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MECHANISMS FOR STRAIN WITHIN THE UPPER DEVONIAN CLASTIC SEQUENCE OF THE APPALACHIAN PLATEAU, WESTERN NEW YORK*

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ABSTRACT. The axial ratios of deformed crinoid ossicles within the clastic rocks of western New York indicate more than 15 percent layer-parallel shortening normal to fold axes on the Appalachian plateau (Engelder and Engelder, 1977). Two mechanisms for crinoid deformation are mechanical twinning of its calcite on one or more sets of e-planes $\{01\bar{1}2\}$ and dissolution on sides of the ossicles parallel to fold axes. Dynamic analysis of the calcite shows layer-parallel compression normal to the fold axes. Using Groshong's (1972) calcite strain gauge technique, compressive strain accompanying calcite twinning is shown to account for 1 to 5 percent layer-parallel shortening or less than half the compression indicated by the axial ratio of the ossicles. The remainder of the compression is due to pressure solution. This study concludes that cleavage-forming pressure solution is a more important mechanism than intragranular deformation for layer-parallel shortening on the Appalachian plateau.

INTRODUCTION

Using deformed crinoid ossicles as passive strain markers, it can be shown that the Upper Devonian rocks of western New York have been subjected to as much as 15 percent north-northwest layer-parallel shortening (Engelder and Engelder, 1977). However, deformed brachiopods and worm tubes are more highly strained than the crinoid ossicles and indicate a ductility contrast between the less deformable ossicles and the matrix. Because the ossicles were not passive strain markers deforming homogeneously with the matrix, one wonders how closely the shape change of the ossicles reflects the average strain within the Appalachian plateau. To answer this question, an evaluation of the mechanisms responsible for shape change of the ossicles is necessary. The purpose of this paper is to document these deformation mechanisms and the strain associated with them. This paper also documents the first field test of the Groshong (1972) calcite strain gauge technique against an *in situ* strain marker.

Previous work on deformed crinoid ossicles include several studies on the Devonian sediments of the Variscan Rhine geosyncline (Hellmers, 1955; Breddin, 1956a,b; Kurtman, 1960; and Nissen, 1964). Other studies in the Appalachians include the work of Faill (1977). Nissen (1964) used a dynamic analysis of the deformed crinoids to deduce a stress system causing an axial extension parallel to the regional folding axes. He also showed that mechanical twinning accounts for only 50 percent of the measured mean elongation of the crinoid ossicles.

Through this study much can be learned about the partitioning of strain among deformation mechanisms in a foreland fold belt. Recent studies have shown that solution cleavage, not intragranular deformation, is responsible for a large percentage of the bulk strain in foreland fold belts (Nickelsen, 1972, 1974; Groshong, 1975; Alvarez, Engelder, and

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Lowrie, 1976; Alvarez, Engelder, and Geiser, 1978). For example, Nickelsen (1974) used deformed mudcrack polygons in Silurian formations of the Valley and Ridge province to infer that distortion was due to both solution loss perpendicular to cleavage planes and volume constant flow. In the Upper Devonian rocks of the Appalachian plateau of western New York it is possible to evaluate independently the contributions to strain of: (1) intragranular deformation (volume constant flow) and (2) solution loss accompanying the formation of incipient solution cleavage.

CRINOID OSSICLES VIEWED IN THIN SECTION

A crinoid ossicle consists of a single crystal of calcite with its optic axis (c-axis) parallel to the cylindrical axis of the ossicle. Generally the ossicles from western New York lie with their cylindrical axis normal to bedding. Examination of the crinoid ossicles in thin section reveals that the calcite crystals contain many mechanically induced twins. In cross-sectional cuts of the ossicles (cuts parallel to bedding) mechanical twins are commonly seen but dip at a shallow angle (26°) with respect to the plane of the thin section (pl. 1-A). These twins are one mechanism responsible for the distortion of the initially cylindrical ossicles into elliptical shapes.

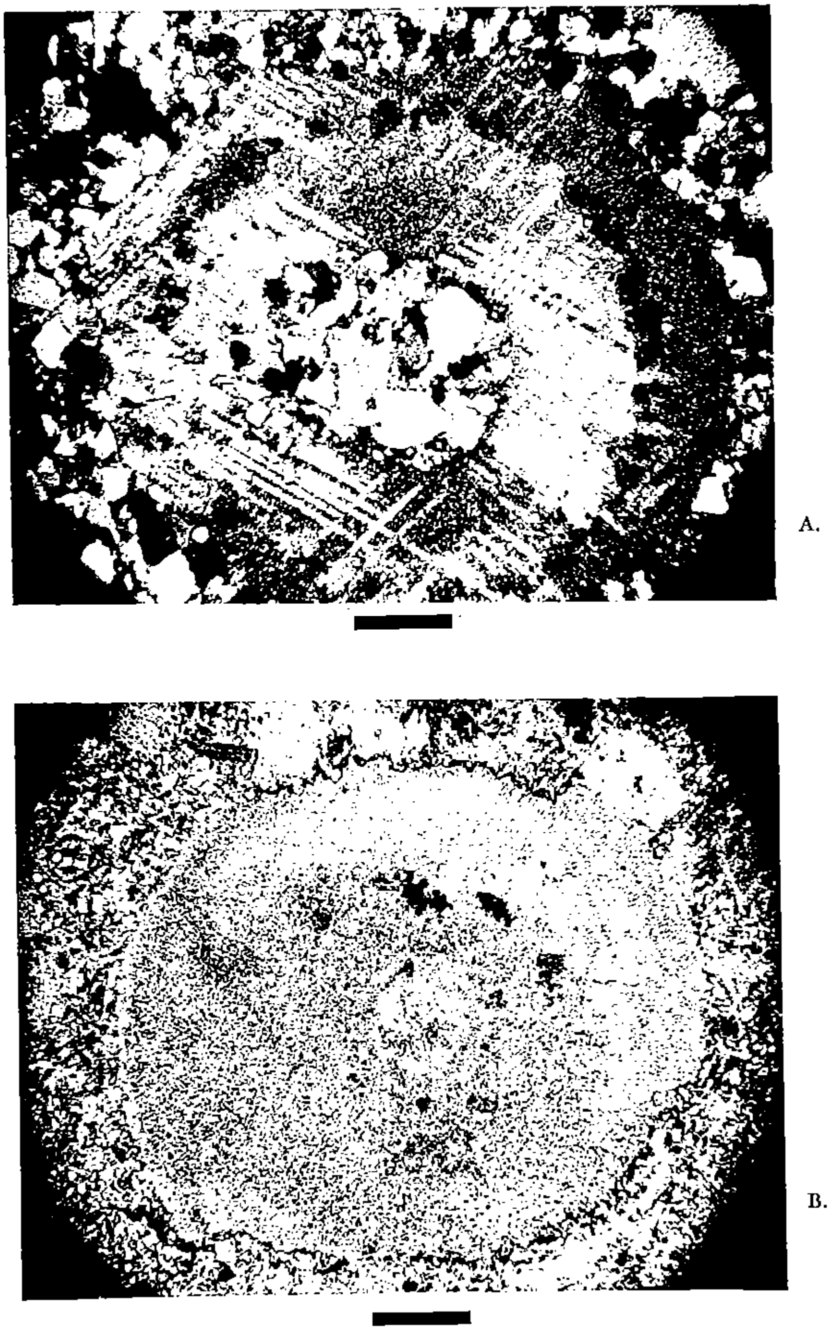
The largest percentage (45 percent) of ossicles from western New York have one twin set (36 of 80). Twenty-four percent have no twins, 30 percent have two twin sets, and 1 percent have three twin sets. The ossicles sampled in western New York are less highly strained by calcite twinning than the ossicles from the Devonian sediments of Germany, where 77 percent of the ossicles have two twin sets and 23 percent have three twin sets (Nissen, 1964).

In thin section the ossicles rarely appear as ellipses, but rather dissolution has truncated the sides normal to the direction of flattening (pl. 1-B). The truncated sides are irregular whereas the sides normal to the long axis of the ossicles are smooth. The irregular surface has the classical stylolitic outline and is caused by dissolution around quartz grains penetrating the calcite ossicle. An insoluble residue similar to that found along stylolites in limestone fills the space between the calcite ossicles and quartz grains.

Although dissolution is found along the edge of ossicles, planes of dissolution can rarely be followed into the matrix for distances of more than a few millimeters. Boundaries between calcite (ossicles) and the siltstone matrix seem particularly susceptible to dissolution. At some sample localities, such as SMB and ADI, insoluble residues extend several centimeters before disappearing in the matrix (pl. 2).

Overgrowths of calcite are sometimes responsible for the shape change of the ossicles (pl. 1-A). When viewed in thin section, these overgrowths have been truncated by dissolution. When ossicles with overgrowths are twinned, the twins run continuously from the ossicle into the overgrowth. It should be emphasized that overgrowths are not common and thus not a major mechanism for the shape change of the ossicles.

PLATE 1

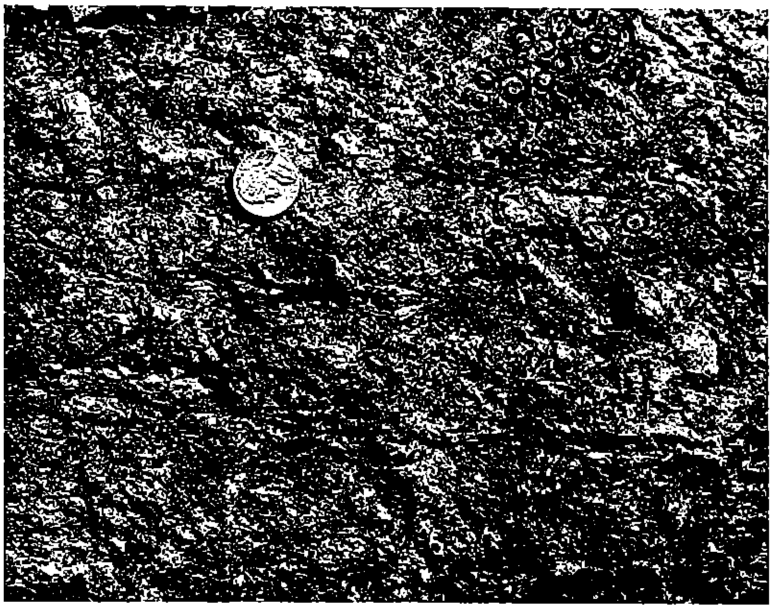


Photomicrographs of crinoid ossicles with 0.5 mm scale bars.

A. Ossicle from location AND with two twin sets dipping about 26° with respect to the plane of the thin section. Note the calcite overgrowths with mechanical twins running from the initial ossicle into the overgrowth. Crossed nicols;

B. Ossicle from location ADI with edges truncated by dissolution. Dissolution plane marked by dark insoluble residue. Plane light.

PLATE 2



Photograph showing a sample from locality SMB with the long axes of deformed ossicles parallel to solution cleavage planes (approximately east-west). The scale is a 2.1 cm diameter coin. Sample is oriented so that north is toward the top of the photograph.

From these observations it is clear that two mechanisms are responsible for the present shape of the crinoid ossicles: (1) plastic deformation as indicated by mechanical twinning of the calcite comprising the ossicle (volume constant flow), and (2) preferential dissolution of the edges of the calcite crystal normal to the direction of layer-parallel shortening.

STRAIN WITHIN THE APPALACHIAN PLATEAU

Strain associated with the mechanical twinning of calcite.—If the crinoid ossicles were passive strain markers, an intragranular deformation mechanism should be responsible for their shape change. The dominant low-temperature intragranular deformation mechanism of calcite is mechanical twinning parallel to the e-planes of calcite (Turner, 1953). Strain of a calcite crystal by mechanical twinning is equivalent to simple shear in the plane containing both the c-axis and the normal to the e-plane (fig. 1). Shear strain is toward +g [e_1:r_2], and volume remains constant so that two principal strain axes are in the plane containing the c-axis and the pole to the e-twin plane, whereas strain along the third principal axis is zero.

The amount of twinning necessary for deformation of the crinoid ossicle to a certain axial ratio is predictable. A calcite crystal that has been half twinned on a single set of e-planes exhibits a tensor shear strain of 17 percent in the plane containing both the c-axis and the normal to the

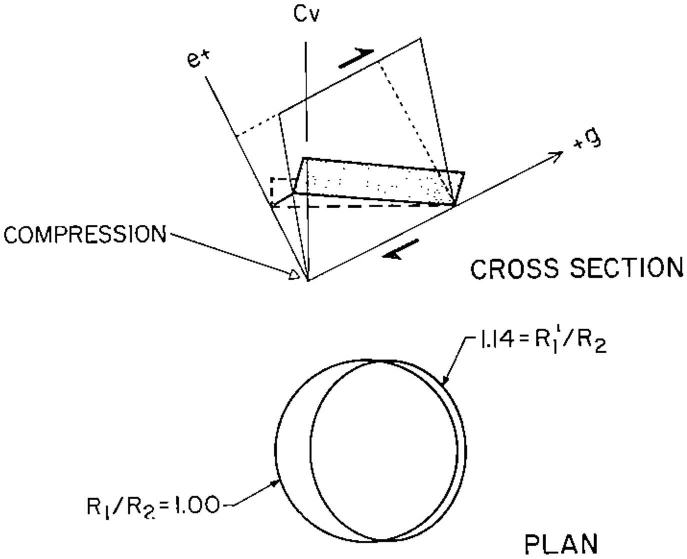


Fig. 1. Cross section and plan view of a crinoid ossicle before and after 50 percent of the calcite crystal has been twinned. Compression shows the most favorably oriented stress axis to produce twinning. C_v is the optic axis of the host grain and parallel to the cylindrical axis of the ossicle, e+ is the pole to $\{01\bar{1}2\}$, +g is the intersection of e and r $\{10\bar{1}1\}$. C_v, e+, and g+ are shown for the untwinned grain. All axes are coplanar. The angle between e and C_v is 26°. Positive shear of the original ossicle (dashed rectangle in cross section) is produced by twinning.

e-plane (Groshong, 1972). Circular markers in a material subject to 17 percent tensor shear strain will deform into ellipses with axial ratios of 1.41. For twinning of calcite this axial ratio is achieved only if the calcite crystal is viewed normal to the plane of the shear couple (the plane containing both the c-axis and normal to the e-plane). When viewed from any other direction the half-twinned calcite crystal will exhibit less than 17 percent tensor shear strain.

When viewed parallel to its cylindrical axes (looking down the c-axes) compression of an ossicle by twinning on a single set of e-planes causes no change in length normal to the principal axis of maximum shortening (fig. 1). If 50 percent of the calcite ossicle is twinned on a single set of e-planes, an ossicle viewed down the original c-axes would be an ellipse with an axial ratio of 1.14. To deform by twinning to an axial ratio typical of crinoids from western New York (1.15-1.20), more than 50 percent of the calcite crystal will be twinned.

Using a technique devised by Groshong (1972), twinned calcite grains serve as strain gauges in a strain analysis of lightly deformed rocks. Groshong's (1972) technique for measuring strain relies on Conel's (ms) observation that tensor shear strain (Γ) for individual grains of calcite is a function of the thickness of the mechanically twinned portion of the grain (t_i) by the equation:

$$\Gamma = 1/2 \tan \Psi = 0.347\,(t_i/t)$$

where Ψ is the angular shear fixed at 38°17′ for calcite twin gliding, and t is the thickness of the grain normal to the twin set. The key assumption of this technique is that the amount of shear strain in a given twin set is a function of its orientation relative to the principal strain axes. Strain from five twin sets are used to solve a system of five simultaneous equations for the five unknown components of the strain tensor. Because simple shear of calcite by twinning is volume constant, the sixth component of the strain tensor $\epsilon_z = -(\epsilon_x + \epsilon_y)$. More than 10 twin sets are used to compute a best fit strain tensor using the method of least squares (Groshong, 1972).

Strain was measured in several samples of fossil hash using Groshong's calcite strain gauge technique and his computer program (fig. 2; table 1). The thick twin/thin twin ratio was fixed at 0.5. The principal compressive strain varies from 1.27 to 7.37 percent and plunges no more than 30°. In some samples (RAW, CAM, ADI) the percentage of negative expected values are large compared with those for naturally deformed rock reported by Groshong (1975) and Groshong and Spang (1977); however, the estimated errors are just a fraction of the magnitude of the strains, suggesting a reasonably good best fit to a strain tensor. The estimated error is $\mathrm{Err}_x + \mathrm{Err}_y/2$ where Err_x and Err_y come from the least-squares fit of the strain tensor as given in Groshong's computer program.

Strain associated with solution cleavage.—Figure 3 shows the percentage of calcite twinned plotted against the axial ratio of ossicles. The value for percentage of twinned calcite is a maximum representing calcite grains with the most favorable orientation for twinning; there are many grains oriented so that less shear strain (twinning) occurred. Figure 3 indicates

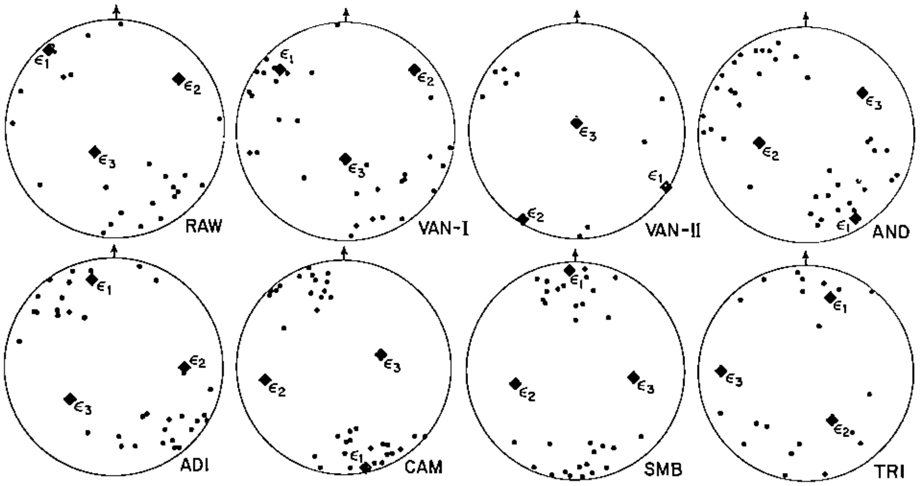


Fig. 2. Dynamic analysis of calcite from several samples from western New York. Compression axes (σ_1) are shown by solid dots in lower-hemisphere equal area projections. Principal strain axes calculated using Groshong's (1972) technique are plotted where ϵ_1 is the maximum compressive strain.

that less than 30 percent of the total compressive strain occurs by twinning. For example, the ossicles at AND have an axial ratio of 1.15 (Engelder and Engelder, 1977) recording a compressive strain of 15 percent. Yet only 5 percent compressives strain is recorded by calcite twins. The other 10 percent is actually a layer-parallel shortening accompanying truncation of edges of the ossicles by pressure solution. At VAN, RAW, SMB, and ADI the compressive strain from calcite twinning is low enough so that 12 to 16 percent compressive strain must be accounted for by pressure solution. At TRI, 4 percent shortening must be accounted for by pressure solution.

At ADI an independent check for the amount of layer-parallel shortening by pressure solution is possible. There solution cleavage planes pass completely through fossils leaving an offset that can be used to measure the amount of shortening across the fossil. As much as 0.5 mm of rock is removed from each solution cleavage plane in a rock containing two to three solution cleavage planes per centimeter. Here removal of material by solution represents as much as 15 percent layer-parallel shortening.

TABLE I

Three-dimensional strain tensors (Compressive strain is negative)

Section	No. of sets	% Negative expected values	Principal strain (%)	Estimated error ±	Bearing (°)	Plunge (°)
TRI	21	9%	1.04	0.35	273	23
			0.23		152	51
			-1.27		17	30
SMB	32	6%	1.13	0.26	95	46
			0.45		258	43
			-1.58		356	8
ADI	34	47%	4.03	1.41	234	49
			1.29		91	35
			-5.32		347	19
CAM	36	34%	5.22	2.62	70	60
			2.15		261	29
			-7.37		168	5
AND	42	20%	5.35	1.37	54	32
			0.52		262	54
			-5.88		152	13
VAN I	31	23%	0.88	0.62	180	68
			0.44		48	15
			-1.32		314	15
VAN II	9	11%	1.75	1.97	11	84
			-0.26		211	5
			-1.49		121	2
RAW	25	40%	1.53	0.76	221	64
			0.09		53	25
			-1.63		320	4

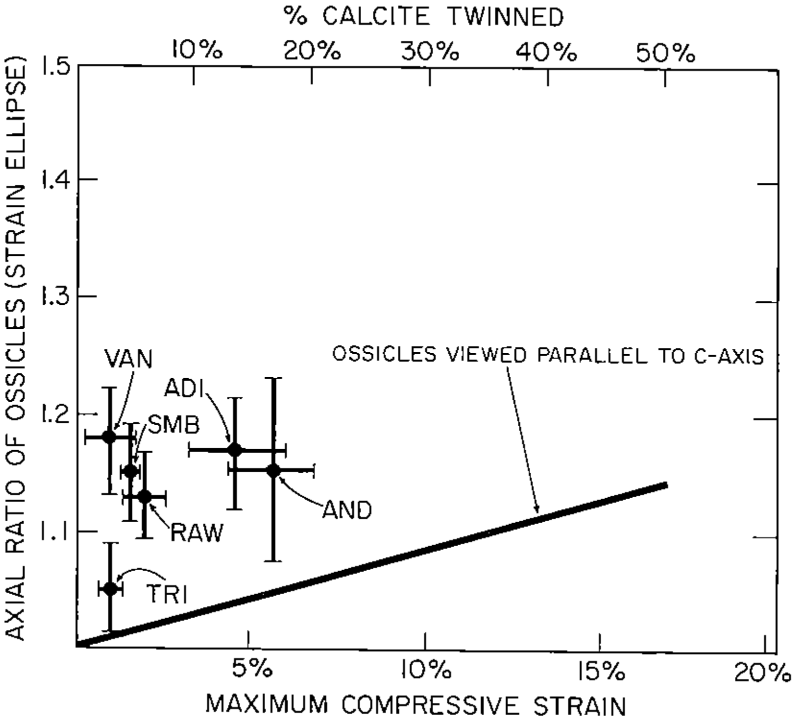


Fig. 3. Plot of axial ratio of ossicles calculated using Shimamoto and Ikeda's (1976) technique versus maximum compressive strain calculated using Groshong's (1972) calcite strain gauge technique. Percentage of twinned calcite for grains most suitably oriented for twinning is scaled to the equivalent maximum compressive strain. Also plotted is the line representing the percentage of twinned calcite necessary for distortion of the ossicles to a certain axial ratio as viewed down the c-axis.

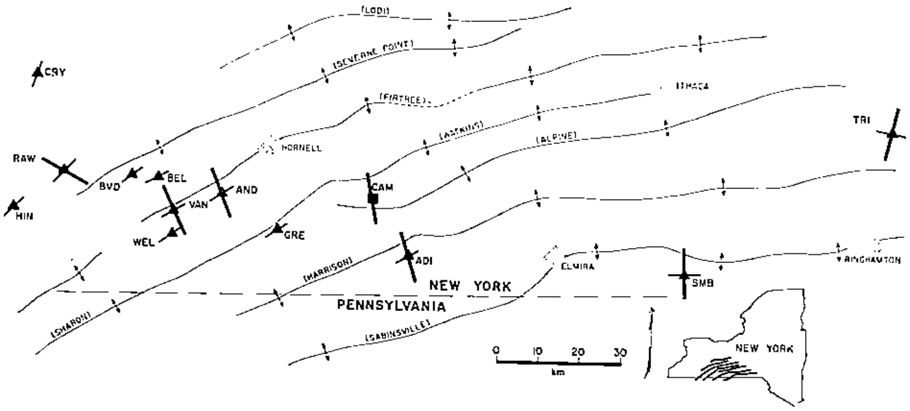


Fig. 4. Orientations of maximum compressive strain in the bedding plane calculated using Groshong's (1972) technique shown by heavier solid lines. Orientations of long axes of strain ellipse from deformed ossicles calculated using Shimamoto and Ikeda's (1976) technique shown by the light solid lines. Sample localities given by three letter symbols. Triangles are localities of deformed crinoids. Square is a sample of deformed limestone without crinoids.

Field test of the calcite strain gauge technique.—Presumably the deformed ossicles provide an *in situ* strain marker against which the calcite strain gauge technique may be checked. This field check will be completely successful only if calcite twinning is the only deformation mechanism, but I have already indicated that the shape change of the crinoids is also caused by dissolution. However, the relative magnitude of the strain and the orientation of the principal axes can be checked. Because calcite twinning is one of two deformation mechanisms responsible for the present "elliptical" cross section, the strain measured by the Groshong (1972) technique should be less than indicated by their elliptical cross section. Figure 3 shows that mechanical twinning of calcite accounts for less than half the strain necessary to deform initially circular ossicles into their present elliptical shape.

The orientation of maximum compression measured by Shimamoto and Ikeda's (1976) tensor superposition technique is within 20° of the horizontal maximum compression calculated by the calcite strain gauge technique (fig. 4; table 2). This further confirms the sensitivity of the calcite strain gauge technique in measuring a natural rock strain. The principal finite strains indicated by the twinning and by the final shape of the ossicles have nearly the same orientation (± 4.5°). Note the direct relation between the percentage of negative expected values (table 1) and the difference in orientation between compressive strain as measured by the calcite strain gauge technique and tensor superposition technique (table 2).

DISCUSSION

The strain analysis.—A combination of truncation by solution plus intragranular deformation accounts for the present shape of the ossicles in western New York. An inherent assumption of the strain analysis here and in Engelder and Engelder (1977) is that the shape produced by this

TABLE 2

Comparison of two techniques for obtaining orientation of maximum compressive strain

	Calcite strain gauge technique		Tensor superposition technique		
Sample	Orientation	% negative expected values	Orientation	Best results w.r.t. % neg. E.V.	difference in angle
TRI	N12°E	9%	N14°E	✓	2°
SMB	N02°W	6%	N03°W	✓	1°
ADI	N16°W	47%	N28°W		
AND	N23°W	20%	N32°W	✓	9°
VAN	N25°W	23%	N31°W	✓	6°
RAW	N63°W	40%	N44°W		

AVG DIFF = 4.5°

combination of intragranular deformation and dissolution actually reflects the regional finite strain within the Upper Devonian clastic sequence. Strain analyses assume that the shape of a strain marker results from the internal reorganization of the marker whereas in western New York a major deformation mechanism, pressure solution, is clearly external to the marker or at least restricted to the boundaries.

How can I show that the shape produced by pressure solution reflects finite strain? Some work has been done on this question. Hara (1966) and Mukhopadhyay (1973) used quartz grains whose present shape is attributed to dissolution to map finite strain fields. Mosher and Wood (1976) and Mosher (1976) measured finite strain in a conglomerate by using pebbles whose final shape is the product of pressure solution. Beutner (1978) calculated a cleavage related strain ellipsoid using detrital chlorite grains whose present shape is a product of pressure solution. In all four cases finite strain was measured using a marker whose shape change was due to a mechanism restricted to the marker's boundary.

The maximum compressive strain expected for folds is normal to the fold axis. In western New York truncation by pressure solution is normal to the fold axes through all changes in strike. This alone suggests that changes in shape by pressure solution reflect the orientations of the principal finite strain axes assuming that the finite strain and fold axes are the same orientation. Likewise, I have already shown that finite strain indicated by calcite twinning has nearly the same principal axes (± 4.5) as finite strain indicated by pressure solution associated shape changes. In many cases the shape change by pressure solution is much larger than by calcite twinning. Here the orientation of principal strain axes calculated by the tensor superposition technique would diverge from the strain indicated by calcite if the shape of the ossicles did not reflect the same finite strain as the twinned calcite.

The samples from which data were gathered for Groshong's (1972) strain gauge technique were calcite-cemented siltstones or limestones composed of calcite-cemented fossil hashes. There was not preferred orientation to the crystals of calcite cement. The effect of measuring strain in just the crinoid ossicles with c-axes normal to bedding is shown in figure 2. A sample using randomly oriented calcite (VAN-I) is compared with a sample using just crinoid ossicles (VAN-II). In both cases the maximum compressive strain (ϵ_1) is horizontal and oriented northwest-southeast, and the maximum extensional strain (ϵ_3) is nearly vertical. The crinoids are oriented properly to record a horizontal compression and a vertical extension.

Comparison with deformed crinoids from Lindlar, Germany.—Both this and Nissen's (1964) study of crinoids show that the elliptical shape of the ossicles cannot be entirely attributed to strain by mechanical twinning. In the Lindlar, Germany rocks twinning produced a mean axial ratio of about 1.10. In the rocks from western New York twinning produced no more than an axial ratio of about 1.05 at AND and less at other outcrops. To account for the difference between strain by twinning and the axial ratio, Nissen (1964) postulates that crinoids have an initial elliptical outline whose preferred orientation was controlled by fluvial processes. For the rocks from western New York, truncation by dissolution on surface normal to the compression axes accounts for the differences.

In western New York the long axes of crinoids are parallel to the fold axes (fig. 4), whereas the long axes in Germany depart significantly from the regional fold axes (Nissen, 1964). Paleocurrent directions in the Upper Devonian marine sandstones of western New York are generally toward the west (McIver, 1970). Fluvially oriented elliptical crinoids should initially have had long axes oriented at 30° from the axial traces of folds in the western part of the sample area (fig. 4). Intragranular strain is not large enough to distort fluvially controlled elliptical ossicles into an elliptical shape with long axes normal to the tectonic compression.

Strain reflecting a bedding-parallel compression within the Appalachian plateau differs from strain in the Devonian sediments of Germany (Nissen, 1964). This difference is seen in the dynamic analysis of crinoids from western New York where compression axes form point maxima parallel to bedding, whereas a composite of all compression axes from the dynamic analysis of Lindlar crinoids (Nissen, 1964, fig. 6) shows a great circle girdle in the a-c plane of the rock. Dynamic analysis of the ossicles from Lindlar, Germany is compatible with an axial extension ($\sigma_3 < \sigma_2 = \sigma_1$), where σ_3 is parallel to the axes of regional folding. Twinning on two sets of e-planes apparently produces a mean elongation parallel to axes of regional fold. Likewise, Groshong and Spang (1977) report this result for a small fold in Maryland.

The dynamic analysis of a low-grade metamorphic limestone from the Appalachian Piedmont shows compression axes in the a-c plane approximately normal to the cleavage (Nickelsen and Gross, 1959). Nickelsen and Gross (1959) suggest that major distortion is restricted to the a-c plane, a situation compatible with the deformation of the rocks from western New York. Likewise, Cloos (1947) shows in the South Mountain fold that strain parallel to b (the fold axis) is generally small when compared to the strain in the a-c plane.

Rheology.—In his study of strain and pressure solution of single layer folds from the Silurian McKenzie formation, Groshong (1975) observed that pressure solution was the mechanism responsible for more strain than twin gliding. Groshong presents a rheological model which presumes that intragranular strain has a yield stress, whereas, pressure solution does not. Alvarez, Engelder, and Lowrie's (1976) work on the formation of cleavage in a rock with unstrained fossils supports Groshong's idea. This same rheological model is also appropriate for the Upper Devonian rocks of western New York, where pressure solution accounts for a greater portion of the shape change of the crinoids than twin gliding. Pressure solution is seen at the boundaries of some ossicles that have not been twinned, whereas twin gliding never occurs within ossicles that show no evidence of pressure solution at their boundaries.

The timing of mechanical twinning relative to the onset of pressure solution may be inferred from plate 1-A. Overgrowths of calcite that are crystallographically continuous with the initial ossicle are assumed to be one sink for calcite dissolution. These overgrowths have mechanical twins continuous with those in the initial ossicles. The overgrowths were deposited prior to twinning, suggesting that dissolution was initiated prior to twinning.

Implications regarding décollement tectonics in western New York.—The Appalachian plateau may have been distorted by décollement tectonics in one of two different ways. The arcuate trend of the plateau folds in New York and Pennsylvania suggests that lateral spreading occurred to accommodate rocks as they moved northwest and stretched about an arc of increasing radius. However, lateral spreading is not necessarily required to accommodate décollement tectonics within an arcuate mountain belt (Engelder and Engelder, 1977; fig. 3). If décollement blocks shift relative to each other on strike-slip faults as proposed by Rodgers (1963) and Gwinn (1964), blocks can move outward about an arcuate trend without lateral spreading and without leaving gaps provided one or more triangular shaped "keystones" blocks move shorter distances. A major keystone block may be located in northwestern Pennsylvania (fig. 5).

Evidence for the existence of a large keystone block (about 2400 km^2) is meager because there is no proof that the lineaments shown in Rodgers (1970) and in figure 5 are strike-slip faults. Engelder and Engelder's (1977) initial idea concerning a possible keystone block was triggered by the observation that the larger anticlines on either side of the keystone require more lateral transport to generate the greater amplitudes. There is some evidence for keystone blocks with areas of 10 to 25 km^2 in the Philipsburg-Houtzdale area of northwestern Pennsylvania. Here quadrangle mapping by Edmunds (1968), Glover (1970), and Glass (1972) shows a complex system of strike-slip faults with unknown amounts of offsets. Possible keystone blocks are outlined by the left-lateral strike-slip faults bounding the east side and right-lateral strike-slip faults bounding the southwest side. Early mapping by Nickelsen and Williams (1955) and Nickelsen and Hough (1967, fig. 2) in the Houtzdale quadrangle also shows that left-lateral strike-slip faults strike between N 20 W and N 50 W, whereas right-lateral strike-slip faults strike between N 50 W and east-west. The major keystone block shown in figure 5 requires the same geometry of left-lateral and right-lateral strike-slip faults.

The nature of fossil distortion both in northwestern Pennsylvania (Nickelsen, 1966) and in western New York further supports the necessity for keystone tectonics on the Appalachian plateau. Deformed *Lingula* in the Pennsylvanian age rocks of the Philipsburg-Houtzdale area show less than 4.4 percent extension (lateral spreading) according to Nickelsen (1966), whereas the 7 to 10 percent shortening normal to fold axes must be accommodated by vertical extension. The implication here is that the small amounts of lateral spreading indicated by the deformed *Lingula* do not obviate keystone tectonics on the Appalachian plateau.

Examination of the strain recorded by calcite twins further suggests that Appalachian décollement blocks moved without lateral spreading and were bounded by zones of simple shear. Five of seven samples show axes of maximum extension plunging at more than 45° (fig. 3; table 1). These samples indicate that the décollement blocks were shortening and becoming thicker rather than spreading laterally (block B in fig. 5). One sample (TRI) in which extension is parallel to bedding is located in a hypothesized zone of simple shear (Engelder and Engelder, 1977). The extension and compression axes are compatibly oriented for right lateral simple shear in a north-south zone (block C in fig. 5).

A model for slip by décollement without lateral spreading is further supported by the presence of solution cleavage. This is a deformation mechanism for compressive strain without extension. Because a major fraction of the compressive strain on the Appalachian plateau is by solution cleavage, significant lateral spreading is not necessary to accommodate plateau deformation.

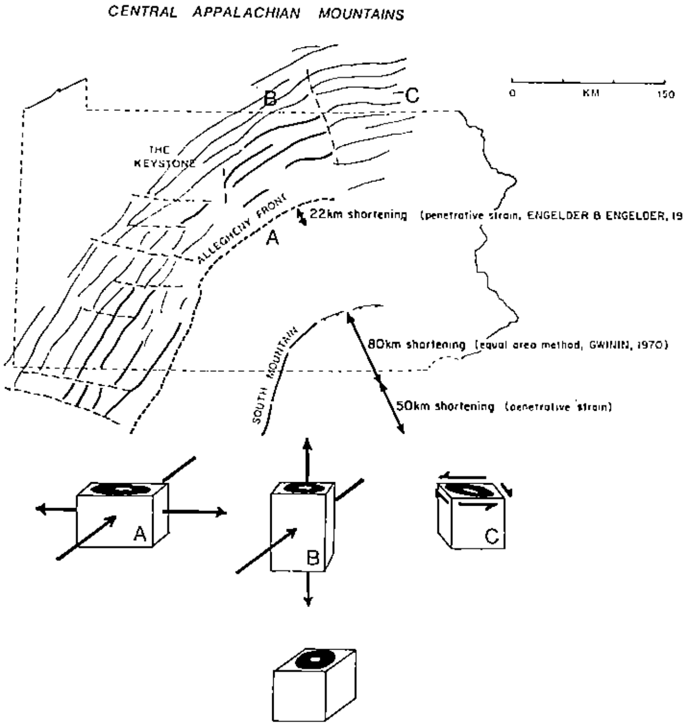


Fig. 5. Map of Central Appalachian Mountains showing structures on the Appalachian plateau (after Rodgers, 1970). Fold axes are shown as solid lines striking northeast with heavier lines showing those anticlines that are more than 300 m above adjacent synclines. Dashed cross-strike lines are zones of potential strike-slip movement. Models for volume constant distortion of rocks containing crinoid ossicles include: A (lateral spreading), B (vertical extension), and C (simple shear). Conservative estimates given for layer-parallel shortening of the Central Appalachian Mountains.

There is a debate in the literature concerning the relative importance of lateral spreading versus vertical extension. Faill (1977) argues using data on deformed fossils from the Valley and Ridge that indicate extension occurred about an arcuate trend. The distortion of crinoids for this case is shown by block A in figure 5. However, Faill's work did not benefit from an analysis using Groshong's (1972) calcite strain gauge technique.

The results presented here confirm other calculations showing that layer-parallel shortening of the Appalachian plateau is a necessary consequence of décollement tectonics. In a study of folds within the Appalachian plateau Wiltschko and Chapple (1977) concluded that significant layer-parallel shortening must occur at stratigraphic levels above the salt-bearing part of the Silurian Salina group. Their calculation is based in part on an analysis of the geometry of folds within the Appalachian plateau. That penetrative layer-parallel shortening is a major consequence of décollement tectonics was also a conclusion of Elliott's (1976) study of the energy balance of thrust sheets, where the major sink for energy put into the décollement sheet was in penetrative deformation.

Using the equal area method of Bucher (1955), Gwinn (1970) estimated a layer-parallel shortening of 80 km at South Mountain. However, this method does not account for the area loss that accompanies the formation of solution cleavage (Geiser, 1978). If the shortening accompanying the formation of solution cleavage is prevasive from the outer limits of the Central Appalachian Mountains to South Mountain and equivalent to that in western New York (~ 15 percent) then shortening at South Mountain is an additional 50 km for a total of 130 km (fig. 5).

CONCLUSIONS

The mechanisms for penetrative deformation within the Appalachian plateau are two: (1) intragranular strain by mechanical twinning of calcite, and (2) shortening on spaced solution cleavage planes. The former accounts for 1 to 5 percent layer-parallel shortening, whereas the latter accounts for 4 to 18 percent layer-parallel shortening.

ACKNOWLEDGMENTS

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