# Fossil distortion and décollement tectonics of the Appalachian Plateau

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## ABSTRACT

**Fossil distortion and solution cleavage are associated with low-amplitude folds on the outer fringes of the Appalachian foreland fold belt. Deformed fossils, sampled from Upper Devonian rocks in western New York, correspond to horizontal strain ellipses with axial ratios of as much as 1.5 and with long axes precisely parallel to the Appalachian fold trend. This strain is indicative of at least a 10% layer-parallel shortening normal (north-northwest) to the fold trend. Assuming a rigid basement, 10% layer-parallel shortening requires 5 km of displacement along a décollement thrust on the south-southeast side of any 50-km-wide portion of the affected area.**

## BACKGROUND

Décollement tectonics under the Appalachian Plateau was first appreciated following the interpretation of a well log from the Burning Springs anticline, West Virginia (Bayles and others, 1957). Woodward (1959a, 1959b) recognized a fold over an imbricate duplication of competent Middle and Lower Devonian formations with underlying Silurian, Ordovician, and Cambrian units essentially undeformed. In further discussing the Burning Springs anticline, Rodgers (1963) suggested that the imbrication occurs at the northwestern boundary of a large décollement block of upper Paleozoic strata that shifted northwestward relative to the surrounding Appalachian Plateau. As he was also aware of similar anticlines on the plateau in central Pennsylvania and western New York, Rodgers speculated that other large blocks moved to the northwest as décollement structures. Using well logs from many plateau anticlines with oversteepened southeast limbs, Gwinn (1964) showed that each was related to one or more high-angle thrust faults that appear to flatten into bedding in the evaporites of the Upper Silurian Salina Group. Gwinn interpreted plateau lineaments as boundaries between décollement blocks which moved independently. That décollement slip of the plateau extends well into New York was confirmed by structures in a salt mine in the core of the Firtree anticline (Prucha, 1968) and on its south flank (Jacoby and Dellwig, 1974).

Gwinn (1964) was the first to imply that penetrative straining of the Appalachian Plateau is a necessary consequence of décollement tectonics. He recognized that folds developed within a single décollement block and were not formed prior to definition of the block by the strike-slip faults or transverse steps (lineaments). Since there is no evidence that the slip plane at the northwest edge broke through to the surface at the initiation of slip, movement on the slip plane prior to folding can occur only if the upper portion of the décollement block shortens by either elastic or nonrecoverable strain. Nickelsen (1966) first measured nonrecoverable strain in the Appalachian Plateau by showing that distorted brachiopods in the Philipsburg quadrangle, Pennsyslvania, have been shortened 10% normal to the local fold axes. This "lateral compaction" of unconsolidated sediments preceded any major folding on the plateau. Other recent studies also recognize the importance of penetrating strain in the rocks of the Appalachian foreland sequence (Groshong, 1975; Faill, 1977; P.A. Geiser, in prep.).

## DEFORMED FOSSILS

We report here the discovery of deformed fossils and solution cleavage in Upper Devonian sedimentary rocks of western New York, 150 km northwest of the last major fold in the Pennsylvania Appalachians (Figs. 1, 2). At the surface, the structural geology of this area consists of extremely subdued and regularly spaced folds striking north of east, with limb dips of no more than 1° to 2° (Wedel, 1932). Subsurface data show anticlines over imbricated high-angle faults (Bradley and Pepper, 1938). These structures are similar to those described by Gwinn (1964) on the Appalachian Plateau farther south in Pennsylvania.

Crinoid ossicles lying on the bedding plane are the most useful strain markers in the Upper Devonian section (Fig. 1). When viewed in thin section, the calcite of many ossicles contains mechanical twins indicative of a strained rock. In outcrops, distortion in lightly strained rocks is seen more easily in the preferred orientation of these simple elliptical ossicles than in the subtle changes in shape of other fossils such as brachiopods.

We concerned ourselves with strain associated with layer-parallel shortening. Because ossicles were rarely normal to bedding, we did not attempt to measure

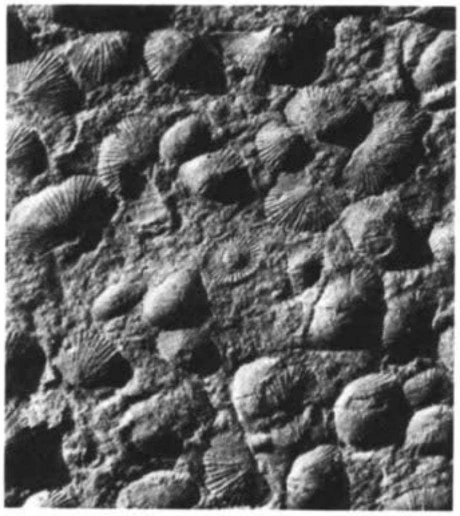

Figure 1. Deformed crinoid ossicle surrounded by deformed brachiopods. Top of photo facing north. Long axis of crinoid is 4 mm and strikes N60°E. Sample locality WEL.

strain in that direction. Strain determinations were made on oriented slabs by measuring the long and short axes of crinoid ossicles and the strike of the long axes either on a weathered bedding plane or on a cut sawed parallel to bedding. Measurements were made directly from rock slabs rather than from photographs, because ossicles that are tilted with respect to the bedding plane (and would thus give erroneous results) were difficult to detect in photographs. The axial lengths were measured to the nearest 0.1 mm using a pocket comparator, and the strike was obtained with a protractor. Two to four persons each measured a set of as many as 50 ossicles in each slab.

To obtain a representative strain ellipse from data showing a variation in axial ratio and strike of the long axes, we used Shimamoto and Ikeda's (1976) algebraic method for strain estimation from deformed elliptical objects. The axial ratio and orientation for the strain ellipse representing individual slabs (Fig. 2) are averages of the strain ellipses obtained from the measurements taken by two to four persons. The strain ellipse parallel to bedding as calculated using deformed ossicles does not exceed 1.23 ± 0.01. The maximum variation of axial ratio among persons measuring one slab was ±0.04. In general, the strike of the long axis conforms with the strike of the local folds. The axial ratio decreases to 1.05 northwest of the outer fold at location CRY and at locations TRI and GLE on the eastern terminus of the folds mapped by Wedel (1932).

Our objective is to focus attention on the pervasiveness and importance of previously unrecognized regional strain and not to arrive at an exact measurement of absolute two-dimensional strain using a specific technique. We use the eliptical ossicles only as an indication of the orientation of the strain ellipse for layer-parallel shortening. In order for the deformed ossicles to represent the true strain ellipse, there must have been homogeneous deformation, no ductility contrast between the matrix and the ossicles, and no volume change during strain.

At the location WEL we sampled thin-walled brachipods whose distortion was greater than the distortion of crinoids in the same slab. We measured the orientation of the hinge line and of the notch marking the symmetry line of the shell. Using Wellman's (1962) technique for determining a strain ellipse, three different operators found an axial ratio of 1.29 ± 0.02 and an orientation of the long axes of N57°E ± 5°. The axial ratio for ossicles at this locality was 1.2 ± 0.01. This shows that the brachiopods are weaker than ossicles and more likely to deform with the matrix.

At locality CAM in Figure 2, deformed worm tubes have an axial ratio of about 1.5, as determined by the Shimamoto and Ikeda (1976) technique (W. Manspeizer, 1977, personal commun.). Because these worm tubes are filled with the clastic matrix, they have the viscosity of the matrix and thus are passive markers whose axial ratio may be most representative of the penetrative strain for western New York.

## MECHANISMS OF LAYER-PARALLEL SHORTENING

Vertical solution cleavage planes (stylolites) found in rocks from the Java Group

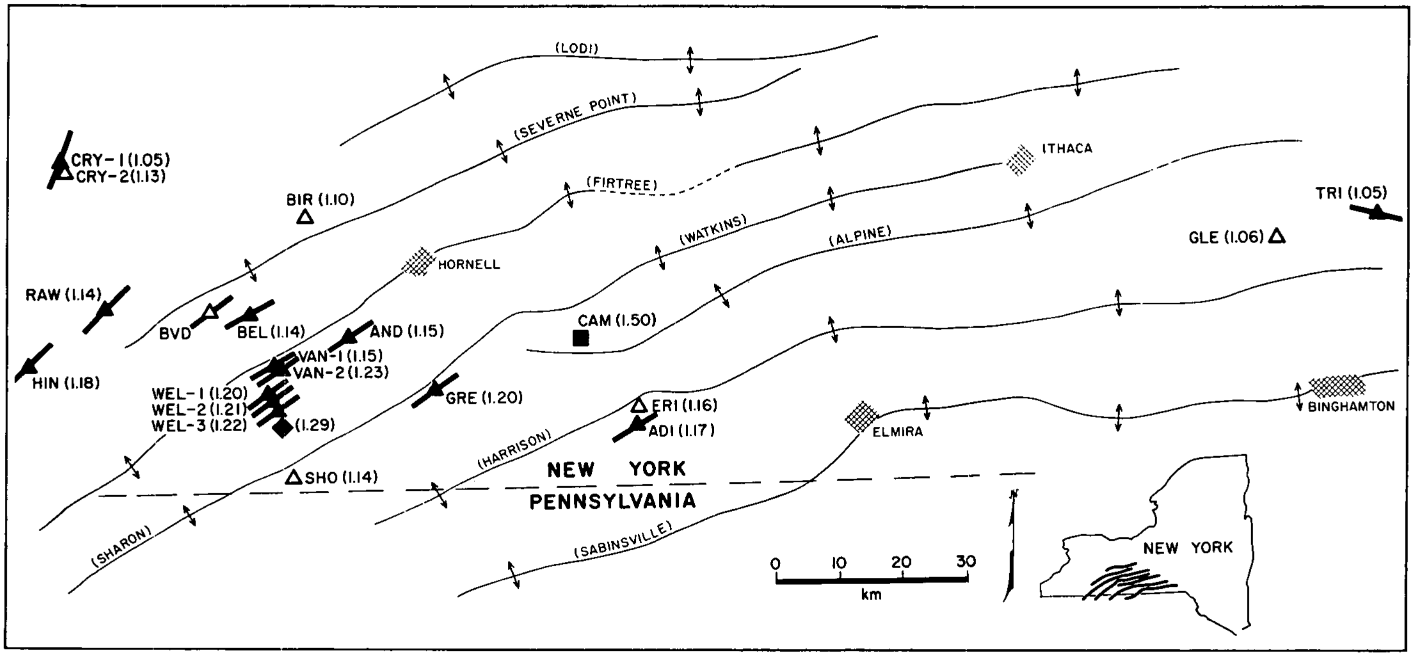

Figure 2. Orientation of long axes and axial ratio of strain ellipses calculated from measurements of ossicles on each individual slab are shown (solid triangles). As many as 3 slabs were taken at one outcrop. Axial ratios only are given for measurements from unoriented slabs (open triangles). At location BVD, a slab could not be taken because of fissile nature of outcrop; orientations were measured in situ. Distorted brachiopods sampled at WEL (solid diamond). Worm tubes sampled at CAM (solid square) by W. Manspeizer. Anticlines mapped by Wedel (1932). Major stratigraphic units from which fossils were sampled include Arkwright (HIN), Conneaut (WEL), Canadaway (RAW, CRY, BVD, BIR, SHO, BEL, VAN, and GRE), Java (CAM, ADI), West Falls (ERI), and Sonyea (GLE, TRI).

at location ADI also serve as a reminder that the strain ellipse from crinoids is only a minimum measure of the true layer-parallel shortening. These solution cleavage planes are parallel to the axial planes of the folds of western New York and to the long axes of the deformed crinoids. At ADI there are two to three solution cleavage planes per centimetre, with as much as 0.5 mm of rock removed from each plane, as indicated by the offset of fossils through which the solution cleavage plane passes. Removal of material by solution represents as much as 15% layer-parallel shortening.

Although the development of solution cleavage planes is not uniform throughout the region, dissolution indicated by the penetration of grains into each other occurs throughout the region. This suggests that the bulk strain of the rocks in western New York includes a significant volumetric strain which cannot be measured using elliptical objects, because no information is available on their initial size.

We conclude that layer-parallel shortening of the Appalachian Plateau was accomplished by two distinct processes: (1) the pervasive deformation of a rock containing inclusions that deform less than its matrix and (2) the solution and removal of rock along irregularly spaced vertical planes.

## DEFORMATION OF DÉCOLLEMENT ROCKS

The regional extent of penetrative strain within the plateau is of considerable import for palinspastic reconstructions and for the development of models for fold mechanics and décollement tectonics of the Appalachians. The strain, as measured by deformed fossils in the Upper Devonian clastic section of western New York, may be attributed to either of two deformational histories. Both deformational histories arise from distortion of the Appalachian Plateau accompanying north-northwest–directed slip on a décollement structure. One possibility is that as the plateau block moved, it became shortened in the north-northwest direction and spread laterally (east-northeast–west-southwest). This deformation would minimize north-northwest–directed slip on a décollement to achieve layer-parallel strain with an axial ratio value of 1.2. Uniform lateral spreading along an arcuate fold bend would require that the plateau must have moved north-northwest as one, more-or-less coherent block. A second possibility is that lateral spreading was of minor significance during distortion of the plateau and that the net strain resulted from north-northwest–directed layer-parallel shortening. A deformation of this nature would require considerably greater décollement slip to cause penetrative strain with an axial ratio value of 1.2. Deformation of this sort would be more likely for a plateau broken into several differentially moving blocks.

The exact nature of the distortion of the plateau is not clear, because there are data to support either of the proposed deformational histories. The arcuate trend of the plateau folds in New York and Pennsylvania suggest that spreading must occur to accommodate rocks stretched about an arc of increasing radius. Likewise, Nickelsen (1966) reported stretching of brachiopods by brittle fracture, which is unequivocal evidence for lateral spreading around an arc of increasing radius.

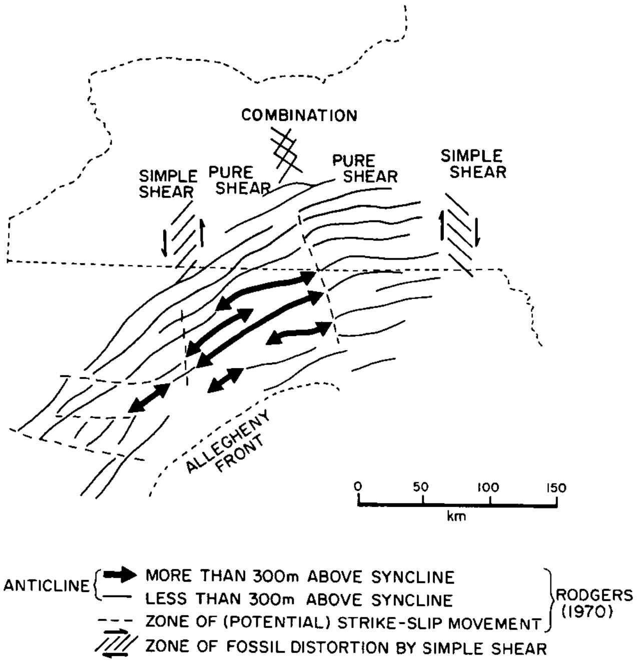

Figure 3. Nature of strain in western New York assuming that décollement blocks moved northward without major lateral spreading.

Yet there are equally compelling data suggesting that farther to the north-northwest on the plateau, lateral spreading was minor relative to north-northwest–directed layer-parallel shortening. Both Wedel's (1932) and Rodgers's (1970) maps show several abrupt changes in strike of the plateau folds. These folds either formed very late and were not controlled by early uniform spreading, or else uniform spreading did not occur on the north-northwest fringes of the foreland fold-and-thrust belt. Such abrupt changes in strike suggest that folding in different portions of the plateau developed independently. A further implication is that blocks were shifting incoherently relative to each other.

The presence of vertical solution cleavage planes is a second feature of the plateau which suggests that north-northwest layer-parallel shortening was far more important than lateral spreading. No lateral spreading should accompany shortening on solution cleavage planes.

Rodgers (1963) showed that the Burning Spring anticline décollement sheet moved west-northwest relative to adjacent Appalachian Plateau rocks. The boundary across the direction of motion is an anticline. Boundaries nearly parallel to the direction of motion he thought were strike-slip faults, characterized by diagonal trends relative to the fold axes with generally small stratigraphic displacements. Rodgers's (1970) map shows many possible transverse faults on the Appalachian Plateau, including two that mark the boundary of a block that moved north-northwest in western New York (Fig. 3). In essence, the parallel strike-slip faults suggest that some blocks shifted without spreading, so that lateral spreading in the northwest portion of the Appalachian Plateau was not geometrically necessary. The zones of possible strike-slip movement outline an arch with a keystone. In Figure 3, the plateau block that forms the keystone is that block with less northwest-directed slip than its neighbors. It stayed behind to fill a hole that would have been created had all plateau blocks moved northwest along an arcuate trend with only minor spreading.

There is a remarkable correlation between the strike of the folds and the long axes of the crinoid ossicles. The exceptions are found at either end of the fold belt in western New York, where CRY is misoriented by 35°, HIN and RAW are misoriented by 15°, and TRI is misoriented by 25°. All of these samples are misoriented in the proper sense to indicate simple shear (zones of possible strike-slip movement) at the edge of a block shifting to the north-northwest.

## IMPLICATIONS REGARDING DECOLLEMENT TECTONICS IN WESTERN NEW YORK

A conservative estimate for layer-parallel shortening in western New York is 10%. Structures now separated by 40 km contain rocks that were 4 km farther apart prior to deformation. This requires at least 4 km of slip along a major décollement structure below the Sharon anticline.

Pervasive layer-parallel shortening is found northwest of the last major fold, as indicated by strain at CRY, HIN, and RAW. Although rocks 40 km south-southeast of the last fold have moved 4 km closer to the outermost structure, 4 km is only a minimum estimate for décollement slip. First, we have no estimate for additional slip toward the north-northwest for rocks at the last fold. In addition, according to the evidence of worm tubes, solution cleavage, and deformed brachipods, we suggest that layer-parallel shortening and, hence, slip on a décollement structure may be much larger than represented by the 10% shortening.

Data from Nickelsen (1966), Faill (1977), and this paper suggest that layer-parallel shortening may pervade the entire width of the Appalachian Plateau from the Lodi anticline to the Allegheny front. Since the distance from the Allegheny front to the Lodi anticline is about 150 km, slip on the décollement at the Allegheny front would have to be at least 15 km to accommodate 10% layer-parallel shortening. Slip to accommodate the actual layer-parallel shortening might be considerably larger. Slip movement of 15 km is far greater than that proposed by Rodgers (1963) and Gwinn (1964), both of whom stressed folding and imbrication by high-angle faulting as the main mechanisms of layer-parallel shortening within décollement blocks. For palinspastic reconstruction of the Pennsylvania Appalachians, pervasive strain within both the Valley and Ridge province (Faill, 1977) and the Appalachian Plateau may account for much more décollement slip on the southeast side than calculated by Gwinn (1970) for folding and faulting.

## REFERENCES CITED

Bayles, R. E., Henry, W. H., Fettke, C. R., Harris, L. D., Flowers, R. R., and Haught, O. L., 1956, Wood Country deep well: West Virginia Geol. and Econ. Survey Rept. Inv. 14, 62 p.

Bradley, W. H., and Pepper, J. F., 1938, Geologic structure and occurrence of gas in part of southwestern New York: Pt. 1, Structure and gas possibilities of the Oriskany sandstone in Steuben, Yates and parts of adjacent counties: U.S. Geol. Survey Bull, 899-A, 68 p.

Faill, R. T., 1977, Fossil distortion, Valley and Ridge province, Pennsylvania: Geol. Soc. America Bull., v. 9, p. 262-263.

Groshong, R. H., 1975, Slip cleavage caused by pressure solution in a buckle fold: Geology, v. 3, p. 411-413.

Gwinn, V. E., 1964, Thin-skinned tectonics in the plateau and northwestern Valley and Ridge provinces of the central Appalachians: Geol. Soc. America Bull., v. 75, p. 863-900.

— 1970, Kinematic patterns and estimates of lateral shortening, Valley and Ridge and Great Valley provinces, central Appalachians, south-central Pennsylvania, *in* Fisher, G. W., Pettijohn, F. J., Reed, J. C., and Weaver, K. N., eds., Studies of Appalachian geology—Central and southern (Cloos volume): New York, Interscience Pubs., p. 127-146.

Jacoby, C. H., and Dellwig, L. F., 1974, Appalachian foreland thrusting in Salina salt, Watkins Glen, New York, *in* Coogan, A. H., ed., Fourth symposium on salt: Northern Ohio Geol. Soc., p. 227-233.

Nickelsen, R. P., 1966, Fossil distortion and penetrative rock deformation in the Appalachian plateau, Pennsylvania: Jour. Geology, v. 74, p. 924-931.

Prucha, J. J., 1968, Salt deformation and décollement in the Firtree Point anticline of central New York: Tectonophysics, v. 6, p. 273-299.

Rodgers, J., 1963, Mechanics of Appalachian foreland folding in Pennsylvania and West Virginia: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 1527-1536.

— 1970, The tectonics of the Appalachians: New York, John Wiley & Sons, 271 p.

Shimamoto, T., and Ikeda, Y., 1976, Simple algebraic method for strain estimation from deformed ellipsoidal objects: 1, Basic theory: Tectonophysics, v. 36, p. 315-337.

Wedel, A. A., 1932, Geologic structure of the Devonian strata of southcentral New York: New York State Mus. Bull. 294, 75 p.

Wellman, H. W., 1962, Graphical method for analysing fossil distortion caused by tectonic deformation: Geol. Mag., v. 99, p. 348-352.

Woodward, H. P., 1959a, Structural interpretations of the Burning Springs anticline, *in* Woodward, H. P., ed., A symposium on the Sandhill Deep Well, Wood County, West Virginia: West Virginia Geol. Survey Inv. Rept. 18, p. 159-168.

— 1959b, The Appalachian region: World Petroleum Cong., 5th, New York, Proc., sec. 1, paper 59, p. 1061-1079.

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