Pergamon

Journal of Structural Geology, Vol. 17, No. 6, pp. 911 to 915, 1995

0191-8141/95 $9.50+0.00

0191-8141(94)00127-8

# Tectonic stylolites in the 'undeformed' Cumberland Plateau of southern Tennessee

L. BRUCE RAILSBACK and LYNN M. ANDREWS

Department of Geology, University of Georgia, Athens, GA 30602-2501, U.S.A.

(*Received* 15 *June* 1994; *accepted in revised form* 18 *November* 1994)

**Abstract**—Numerous tectonic stylolites (i.e. stylolitic planes), most of which are nearly vertical and strike about N30E, cut through otherwise undeformed carbonates in the Cumberland Plateau of southeastern Tennessee. These stylolites confirm previous arguments that tectonic stylolites should form in flat-lying strata in front of fold-thrust belts. The uniform trend of the teeth of the stylolites at N50W to N70W suggests that they formed as the result of Alleghanian compression, but the stylolites lie beyond the geographic limits of other, larger-scale, Alleghanian structures. Field evidence shows that the Monteagle stylolites, which are evenly spaced, formed along pre-existing fractures, illustrating that even spacing is not necessarily evidence of self-organization.

## INTRODUCTION

Tectonic stylolites, or transverse stylolites, are subplanar pressure dissolution features that are generally not parallel to bedding and that have formed as the result of tectonic compression. Tectonic stylolites are typically found in deformed carbonates in mountain belts (e.g. Groshong 1975b, Marshak & Engelder 1985, Dean *et al.* 1988). Tectonic stylolites can also form beyond orogenic regions, as Illies (1975) and Illies & Greiner (1978, 1979) have demonstrated in the faulted but not folded Rhinegraben region in the Alpine foreland, and as shown by Schultz *et al.* (1992) in the St. Genevieve fault zone of Missouri and by Arthaud & Mattauer (1969) in Languedoc. In the Appalachian region, Engelder & Engelder (1977) and Groshong (1975a) reported tectonic stylolites from gently folded rocks in the foreland fold belt of New York. However, modelling by Beaumont *et al.* (1988) indicates that at least vertical flexure should extend into unfolded forelands 100's of kilometers beyond thrusts, and Marshak & Engelder (1985) hypothesized from field evidence that tectonic stylolites form in flat-lying strata prior to thrusting and folding.

This paper reports on tectonic stylolites from undeformed carbonates in the Cumberland Plateau of southeastern Tennessee, and it thus confirms the models and hypotheses noted above. The presence of these pressure dissolution surfaces in undeformed, flat-lying carbonates illustrates that, despite their name, tectonic stylolites are not confined to regions of larger-scale tectonic deformation. Instead, they have the potential to record subtle or distant tectonic deformation in seemingly undeformed rocks.

## GEOLOGIC SETTING

The tectonic stylolites described below are from three localities in roadcuts along Interstate Highway 24 southeast of Monteagle in Marion County, Tennessee, U.S.A. (Fig. 1). Interstate 24 splits southeast of Monteagle as it descends from the Cumberland Plateau. Locality 1 (35°12′04″N, 85°48′50″W) is on the western, southbound side, Locality 2 (35°10′32″N, 85°47′52″W) is at the southern reunion of the two halves of the highway, and Locality 3 (35°12′14″N, 85°47′26″W) is on the eastern, northbound side. All three localities are in Mississippian carbonates. Locality 1 is in dolostones of the Pennington Formation, Locality 2 is in fine-grained dolostones of the St. Louis Formation, and Locality 3 is in undolomitized grainstones of the Bangor Formation. Our dissolution experiments show that the host rocks for the stylolites have insoluble residue contents, mostly of clay, as low as 2% in the Bangor Formation but as high as 19% and 21% in the Pennington and St. Louis Formations, respectively.

The strata at these localities are flat-lying and unfaulted. The Monteagle Quadrangle geologic map by Moore & Briggs (1979) shows no faults, and structure contours on the top of the Bangor Limestone yield dips of only 0.23° SE to the north of the study area and 0.11° SE south of the localities studied. The study area is about 22 km northwest of the Sequatchie Thrust, the westernmost thrust of the Valley and Ridge province of the Appalachians in southeastern Tennessee. Cross-sections by Woodward (1985) show folds 1–2 km in front of the westernmost thrust in some parts of Tennessee, but never as far into the interior as the study area at Monteagle. The Monteagle localities are thus in flat-lying, undeformed strata that are, by any definition, beyond the Appalachians and seemingly beyond the direct influence of Alleghanian or earlier tectonism.

## OBSERVATIONS

The tectonic stylolites at all three localities generally have strikes near N30E (Fig. 2). Eighty-three per cent of

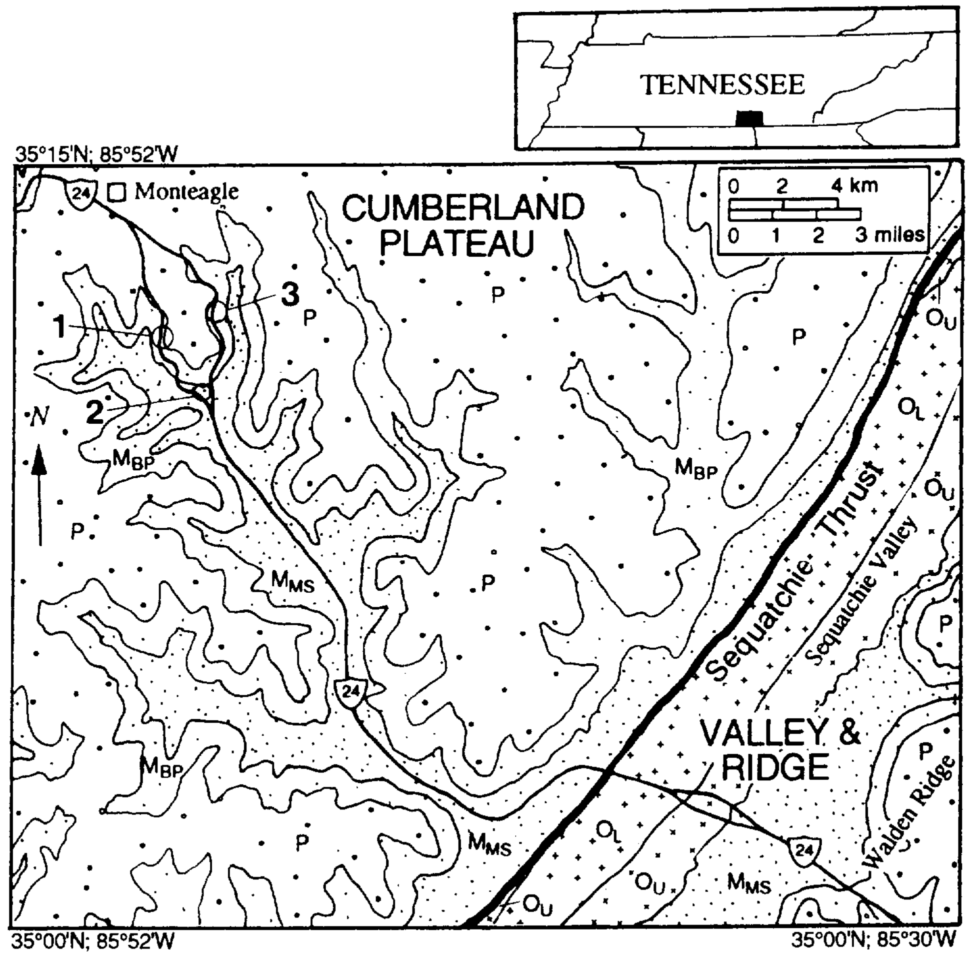


Fig. 1. Simplified geologic map of the southeastern Cumberland Plateau and part of the Valley and Ridge Province of the Appalachians. Map at top shows location in state of Tennessee, in south-central U.S.A. Localities studied, which are marked with numbered circles, are roadcuts along Interstate Highway 24 southeast of Monteagle. $O_L$ = Lower Ordovician, $O_U$ = Upper Ordovician, $M_{MS}$ = Mississippian St. Louis and Monteagle Limestones, as well as underlying Devonian and Mississippian units, $M_{BP}$ = Mississippian Bangor and Pennington Formations, P = Pennsylvanian siliciclastics. Simplified from map by Swingle *et al.* (1966).

the stylolites measured have strikes within 10° of N30E, and 95% are within 20° of N30E. At Locality 1, the stylolites that deviate more than 20° in strike from N30E are offsets along, or branches at the ends of, longer stylolites with strikes nearer N30E. Almost all of the stylolites are nearly vertical: 70% have dips of at least 85°, 85% have dips greater than 80°, and 98% have dips greater than 70°.

The orientations of the teeth of these stylolites are even more uniform. Ninety-five per cent of the teeth measured trend within 10° of N60W, and 37% trend between N50W and N54W. The teeth are thus generally perpendicular to the stylolite planes, but that is not true in all cases. For example, one stylolite at Locality 1 strikes N32E and has teeth trending N63W, but where the stylolite abruptly turns and strikes N67E, the trend of the teeth changes only to N68W. At the branching stylolites noted above, trends of teeth similarly remain at about N50W to N70W, so that orientations of teeth vary much less than orientations of stylolites themselves.

Measured perpendicular distances between stylolites range from 8 cm to 130 cm (Fig. 3). Longer distances between stylolites may exist but are covered. Fifty-nine per cent of the inter-stylolite distances measured are between 40 and 70 cm, and 35% are between 40 and 50 cm. The mean spacing of stylolites is 60 cm at Locality 1 and 43 cm at Locality 2. The stylolites themselves are up to 0.5 mm thick, and their maximum amplitude is 13 mm.

Dissolution of one stylolite seam from the Pennington dolostones at Locality 1 yielded insoluble residue abundances of about 0.25 g of insoluble material per cm$^2$ of stylolite area. That residue content, combined with a measured dolostone density of 2.83 gm cm$^{-3}$ and a measured insoluble content of 19% of the host rock, implies a horizontal loss of about 0.46 cm of dolostone per stylolite. That horizontal loss, with a stylolite every 50 cm, yields layer-parallel shortening of about 0.92%. For comparison, maximum offsets of 7 to 13 mm (described above) every 50 cm yield a shortening of 1.4 to 2.6%.

At Locality 1, at least one stylolite can be traced into a smooth, unstylolitized joint that curves away from the trend of the stylolite. Another stylolite of typical thickness continues relatively straight but thins to an end beyond the point at which a joint curves away. Thus, at least some stylolite planes appear to be coincident with joints, but do not continue along the hooked ends of

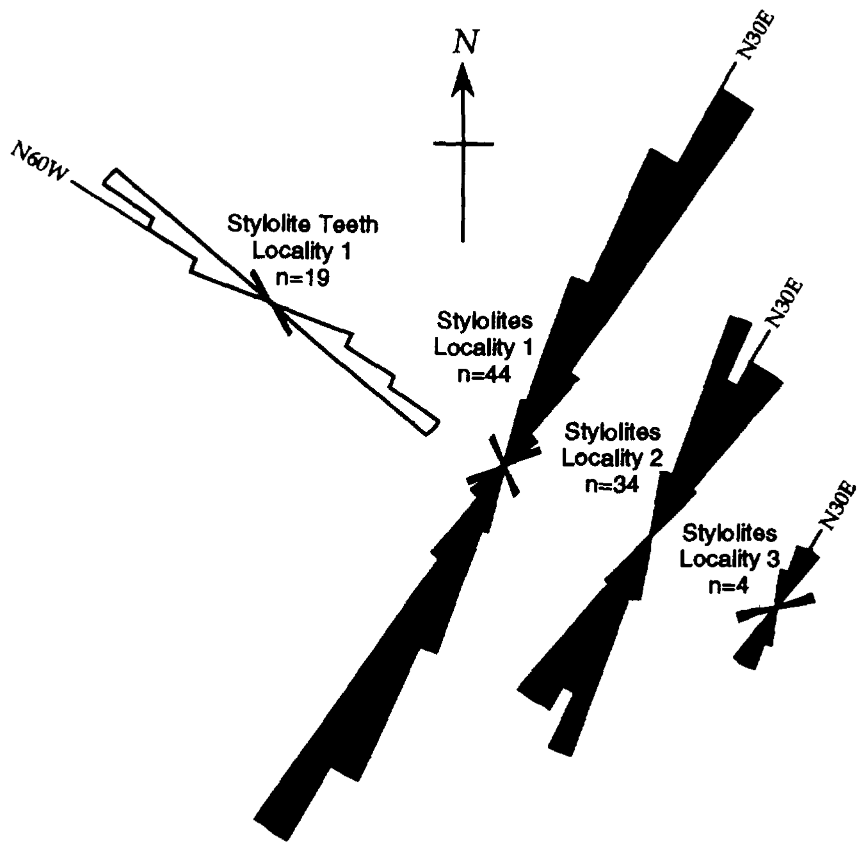


Fig. 2. Trends of teeth of tectonic stylolites (open rose diagram) and strikes of tectonic stylolites (filled rose diagrams) from roadcuts near Monteagle, Tennessee. See Fig. 1 for locations of Localities 1, 2 and 3.

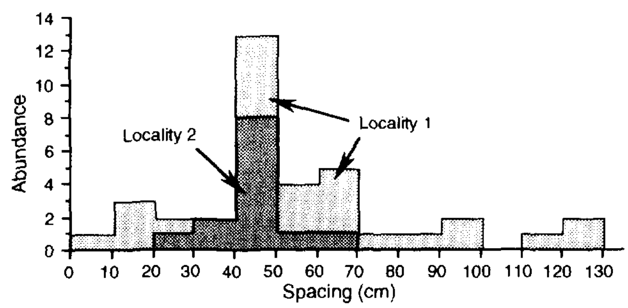


Fig. 3. Distances between adjacent tectonic stylolites in roadcuts near Monteagle, Tennessee. See Fig. 1 for locations of Localities 1 and 2.

those joints as the latter increasingly deviate from N30E. Other joints that strike N29W have similar hooked terminations but are not coincident with stylolites.

## DISCUSSION

### *Tectonic stylolites and tectonism*

The uniformity of orientations of stylolite teeth near Monteagle suggests that one compressive event, rather than multiple events, was responsible for stylolitization. The teeth have orientations perpendicular to many Alleghanian structures. For example, the Sequatchie Thrust, the westernmost thrust of the Valley and Ridge in southeastern Tennessee, strikes N33E, and the Chattanooga Thrust, the next thrust to the east, strikes N29E. The axis of the syncline in front of the Chattanooga Thrust similarly trends N27E. The similarity of the observed shortening direction for stylolitization (N50W to N70W) to the inferred shortening direction for Alleghanian thrusting and folding (perpendicular to those structures and thus about N60W) clearly suggests that the stylolites resulted from the same tectonic event. The development of the Monteagle tectonic stylolites in three different stratigraphic units with very different lithologies and clay contents suggests that their development was not a fluke resulting from unique circumstances but was instead a widespread response to tectonic compression.

The development of these stylolites in otherwise undeformed strata confirms the hypothesis that stylolites form in flat-lying rocks 'prior to the development of ramps and associated folds' (Marshak & Engelder 1985; see their fig. 11). As noted above, tectonic stylolites are known from weakly deformed foreland, non-orogenic settings. Stylolitization in the flat-lying unfaulted strata at Monteagle suggests, however, that other tectonic stylolites may exist elsewhere as records of tectonic activity in strata that otherwise appear undeformed.

Analysis of Monteagle stylolites yields minimum layer-parallel shortening of about 1–2%, whereas Craddock & van der Pluijm (1989) used twinning to detect 2–4% shortening in front of the Appalachian and Ouachita active plate margins. Several studies (e.g. Engelder & Engelder 1977, Dean *et al.* 1990) have found that pressure dissolution accounts for major shortening within fold-thrust belts. Taken together, the twinning studied by Craddock & van der Pluijm (1989) and the stylolitization described above suggest that considerable shortening also occurred in the seemingly undeformed regions beyond the Appalachian fold-thrust belt. Shortening of this type may account for movement along the blind thrusts in front of the Appalachians documented by Woodward (1985).

*Tectonic stylolites and pre-existing fractures*

The coalescence of tectonic stylolites with fractures having hooked terminations provides good evidence that these stylolites formed along pre-existing fractures. If the hooked fractures postdated the stylolites, they would offset or disrupt them, and the disappearance of hooked fractures into stylolites suggests that stylolitization has consumed the fractures where they were straightest and most nearly perpendicular to maximum compression. Furthermore, stylolite teeth not perpendicular to stylolite surfaces are typical of stylolites formed on pre-existing surfaces (e.g. Dean *et al.* 1988), whereas teeth of stylolites formed *de novo* are usually perpendicular to the stylolite surface. The origin of the fractures is not obvious, but the similarity of their strike to trends of Mississippian isopach maps (e.g. the N38E trend on Plate 7 of DeWitt & McGrew 1979) suggests that the fractures resulted from extension during Mississippian deposition (as similarly suggested in West Virginia by Dean *et al.* 1988).

The relatively even spacing of stylolites formed along pre-existing fractures also casts a note of warning regarding the origin of evenly-spaced stylolites. Merino *et al.* (1983), Merino (1984), Ortoleva (1987), Ortoleva *et al.* (1987), Dewers & Ortoleva (1990), Merino (1992), Ortoleva *et al.* (1993) and Ortoleva (1994) have proposed a widely cited and mathematically elegant model for chemical self-organization of stylolites that results in formation of evenly-spaced stylolites. The clustering of inter-stylolite distances documented in Fig. 3 could be taken as evidence for this chemical self-organization model. However, the origin of those stylolites along pre-existing fractures, which also are commonly evenly spaced (Hobbs *et al.* 1976), shows that evenly spaced tectonic stylolites deserve careful examination before they should be used as evidence of chemical self-organization.

## CONCLUSIONS

(1) Tectonic stylolites are present in undeformed, flat-lying and unfaulted, carbonates in the southeastern Cumberland Plateau. Their presence confirms previous arguments that tectonic stylolites should exist in foreland regions that are otherwise undeformed.

(2) The tectonic stylolites near Monteagle formed along pre-existing fractures as the result of compression associated with Alleghanian tectonism.

(3) The relatively even spacing of tectonic stylolites near Monteagle illustrates that regular spacing of stylolites can result from stylolitization along pre-existing fractures, so that regular spacing need not represent chemical self-organization.

*Acknowledgements*—Stuart L. Dean, Steven M. Holland, Richard H. Groshong, Jr., and an anonymous *JSG* reviewer provided valuable comments on various drafts of the manuscript. Conversations with David V. Wiltschko, Christopher Beaumont and Stephen Marshak were also of great help. The authors thank Steven M. Holland and his University of Georgia graduate stratigraphy class for their cooperation in the field.

## REFERENCES

Arthaud, F. & Mattauer, M. 1969. Exemples de stylolites d'origine tectonique dans le Languedoc, leurs relations avec la tectonique cassante. *Bull. géol. Soc. Fr.* **11**, 738–744.

Beaumont, C., Quinlan, G. & Hamilton, J. 1988. Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America. *Tectonics* **7**, 389–416.

Craddock, J. P. & van der Pluijm, B. A. 1989. Late Paleozoic deformation of the cratonic carbonate cover of eastern North America. *Geology* **17**, 416–419.

Dean, S. L., Kulander, B. R. & Lessing, P. 1990. The structural geometry and evolution of foreland thrust systems, northern Virginia: alternative interpretation. *Bull. geol. Soc. Am.* **102**, 1442–1443.

Dean, S. L., Kulander, B. R. & Skinner, J. M. 1988. Structural chronology of the Alleghanian orogeny in southeastern West Virginia. *Bull. geol. Soc. Am.* **100**, 299–310.

Dewers, T. & Ortoleva, P. J. 1990. Interaction of reaction, mass transport, and rock deformation during diagenesis: Mathematical modeling on intergranular pressure solution, stylolites, and differential compaction/cementation. In: *Prediction of Reservoir Quality Through Chemical Modeling* (edited by Meshri, I. D. & Ortoleva, P. J.). *Mem. Am. Ass. Petrol. Geol.* **49**, 147–160.

DeWitt, W., Jr. & McGraw, L. W. 1979. The Appalachian Basin region. In: *Paleotectonic Investigations of the Mississippian System in the United States. Part I. Introduction and Regional Analysis of the Mississippian System* (edited by Craig, L. C. & Connor, C. W.). *Prof. Pap. U.S. geol. Surv.* **1010-C**, 13–48.

Engelder, T. & Engelder, R. 1977. Fossil distortion and décollement tectonics of the Appalachian Plateau. *Geology* **5**, 457–460.

Groshong, R. H., Jr. 1975a. "Slip" cleavage caused by pressure solution in a buckle fold. *Geology*, **3**, 411–413.

Groshong, R. H., Jr. 1975b. Strain, fractures, and pressure solution in natural single-layer folds. *Bull. geol. Soc. Am.* **86**, 1363–1376.

Hobbs, B. E., Means, W. D. & Williams, P. F. 1976. *An Outline of Structural Geology*. Wiley, New York.

Illies, H. 1975. Intraplate tectonics in stable Europe as related to plate tectonics in the Alpine system. *Geol. Rdsch.* **64**, 677–699.

Illies, H. & Greiner, G. 1978. Rhinegraben and the Alpine system. *Bull. geol. Soc. Am.* **89**, 770–782.

Illies, H. & Greiner, G. 1979. Holocene movements and the state of stress in the Rhinegraben rift system. *Tectonophysics* **52**, 349–359.

Marshak, S. & Engelder, T. 1985. Development of cleavage in limestones of a fold-thrust belt in eastern New York. *J. Struct. Geol.* **7**, 345–359.

Merino, E. 1984. Survey of geochemical self-patterning phenomena. In: *Chemical Instabilities* (edited by Nicolis, G. & Baras, F.). D. Reidel Publishing Co., Dordrecht, 305–328.

Merino, E. 1992. Self-organization in stylolites. *Am. Scient.* **80**, 466–473.

Merino, E., Ortoleva, P. & Strickholm, P. 1983. Generation of evenly-spaced pressure-solution seams during (late) diagenesis. *Contr. Miner. Petrol.* **82**, 360–370.

Moore, J. L. & Briggs, G. 1979. Geologic Map of the Monteagle Quadrangle, Tennessee (Map GM 94-NE; 1:24,000). Tennessee Department of Conservation, Nashville.

Ortoleva, P. 1987. Modeling geochemical self organization. In: *Irreversible Phenomena and Dynamical Systems Analysis in Geosciences* (edited by Nicolis, C. & Nicolis, G.). D. Reidel Publishing Co., Dordrecht, 493–510.

Ortoleva, P. 1994. *Geochemical Self-Organization*. Oxford University Press, New York.

Ortoleva, P., Merino, E., Moore, G. & Chadam, J. 1987. Geochemical self-organization I: reaction-transport feedbacks and modeling approach. *Am. J. Sci.* **287**, 979–1007.

Ortoleva, P., Dewers, T. & Sauer, B. 1993. Modeling diagenetic bedding, stylolites, concretions, and other mechanochemical structures. In: *Carbonate Microfabrics* (edited by Rezak, R. & Lavoie, D. L.). Springer-Verlag, New York, 291–300.

Schultz, A., Baker, G. S. & Harrison, R. W. 1992. Deformation associated with the St. Genevieve fault zone and mid-continent tectonism. *Geol. Soc. Am. Abs. w. Prog.* **24**, A181.

Swingle, G. D., Miller, R. A., Luther, E. T., Hardeman, W. D., Fullerton, D. S., Sykes, C. R. & Garman, R. K. 1966. Geologic Map of Tennessee (1:250,000). Tennessee Department of Conservation, Nashville.

Woodward, N. B., ed. 1985. Valley and Ridge Thrust Belt: balanced structural sections, Pennsylvania to Alabama. *Univ. Tennessee Studies in Geol.* **12**.