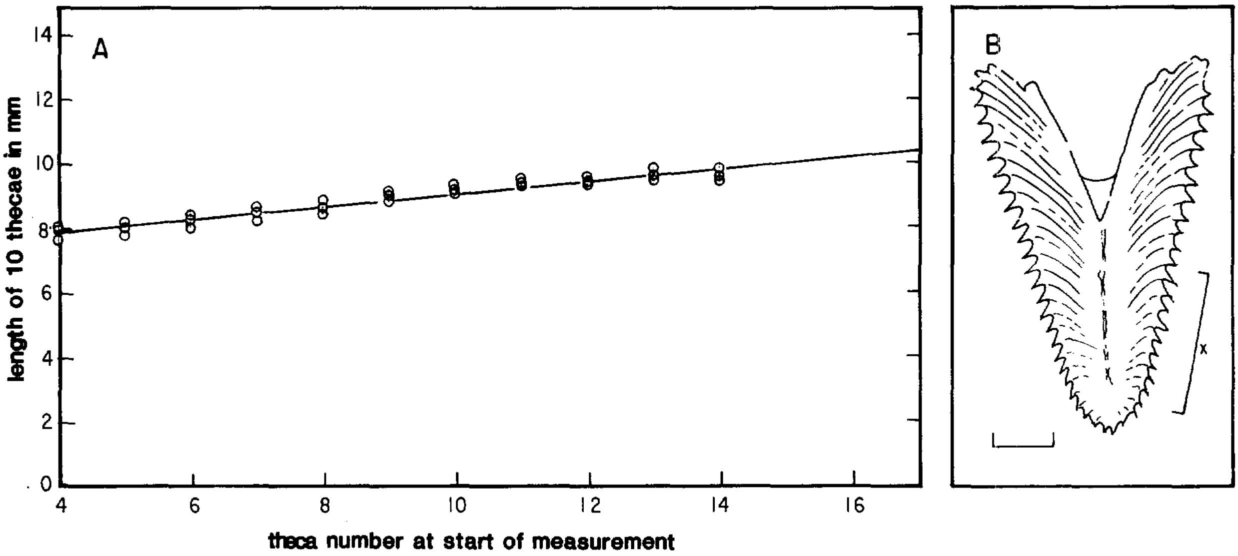


Fig. 3. (a) Lengths between 10 successive thecae, starting from the proximal end, in undeformed specimen of *Oncograptus upsilon*. Measurements off photographs from Palmer & Rickards (1991, fig. 111) and Cooper (1979, fig. 61a). (b) X shows the length between 10 successive thecae, starting from theca number 4. Scale bar is 1/3 cm. Line drawing from Cooper (1979, fig. 61a).

within the cleavage] suggests either a plane strain or constrictional type deformation (*cf.* Gray & Willman 1991b).

DETERMINATION OF STRAIN ELLIPSE FROM DEFORMED GRAPTOLITES

Graptolites are commonly preserved as two-dimensional impressions on bedding surfaces and it is often assumed that graptolites would deform passively with the surrounding rocks. Only rarely are three-dimensional specimens found and most studies on graptolites can only determine the finite strain ellipse on the bedding surface. Any shape change resulting from sedimentary compaction is believed to be negligible as thecal spacing is largely independent of diagenetic flattening (Howe 1983), a view accepted by many palaeontologists who used thecal spacing to distinguish between taxa.

Traditionally, measurements of thecal spacing have been done by counting the number of thecae per inch or centimetre. Howe (1983) pointed out that this method has serious disadvantages. In many species, thecal spacing varies considerably in the proximal end but is more constant distally. The variation and the different dimensions of the thecal spacing in each graptolite species necessitate that the detailed geometry of the undeformed graptolite species be known before the change in length of the deformed graptolite can be computed from measurements of thecal spacing.

For strain ellipse determination, a more appropriate method would be to measure the length between a specific number of thecae in a deformed graptolite specimen and compare this length with the length of the corresponding portion of the underformed fossil. This method can be easily applied to graptolite specimens with well-preserved proximal parts. Thecae can be numbered starting from the first theca and the distance from two known thecae, e.g. the fifth theca to the 15 theca can be measured on both the undeformed and deformed specimens.

Thecal spacing in Oncograptus upsilon

The geometry of undeformed *Oncograptus upsilon* is documented in Bullman (1936), Palmer & Rickards (1991) and Cooper (1979). Bullman illustrates two well preserved specimens of *Oncograptus upsilon* in his text-fig. 1, one from the El Paso Limestone in Texas and another from the turbiditic Darrwil series near Woodend, Victoria. The dimensions of both these specimens are almost the same. Since it may be assumed that *Oncograptus upsilon* preserved in limestone would not suffer from shape changes due to sedimentary compaction, the similarity in the sizes of the *Oncograptus upsilon* indicates that the fossil had probably undergone sedimentary compaction in its chitinous form and maintains its original shape prior to tectonic deformation. Any change in shape of *Oncograptus upsilon* can hence be taken to be due solely to tectonic processes.

The dimensions between a specific number of thecae were determined from the undeformed *Oncograptus upsilon* illustrated in Palmer & Rickards (1991, fig. 111) and Cooper (1979, fig. 61a). The measurements were carried out using a ×7 eyepiece with an enclosed mm scale. The proximal end of *Oncograptus* is curved and it is only feasible to start the linear measurement from the fourth theca onwards. As the dimensions between successive thecae are less than 1 mm, the length between ten successive thecae was chosen. For each starting theca number, four values of the dimensions between 10 successive thecae (see Fig. 3b) have been determined from the two undeformed specimens, each specimen having two stipes (see Table 1). The points on the graph of the lengths between 10 successive thecae vs the theca number at the start of the measurement (Fig. 3a) fall

Table 1. Lengths of 10 thecae (in mm), starting the measurements from the theca number shown in column A. B, C, D and E are from the left and right stipes of specimens shown in Cooper (1979, fig. 61a, columns B & C) and Palmer & Rickards (1991, fig. 111, columns D & E)

A	B	C	D	E
4	8.0	8.0	7.8	8.1
5	8.0	8.0	7.8	8.2
6	8.3	8.3	8.0	8.4
7	8.3	8.5	8.3	8.6
8	8.6	8.8	8.5	8.9
9	9.0	9.1	9.0	8.9
10	9.3	9.3	9.0	9.1
11	9.3	9.5	9.4	9.5
12	9.3	9.6	9.5	9.5
13	9.6	9.8	9.6	9.5
14	9.7	9.8	9.6	9.5

very close to a straight line graph, indicating that there is a systematic increase in the dimensions between 10 successive thecae away from the proximal end of the fossil. This graph can be used to provide the undeformed dimensions for comparison with the equivalent parts of the deformed *Oncograptus upsilon*. If the preservation of the deformed fossil is poor and less than 10 successive thecae are preserved, the corresponding dimensions of the equivalent parts of the undeformed fossil can be obtained from this graph by computation.

Strain measurements from deformed Oncograptus upsilon

Figure 2 shows a specimen of slate from Willey's Quarry, Mt Macedon, Gisborne. Three deformed *Oncograptus upsilon* are preserved in the bedding plane (Fig. 2a). The angle between the cleavage and the bedding (θ') is 7°. The intersection of bedding and cleavage is easily seen on the bedding plane. Measurements were taken of the lengths between 10 successive thecae on each of the six stipes. The change in length along each stipe direction was computed using the known undeformed length between the corresponding 10 successive thecae as shown in Fig. 3(a). The finite strain ellipse was then determined from the 'best fit' ellipse (Fig. 4). The finite strain ellipse on the bedding plane for this specimen indicates that an extension of 79 percent has taken place perpendicular to the intersection of the cleavage with the bedding. The change in length parallel to the cleavage on the bedding surface (e_2) is 12 percent.

PRESSURE SHADOW STRAIN MARKERS

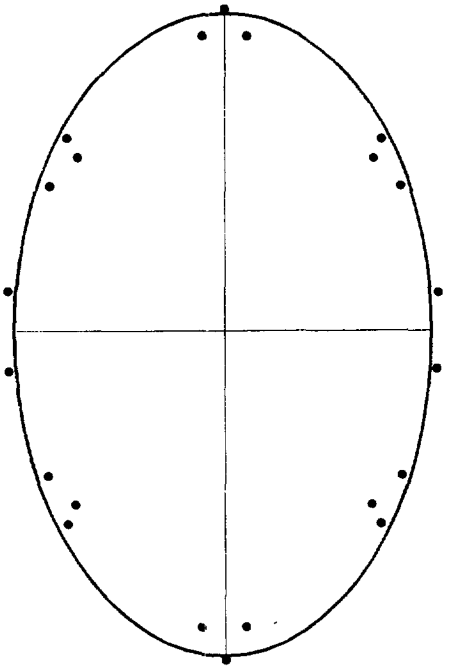


Fig. 4. 'Best fit' ellipse, drawn visually, for stipe-segment length data from the three *Oncogaptus upsilon* graptolites shown in Fig. 2(a). The strain ellipse has maximum and minimum principal extensions of 1.79 and 1.12, respectively.

Given that the pressure shadow fibres are syntectonic and track the local incremental extensional direction (*cf.* Durney & Ramsay 1973), measurements of fibre length relative to the host pyrite radius can be used to determine the maximum principal extension ($1 + e_1$). For pressure shadows with straight fibres, ($1 + e_1$) is given by:

$$1 + e_1 = 1 + (L_1 - L_0)/L_0$$

where L_1 is the fibre length + pyrite radius (measured in the direction of the fibres) and L_0 is the pyrite radius (measured in the direction of the fibres). Fibre lengths in pressure shadows are proportional to the size of the pyrite and therefore define linear arrays on graphs of L_0 (pyrite radius) vs L_1 (pyrite radius + fringe length) (Fig. 5).

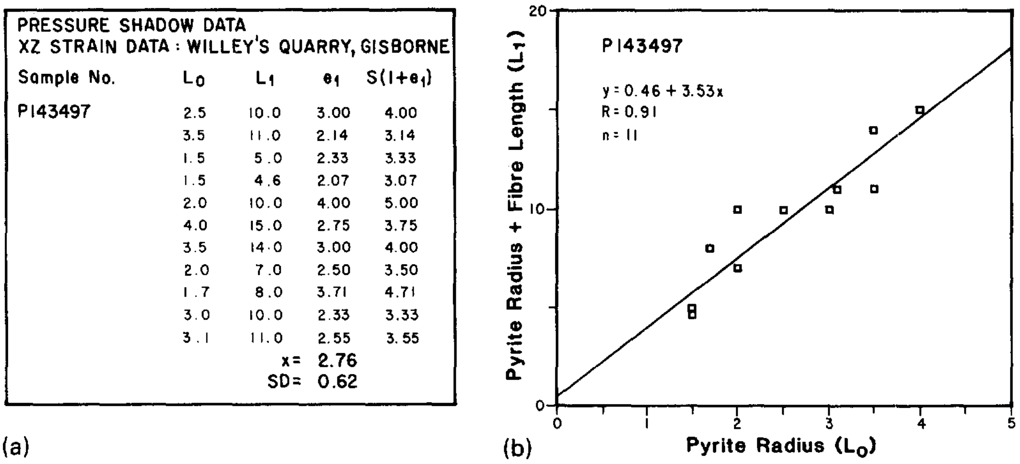
Pressure shadow data measured in P sections (thin sections cut perpendicular to S_1 and the L_{01} intersection lineation) from the graptolite sample shown in Fig. 2(a) (Sample P143497) indicate a subvertical extension (e_1) of 2.76, based on a mean of 11 measurements with a standard deviation of 0.62 (see Fig. 5). Data from another sample from the same locality (Sample P143498) gave an elongation of 2.73, based on a mean of 10 measurements with a standard deviation of 0.96.

ESTIMATION OF VOLUME CHANGE

The strain data from the strain ellipse on the bedding plane obtained from the change in length of the spacing between the graptolite thecae ($1 + e = 1.79$, $1 + e_2 = 1.12$) and the pyrite pressure shadows ($1 + e_1 = 3.76$, $\theta' = 7°$) permit the computation of the principal shortening ($1 + e_3$). Using equation (3-31) in Ramsay (1967),

$$\lambda' = \lambda_1' \cos^2 \theta' + \lambda_3' \sin^2 \theta'$$

where $\lambda' = 1/(1 + e)^2$, $\lambda_1' = 1/(1 + e_1)^2$ and $\lambda_3' = 1/(1 + e_3)^2$, a value of 0.25 is obtained for ($1 + e_3$). The volume



PRESSURE SHADOW DATA
XZ STRAIN DATA : WILLEY'S QUARRY, GISBORNE

Sample No.	L_0	L_1	e_1	$S(1+e_1)$
P143497	2.5	10.0	3.00	4.00
	3.5	11.0	2.14	3.14
	1.5	5.0	2.33	3.33
	1.5	4.6	2.07	3.07
	2.0	10.0	4.00	5.00
	4.0	15.0	2.75	3.75
	3.5	14.0	3.00	4.00
	2.0	7.0	2.50	3.50
	1.7	8.0	3.71	4.71
	3.0	10.0	2.33	3.33
	3.1	11.0	2.55	3.55
		x=	2.76	
		SD=	0.62	

Fig. 5. Pressure shadow data from graphtolite specimen P143497, Willey's Quarry, Mt Macedon near Gisborne. (a) Tabulated data giving pyrite radius (L_0), fibre length + pyrite radius (L_1), the calculated elongation (e_1) and extension in the cleavage ($1 + e_1$) for eleven pressure shadows. x = mean elongation; SD = standard deviation. (b) Plot of pyrite radius (L_0) vs fibre length + pyrite radius (L_1) for the eleven pressure shadows showing 'best fit' regression line to data. Regression line equation ($y = 0.46 + 3.53x$), correlation coefficient (R) and sample size (n) are given. (Graph units are the same for both axes; 1 graph unit = 10 μm.)

change is given by $(1 + e_1)(1 + e_2)(1 + e_3) - 1$. Substituting the values obtained for the principal axes in this equation gives a volume change of 5 percent.

The computation of the volume change is subject to possible errors in the strain ellipse determination on the bedding surface, the computation of the maximum principal extension $(1 + e_1)$ from the pyrite pressure shadows and the angle between the cleavage and the bedding (θ'). The angle between the cleavage and the bedding (θ') was measured from the thin section cut perpendicular to S_1 and the L_{01} intersection, using a polarizing microscope. The error in this angular measurement is likely to be less than half a degree. A ±0.5° error in the measurement of the angle between the bedding and the cleavage would result in the volume change having a range from +11% (for $\theta' = 7.5°$) to −3% (for $\theta' = 6.5°$), using the values of the principal extensions determined from the graptolites and the pyrite pressure shadows. Combining the half a degree error in the θ' angle with a 5% error in the values of the principal extensions the maximum volume reduction would be 17%.

DISCUSSION

This study indicates that a very small volume change of the order of 5 percent has accompanied cleavage development in the shaly rocks at Gisborne, Victoria. This result is markedly different from the very large volume losses of 50 percent or more reported from deformed graptolite studies by Wright & Platt (1982), Jenkins (1987) and those inferred by Etheridge *et al.* (1984) for Victorian slates typified by the Gisborne slates of this paper.

Estimates of large volume loss have been linked to lack of extension parallel to cleavage in the Martinsburg Slates of central Pennsylvania. However, thin section examination of some of the slates from Wright & Platt's (1982) study has shown the presence of fibres in pressure shadows on framboidal pyrite indicating that subvertical extension did accompany fabric development in the Martinsburg Slates (see Gray & Wright 1984, Gray in preparation). Furthermore, the Wright and Platt data come from geographically widely separated samples as well as from different regional fold structures (cf. Cooper 1990) and therefore they assume homogeneous deformation on a regional scale which is most unlikely (e.g. Beutner & Charles 1985, Woodward *et al.* 1986).

The results presented in this paper are in general agreement with other volume loss/gain determinations from slates/psammites from the central Victorian slate belt. Studies in slates using thecal angle variations from variously oriented graptolites in bedding (cf. Ramsay & Huber 1983, pp. 136–140) combined with pressure shadow data show volume losses less than 13% (Gray & Willman 1991a, Table 2). Precision measurements of some 2000 quartz grain centre spacings from a sandstone from Clunes (sample 81) gave a mean tectonic whole-rock dilatation of 1.004 (0.4% volume gain) indicating close to constant volume deformation accompanying fabric development (Durney & Gray, in preparation).

Dissolution features (corroded, splinter-like quartz and mica grains; truncated detrital quartz grains rimmed by dark seams; layer silicate domains as former seam-like residues) indicate that pressure solution has operated during cleavage development in these rocks. The volume strain determinations however indicate approximately constant volume deformation with a mass redistribution rather than a mass loss from the local rock volume. The extensive development of beards and pressure shadows in the strongly domainal fabric of the Gisborne slate requires such a mass redistribution, particularly of quartz, associated with cleavage-parallel extension (e.g. Gray 1978, Gray & Wright 1984, Beutner & Charles 1985, Yang & Gray 1984, fig. 4). Any tectonic crystallization and recrystallization of mica (e.g. Kanagawa 1991) reflected in beard structures and pressure shadows must have also played a significant role in this deformation process.

Arguments for large volume losses requiring large throughput of fluids (e.g. high fluid/rock ratios) are also not supported by oxygen stable isotope studies of quartz veins within the central Victorian turbidite succession (Gray *et al.* 1991). Isotopic signatures of coexisting vein-host rock pairs (Gray *et al.* 1991, figs. 12 & 14) indicate rock buffering of fluids under low fluid/rock ratios where fluids reflect the host rock isotopic composition averaged over the thickness of a stratigraphic stage (i.e. tens to hundreds of metres).

We suggest that cleavage development by pressure solution in low metamorphic grade rocks generally involves mass redistribution with only small volume losses (<10%). This is supported by the volume of veins in cleaved sequences (generally <10%) and the local derivation of vein fill minerals (e.g. Beach 1974). In some instances, mass loss may be higher (e.g. Beutner & Charles 1985) but this is the exception rather than the rule. Such regions of higher mass loss may equate with zones of higher and/or more focused fluid flow.

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