The relationship between pencil cleavage and lateral shortening within the Devonian section of the Appalachian Plateau, New York

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ABSTRACT

Here we call attention to a weakly developed pencil cleavage as an indicator of the pervasiveness of lateral shortening within the sedimentary sequence of the Appalachian Plateau. The pencil cleavage appears in Upper Devonian shales as a set of closely spaced vertical partings, and it gives the shale a crude lineation similar to the pencil structures in slate districts. The strike of the shale pencil structures parallels the strike of stylolitic solution cleavage in limestones and is normal to the direction of lateral shortening indicated by deformed fossils. These deformation markers generally conform with the variation in trend of the Appalachian Plateau folds. Where the strike of the pencil cleavage diverges from the fold axes, the relation between cleavage and folding suggests that the cleavage formed first.

INTRODUCTION

In mountain building, a zone of weak deformation migrates in front of zones of more internal, stronger deformation. Such a zone of weak deformation is found in west-central New York where barely perceptible hints of tectonic strain are printed on the Devonian sedimentary sequence of the Appalachian Plateau. Evidence for weak deformation may be obscured by further deformation in more internal zones such as in the Appalachian Valley and Ridge province.

The zone of weak deformation in west-central New York was partially mapped by using tectonically deformed fossils (Engelder and Engelder, 1977). Previous workers mapped subsurface structures, joints, and minor surface faults, but the strain markers such as deformed fossils were overlooked (Wedel, 1932; Bradley and Pepper, 1938; Parker, 1942). Folds mapped by Wedel (1932), having an amplitude of 100-m and 10-km wavelengths (here called major folds to distinguish them from smaller-scale folds common to the Onondaga Limestone and Marcellus Formation), change strike across New York and thus suggest a change in orientation of the lateral shortening associated with the weak deformation (Fig. 1). This change in orientation of lateral shortening was confirmed by using deformed fossils (Engelder and Engelder, 1977). Several mechanisms are responsible for the lateral shortening, including dissolution along stylolites and intragranular flow by mechanical twinning within calcite (Engelder, 1979a). The zone of weak deformation extends northwestward at least to the vicinity of Brockport, New York, where it is manifested as an elastic residual strain indicated by overcoring tests and X-ray analysis (Engelder, 1979b). Calcite deformation twins in the east-trending outcrop belt of the Onondaga Limestone indicate that lateral shortening decreases with distance northward from the low-amplitude folds in the southern half of west-central New York State (Engelder, 1979b).

Because initial sampling was limited, many details concerning the zone of weak deformation were unresolved by previous papers. In this paper we address questions concerning (1) the local variation in lateral shortening across major folds, (2) the divergence of lateral shortening and fold axes in the Syracuse-Binghamton area, (3) the correlation of deformation in fossiliferous rocks and pencil cleavage in shale, and (4) the relationship between pencil cleavage in shale and stylolitic solution cleavage in carbonate-bearing rocks. To answer those questions, we introduce the characteristics of an incipient pencil cleavage in shales of west-central New York and add to Engelder and Engelder's (1977) data set on deformed fossils.

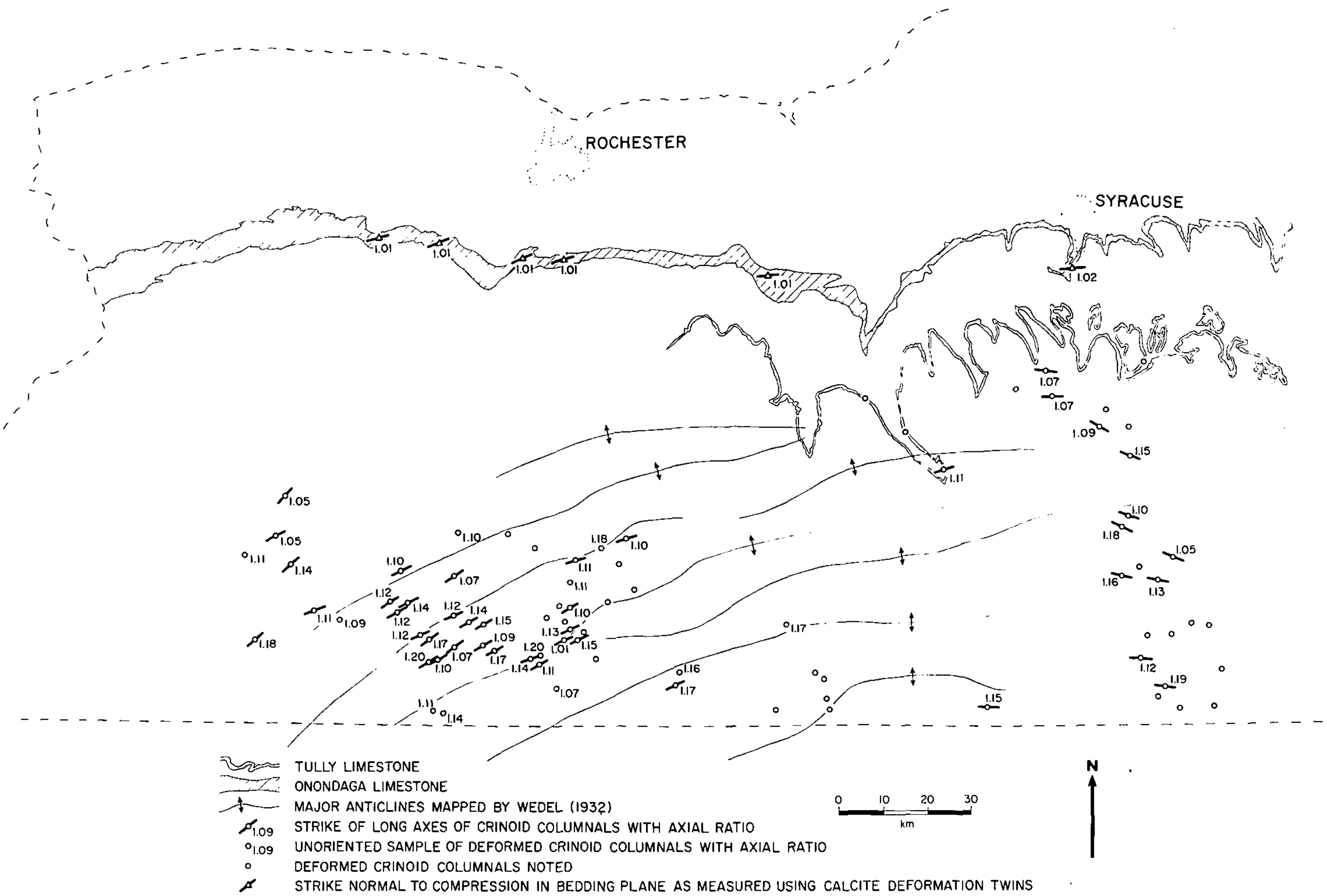

Figure 1. The orientation of the long axes and axial ratio of deformed crinoid columnals plotted with anticlines mapped by Wedel (1932). The axial ratios were calculated after the method of Shimamoto and Ikeda (1976). Also plotted is the orientation of minimum shortening in the horizontal plane as indicated by deformed calcite in the Onondaga Limestone, after the method of Groshong (1972). (The lack of data in the south-central parts of this and subsequent maps marks areas where a U.S. Geological Survey party concurrently mapped some of the same tectonic features.)

FOSSIL DISTORTION

We have observed deformed fossils within 85 outcrops in west-central New York and have measured the strain parallel to bedding using crinoid columnals within 52 of these outcrops (Fig. 1). Fossiliferous outcrops are most common in the Upper Devonian Canadaway, Java, West Falls, and Sonyea Groups (Rickard and Fisher, 1970). Along the northern folds shown in Figure 1, most outcrops are of deep-water marine shales barren of fossils. Lateral shortening as indicated by fossil distortion decreases from about 15% within the area of major folds shown in Figure 1 to less than 10% north of the last major fold. South of the last major fold, the mechanisms for fossil distortion are mechanical twinning, which accounts for about 5% lateral shortening, and dissolution on stylolitic solution-cleavage planes, which accounts for about 10% lateral shortening (Engelder, 1979a). Lateral shortening measured from the mechanical twins within the calcite from the Onondaga Limestone is 2% or less north of the outcrops containing visibly deformed fossils (Engelder, 1979b). In general, the lateral shortening indicated by crinoid columnals is more uniformly distributed than that associated with local fold axes; this is particularly noticeable in the western sector of Figure 1 where the sample density is high. The orientation of strain in the Onondaga Limestone also varies in the same manner as shown for outcrops within the area of major folds to the south.

There is variation in lateral shortening among outcrops; this indicates that, in detail, the strain was not perfectly uniform over areas the size of several 7½-minute quadrangles. However, the sampling of deformed fossils is dense enough to conclude that variations in strain do not depend on the outcrop position relative to individual folds in west-central New York (Fig. 1). Furthermore, regional sampling from the four Upper Devonian groups mentioned above may be used to show that layer-parallel shortening of fossiliferous rock is not dependent on position within an 800- to 1,200-m vertical section.

STYLOLITIC SOLUTION CLEAVAGE

When tectonically driven dissolution is found within limestone, it is manifested by stylolitic solution cleavage spaced at regular intervals and generally oriented at a high angle to bedding (Wagner, 1913; Stockdale, 1922). A solution cleavage appears in the limestones of west-central New York where the Onondaga and Tully Limestones contain well-developed seams with weak to moderate intensities, from the classification of Alvarez and

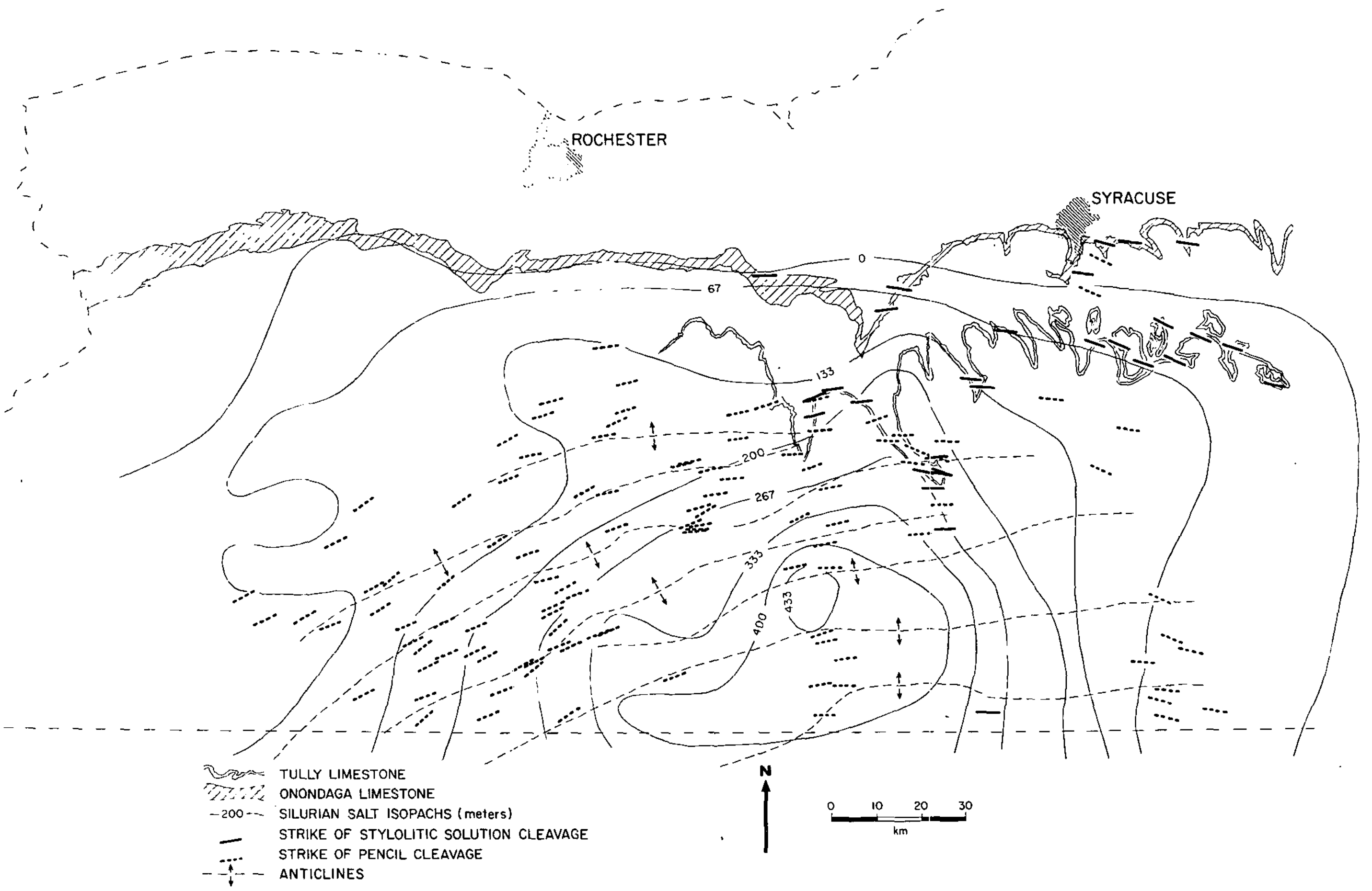

Figure 2. The strike of stylolitic solution cleavage and pencil cleavage plotted with anticlines mapped by Wedel (1932) and an isopach map of Silurian salt after Kreidler (1957).

others (1978; Hall, 1843, p. 131, was the first to describe stylolitic solution cleavage in western New York; see Fig. 2). Where developed, stylolitic teeth rarely exceed an amplitude of a few millimetres, and the trace-length of the stylolitic cleavage rarely exceeds 1 m on bedding surfaces. Insoluble residues occur on all cleavage surfaces. The solution cleavage forms on widely spaced planes (>10 cm) and absorbs an unknown but probably small (<2%) lateral shortening in beds of the Onondaga Limestone where the lateral shortening by mechanical twinning of calcite is also less than 2%. Solution cleavage in some outcrops of the Tully Limestone is more closely spaced and probably absorbs more lateral shortening.

Occasionally, on the outcrop scale, stylolitic solution cleavage may be seen cutting the calcite-cemented siltstones of the West Falls Group. For cleavage cutting the bedding surfaces, the insoluble residues generally make smooth wavy traces, rather than the toothed trace of classic stylolites (see Fig. 1; Engelder, 1979a).

The orientation of the stylolitic solution cleavage has the same uniform distribution across west-central New York as the deformed fossils; the trace of the cleavage is subparallel to the major folds of the Appalachian Plateau except on the eastern end where the trace rotates clockwise relative to fold axes. In west-central New York, the maximum shortening in the fossiliferous clastic rocks is normal to the solution-cleavage planes in the limestone. Again, it should be emphasized that the strain distribution shown by cleavage, crinoids, and calcite compression axes shows a more uniform pattern than that reflected by the fold-axis trends.

PENCIL CLEAVAGE

The name "pencil cleavage" was commonly used in slate districts where the intersection of bedding and cleavage materially facilitates the making of slate pencils (Cloos, 1946). These slates fracture in two directions to break into long narrow strips that have rectangular or rhombic cross sections. A weak pencil cleavage in sections consisting of shale and mudstone interbedded with siltstone in Australia is characterized by

> quasi-planar fractures that are penetrative on the scale of handspecimens. When incipient, the cleavage is barely distinguishable from the irregular fracture that results from weathering. Stronger development of the cleavage makes the quasi-planar fractures more easily visible, and they may be at least as prominent as the bedding fissility. Weathering of very strongly cleaved mudstone produces a characteristic mass of acutely terminated elongate polygonal fragments. (Crook, 1964)

In west-central New York, many of the Upper Devonian shales break into elongate pieces with their long edges defined by the intersection of bedding planes and closely spaced vertical partings striking roughly parallel to the fold axes (Fig. 3). This gives the shale a crude linear fabric that is similar to the pencil structure described by Crook (1964). The closely spaced vertical partings have several characteristics throughout the Upper De-

Figure 3. Photograph of pencil cleavage in shale of the Upper Devonian Canadaway Group and along the Vandermark Creek 4 km east of Scio, New York. The view is a vertical face looking parallel to the strike of the pencil structures (N60°E). Bedding is horizontal, and the parting that forms the pencil structures is vertical. The actual shape of the structures is best ascertained by viewing the loose and disoriented fragments such as the upper of the two pencil structures indicated in the photograph. The coin is 2.4 cm in diameter.

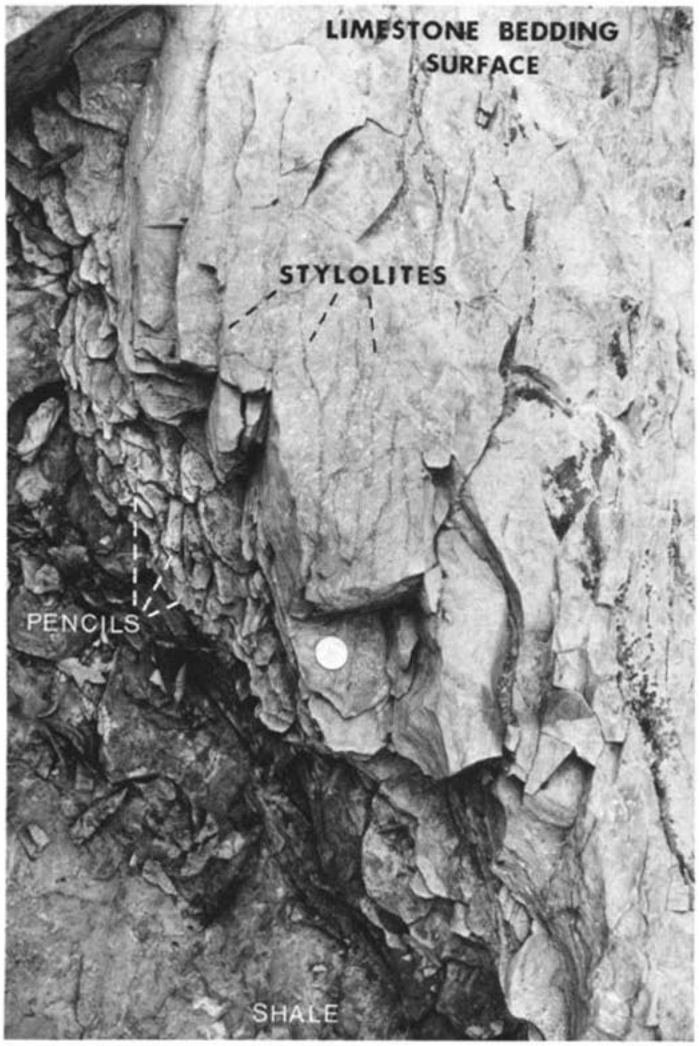

Figure 4. Photograph of the top part of the Tulley Limestone interfingering with shale of the overlying Genesee Group at Taughannock Falls State Park near Ithaca, New York. A zone of stylolitic solution cleavage developed in the limestone grades downward into a zone of pencil cleavage developed in a 20-cm-thick bed of shale. The coin is 2.4 cm in diameter.

vonian shales of west-central New York. The strike of the partings shows a uniform distribution almost identical to that of elongated columnals and compression axes measured from calcite deformation twins. The spacing of the partings is generally less than 5 cm. In some outcrops, a lineation caused by the partings is conspicuous, whereas others have just a subtle hint of a lineation. Although the map pattern of partings is quite uniform, for reasons not yet understood the strike of the partings has been found to vary by as much as 40° in some outcrops. Most partings do *not* have insoluble residues on their surfaces; however, in some cases where limestone and shale are interbedded, the shale partings can be traced into solution-cleavage planes in limestone interbeds (Fig. 4).

There is still some question about what the shale partings actually represent. The role of weathering in accenting the partings is uncertain. Yet, because the partings can be traced into the solution-cleavage planes in limestone and because the partings have an orientation almost identical to that of lateral shortening indicated by deformed fossils, we suggest that the partings are a manifestation of lateral shortening in the shales. For this reason we refer to the elongate structures in shales as pencil structures reflecting an incipient pencil cleavage.

Regionally, the strike of the pencil cleavage in the shale and the solution cleavage in the limestones swings from S70°E in the eastern part of the area studied to N60°E in the western part (Fig. 2). Although the major folds change strike in the same manner, the pencil cleavage is not coaxial with the folds at the eastern end of the belt. In some areas the strike of the solution cleavage and pencil cleavage correlates with isopach lines of the Silurian salt deposits in west-central New York. In the northeastern corner of the map, the strike of both the cleavages diverges from the fold axes and parallels the 67-m isopach line (Fig. 2). Another correlation is found where the 200-m isopach line makes a sharp bend at its northernmost position. Here the local strike of both cleavages diverges from the fold axes to conform more closely with the isopach lines.

DISCUSSION

One question unresolved by Engelder (1979a) was whether or not the lateral shortening measured from the fossiliferous strata of the Appalachian Plateau was independent of rock type. This question is difficult to answer because much of the Devonian section of western New York contains no markers suitable for quantitative strain measurement. By inferring that pencil structure is strain-induced, we combine our map of deformed fossils with our map showing the development of pencil cleavage in shales. Together, these suggest that lateral shortening was regional in extent and pervaded the Devonian section. However, we still have no technique for measuring the lateral shortening represented by the pencil cleavage and so still do not know if layer-parallel shortening is independent of rock type and, thus, uniform throughout a vertical section.

The hint of a similarity in orientation between the shape of the Silurian salt basin and both cleavages reinforces the notion of Rodgers (1963), Gwinn (1964), and Wiltschko and Chapple (1977) that salt played a major role in decollement tectonics on the Appalachian Plateau. The notion is further reinforced by the decrease in lateral shortening at the salt pinch-out. Although lateral shortening is found beyond the zero isopach of the Silurian salt, it is much less than over the salt.

E. C. Beutner (1978, personal commun.) has suggested that we might use our data to make some judgment concerning the timing of cleavage and intragranular strain relative to folding. The options are that the shortening by cleavage and intragranular strain (CIS) either predates, is contemporaneous with, or postdates the shortening by folding (FS). The lack of correlation of strain variations with positions on the folds argues against total contemporaneity. Because strain within the folded region associated with CIS is greater (10% to 15% shortening) than that directly associated with folding (1% to 2% shortening by unfolding the layers), the CIS preceded FS. This must be so, because if the CIS postdates the FS, fold axes should be rotated toward the normal to the CIS shortening axes; they are not. Early CIS is consistent with the viscous buckling theory, which requires significant shortening prior to the initiation of folding.

The metamorphism of a shale to a slate undoubtedly has several distinct phases, depending on pressure and temperature changes. We suggest that the incipient pencil cleavage seen in west-central New York represents an initial phase during which the shale is starting to show signs of lateral shortening and the development of a texture common to metamorphic rocks.

Finally, it is not clear if the pencil cleavage can promote secondary permeability in deeply buried, gas-bearing Devonian shales of the Appalachian Plateau. However, if present in these shales, it might prove useful for exploration and extraction strategies.

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