Late Paleozoic deformation of the cratonic carbonate cover of eastern North America

John P. Craddock, Ben A. van der Pluijm*
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109

ABSTRACT

Paleozoic carbonates that cover the eastern half of the North American craton preserved a bedding-parallel shortening fabric up to 800 km away from the Appalachian-Ouachita orogenic front as recorded by mechanical twins in calcite. A strain fabric is present in 29 of 31 samples from three traverses within the flat-lying cratonic cover sequence: Jasper, Arkansas, to Minneapolis, Minnesota; Bluefield, West Virginia, to Madison, Wisconsin; and Albany, New York, to Hamilton, Ontario. Twinning is found only in Paleozoic carbonates and is absent in Cretaceous limestones. In the two southernmost traverses, the orientation of the principal shortening axis (e1) is perpendicular to the thrust front and parallel to the thrusting direction of the southern Appalachians and the Ouachitas. The magnitude of calcite shortening strain (<6%) and the calculated differential stress (<90 MPa) decrease exponentially away from the orogenic front until twinning is absent. The northernmost traverse shows greater complexity, probably because of its location in the bend of the Appalachian trend. We conclude that the regional strain fabric preserved in the cratonic cover sequence of eastern North America was produced by late Paleozoic orogenic stresses of the Appalachian-Ouachita orogeny, and that compressive stresses were transmitted over distances greater than 1200 km away from the active plate margin.

INTRODUCTION

Elliott (1976) and Chapple (1978) placed the development of fold-and-thrust belts in a mechanical context, and subsequent efforts have further improved our understanding of the formation of orogenic wedges above a regional detachment horizon (e.g., Davis et al., 1983; Platt, 1986). However, the nature and extent of deformation in the foreland of the evolving thrust wedge is poorly understood. In this paper we document subhorizontal shortening fabrics in Paleozoic platformal carbonates of eastern North America as preserved by calcite twin lamellae, which were produced in response to orogenic events in the Appalachians and Ouachitas.

The eastern part of the North American craton is bordered on the east and south by the Paleozoic Appalachian and Ouachita orogenic belts (Fig. 1). The crystalline basement of the craton is overlain by a thin veneer of mainly lower and middle Paleozoic sedimentary rocks. Rodgers (1963), Gwinn (1964), and Wiltschko and Chapple (1977) documented thrust detachments and folds within the foreland of the central Appalachians. Studies of carbonates from the northern Appalachian Plateau showed subhorizontal shortening strains (up to 15%) preserved by deformed fossils, mechanically twinned calcite, and joint/cleavage fabrics (e.g., Nickelsen, 1966; Engelder and Engelder, 1977; Engelder and Geiser, 1980; Geiser and Engelder, 1983). It was concluded that the rock strains are related to events in the Appalachian orogen, and subsequent workers have further emphasized foreland intraplate deformation (e.g., Bosworth, 1984). This would suggest that foreland sediments are deformed in a manner similar to sediments within the evolving thrust belt, and the following questions must be addressed: (1) What are the relative magnitude and orientation of stress and strain in the foreland relative to those in the orogenic belt, and how do they vary in space? (2) What is the lateral extent of crustal deformation at an active plate margin? We present strain data from three sections across eastern North America and evaluate possible mechanisms by which these strain fabrics may have originated; these data are discussed in view of the above questions.

CALCITE STRAINS

Three traverses were made in cratonic eastern North America to collect oriented carbonate samples (see Fig. 1 for distribution). Two traverses (A-A′ and B-B′) are perpendicular to the orogenic fronts of the Ouachitas and the southern Appalachians, respectively, and one east-west traverse was made in New York State.

Twenty-seven samples were collected and strains were analyzed using Groshong's strain guage technique for mechanical twins in calcite (Groshong, 1972; Groshong et al., 1984). Twinning in calcite requires a resolved shear stress of about 10 MPa and can occur on three glide planes, and at very low metamorphic grades this crystal plastic deformation mechanism is independent of temperature and normal stress (Wenk et al., 1983). It has been shown from experiments and empirically that the orientation of the maximum shortening axis (e1) from the calcite strain guage technique is accurate to within ~6° when the number of grains that are oriented unfavorably for twinning (negative expected values: NEV) is low (Groshong et al., 1984).

Twenty-three samples recorded a layer-parallel shortening fabric; two micritic samples had no twins, and dolomite twins were present in two other samples (Table 1). In our analysis we have also included calcite strain data from New York (Engelder, 1979a, 1979b), Oklahoma (Gasteiger, 1980), and the frontal Pine Mountain thrust block of the southern Appalachians in Tennessee (Wiltschko et al., 1985; Kilsdonk and Wiltschko, 1988).

We have listed 51 cratonic calcite strain analyses (Fig. 1 and Table 1), of which 49 gave layer-parallel shortening strains that are parallel to the thrust transport direction in either the Appalachians or the Ouachitas. The samples generally show low NEV percentages and low nominal errors, which is indicative of a coaxial strain history (Table 1). All the data are marked by low e1 strain magnitudes (<6%). Only samples 9 and 10 recorded a layer-parallel shortening event that was oriented oblique to the thrust transport direction.

As we approached the orogenic front in traverses A-A′ and B-B′, we observed an exponential increase in strain magnitude of 3% to 4% (Fig. 2). Differential stress magnitudes calculated by using the method of Jamison and Spang (1976) suggest values up to about 90 MPa near the orogenic front which decrease to <10 MPa at about 800 km into the cratonic cover (Fig. 2). The traverse in New York State shows a more complex variation in strain and higher NEV percentages. This traverse is approximately parallel to the orogenic front of the central Appalachians, but perpendicular to that of the northern Appalachians. Consequently, the finite strain data reflect a combination of two approximately orthogonal shortening directions, and thus the finite shortening value is relatively low (Table 1). Because of this complexity we concentrate here on traverses A-A′ and B-B′; the New York State data are further discussed in Jackson et al. (1988).

When we compare the twinning fabrics of A-A′ and B-B′ with data from detailed studies near the front of the southern Appalachians (samples 16 and 17; Wiltschko et al., 1985; Kilsdonk and Wiltschko, 1988), we find that the cratonic strain fabrics are smaller in e1 magnitude but indis-

*Corresponding author.

tinguishable in orientation from country-rock samples in the orogenic belt (Figs. 1b and 2). The orientation of e1 from samples within the orogenic belt also lies in the bedding plane and is parallel to the thrusting direction.

CAUSES FOR REGIONAL STRAIN

Calcite twinning is a crystal plastic deformation mechanism that is activated at low stress levels; therefore, one must consider ancient as well as recent causes that could have been responsible for producing the strain fabrics.

The relatively recent (Mesozoic to present) causes are (1) sample preparation, (2) roadcut blasting, (3) Pleistocene glacial overburden, (4) contemporaneous stresses, and (5) Mesozoic opening of the Atlantic Ocean. The near-uniform e1 shortening orientation, independent of outcrop and specimen orientation, makes causes 1 and 2 unlikely explanations. The maximum extent of glaciation in North America (cause 3) is shown in Figure 1, and the observed pattern clearly does not correlate with the region covered by the ice. The present-day orientation of the principal stress direction of eastern North America is approximately east-northeast

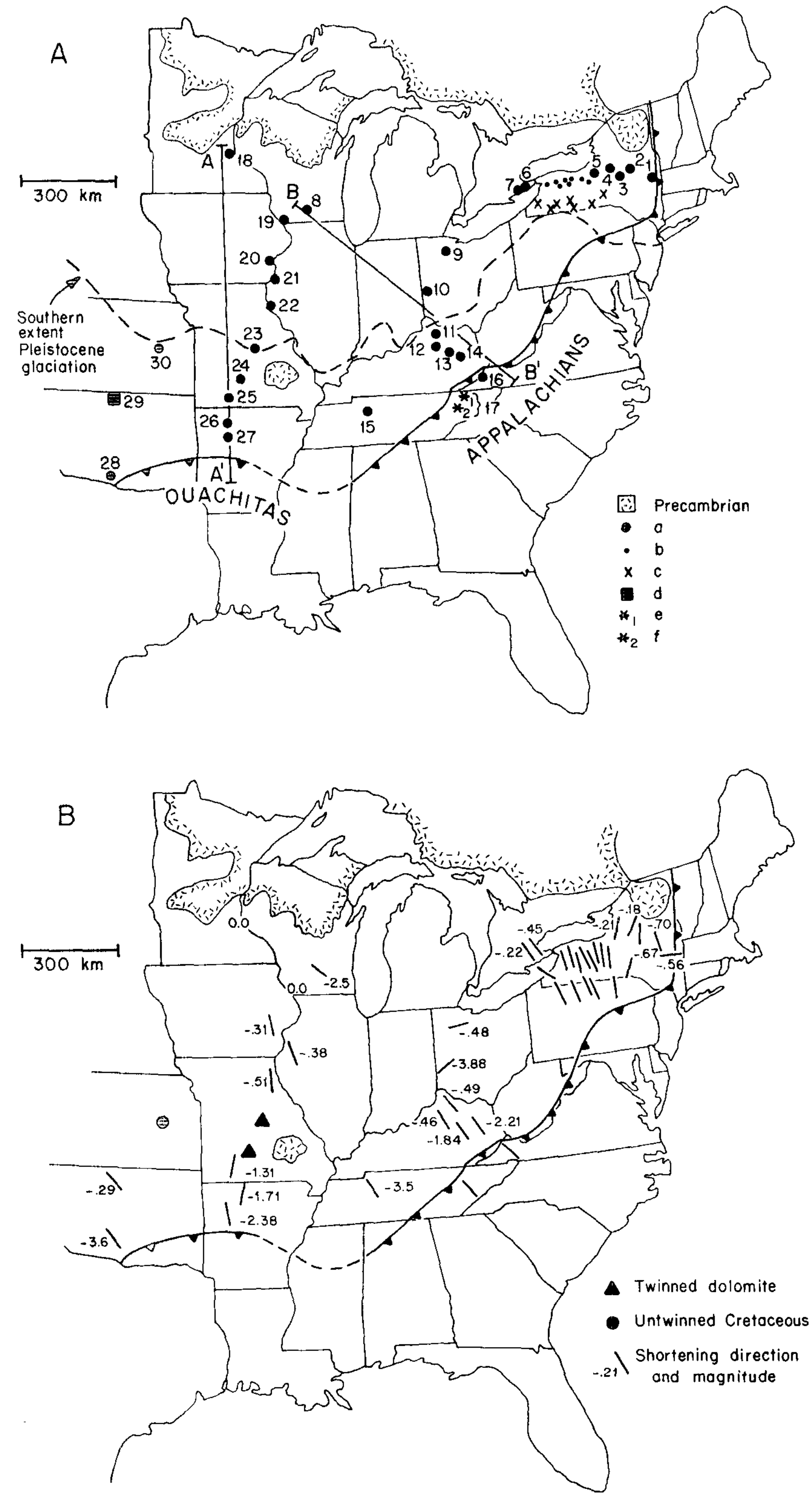

Figure 1. A: Site locations of carbonate samples from eastern North America; a—this study, b—Engelder (1979a), c—Engelder (1979b), d—Gasteiger (1980), e—Wiltschko et al. (1985), f—Kilsdonk and Wiltschko (1988). Data are listed in Table 1; sites from Engelder (1979a, 1979b) are not numbered. B: Orientation and magnitude of shortening strain (e1) for each site (see Table 1). All shortening axes are subparallel to bedding.

(e.g., Zoback and Zoback, 1980), which is almost everywhere at a high angle to the trend of e1, as determined from the twinning fabrics (except sites 1, 9, and 10). The pattern of e1 orientations is also in disagreement with that expected for Mesozoic opening of the Atlantic Ocean. Thus, we also reject causes 4 and 5 for the deformation of the cratonic carbonate cover (see also Engelder, 1982). The rejection of Mesozoic and younger causes is further supported by the absence of twinned calcite in two Mesozoic carbonate samples we examined (site 30).

Paleozoic events, on the other hand, can explain the twinning patterns. Three characteristics of the fabrics that are preserved in the carbonates are especially important. Foremost, the orientation of e1 along our traverses A-A′ and B-B′ is (1) constant, (2) consistently perpendicular to the orogenic front, and (3) parallel to the thrusting direction in the Ouachitas or the southern Appalachians. Second, we observe an exponential decrease in stress and strain magnitude away from the orogenic front. Third, twinning is present only in carbonates that range in age from Ordovician to Carboniferous. These characteristics indicate that the calcite twinning fabrics are related to events in the Appalachian-Ouachita orogen and, in particular, that they are associated with widespread late Paleozoic thrusting in these belts. In order to determine the actual cause of the fabrics, one has to separate the role of stresses associated with thrust formation—*collisional stresses*—from stresses that arise from lithospheric flexure due to loading of the craton—*flexural stresses*. These two mechanisms are discussed separately below.

TABLE 1. CALCITE TWINNING DATA

Sample	Age	NEV (%)	Error (%)	e1 (%)	e1 trend (°)
1	D	12	0.23	-0.56	085
2	D	0	0.27	-0.70	167
3	D	0	0.07	-0.67	001
4	D	5	0.17	-0.18	030
5	D	0	0.04	-0.16	038
6	D	12	0.33	-0.45	160
7	D	10	0.21	-0.22	160
SYR[1]	S,D	32	0.42	-2.16	172
OAK[1]	S,D	25	0.57	-1.35	170
HON[1]	S,D	40	1.81	-5.34	028
LRY[1]	S,D	43	0.24	-0.66	143
AVN[1]	S,D	45	0.06	-0.22	147
STA[1]	S,D	37	0.08	-0.59	169
LAN[1]	S,D	20	0.04	-0.18	004
EVS[1]	S,D	29	0.05	-0.11	013
TRI[2]	S,D	9	0.35	-1.27	017
SMB[2]	S,D	6	0.26	-1.58	176
ADI[2]	S,D	47	1.41	-5.32	167
CAM[2]	S,D	34	2.62	-7.37	168
AND[2]	S,D	20	1.37	-5.88	152
VAN1[2]	S,D	23	0.62	-1.32	134
RAW[2]	S,D	40	0.76	-1.63	140
8	O	10	0.10	-2.52	152
9	D	0	0.06	-0.48	152
10	O	0	0.09	-3.88	167
11	D	12	0.19	-0.46	166
12	D	6	0.20	-0.49	162
13	M	6	0.06	-1.84	149
14	M	0	0.09	-2.21	152
15	M	21	0.75	-3.51	161
16[3]	M	14	0.98	-3.80	150
17[4]	C to P	7	1.21	-3 to -5	140-170
18/19	O	No calcite/dolomite twins			
20	M	3	0.07	-0.31	170
21	M	6	0.11	-0.38	163
22	M	12	0.09	-0.51	172
23/24	O/M	Dolomite twins			
25	M	8	0.07	-1.31	003
26	M	6	0.03	-1.71	009
27	M	0	0.08	-2.38	172
28	M	13	0.61	-3.60	158
29[5]	P	23	0.06	-0.29	117
30	K	No calcite twins			

Note: C-Cambrian, O-Ordovician, S-Silurian, D-Devonian, M-Mississippian, P-Pennsylvanian, K-Cretaceous. NEV = negative expected value. Error = nominal error: 1/2(SE(X) + SE(Y)) x 100 (Groshong et al., 1984); e1 = principal shortening axis.
[1] Engelder, 1979a; all samples Silurian or Devonian.
[2] Engelder, 1979b; all samples Silurian or Devonian.
[3] Thrust belt sample.
[4] 25 samples (Wiltschko et al., 1985, Kilsdonk and Wiltschko, 1988).
[5] 9 samples (Gasteiger, 1980).

Collisional Stresses and Extent of Foreland Deformation

The calcite strain data show that deformation in the Appalachian and Ouachita orogenic belts correlates in orientation and magnitude with strain fabrics in the foreland. If we measure the length of sections A-A′ and B-B′, we obtain an extent of twinning deformation perpendicular to the orogenic front of about 800 km (Fig. 2). Combined with an average shortening of at least 40% to 60% in these orogenic belts (e.g., Woodward, 1987; Hatcher, 1989), these data indicate that regional stresses were recorded >1200 km away from the convergent plate boundary.

The question of whether it is possible to transmit orogenic compressive stresses through a laterally extensive wedge is answered by modern tectonic settings, but also by mathematical modeling of continental deformation. The impingement of India on the Eurasian continent, which produced the Himalayas and the Tibetan Plateau, sustains a stress field that extends more than 1000 km into eastern Asia (e.g., Tapponnier et al., 1986). The tectonic history of this area seems comparable to events at the late Paleozoic Appalachian margin of cratonic North America, where final collision with Africa followed earlier accretion to North America of several other continental elements (e.g., Hatcher, 1987; van der Pluijm and van Staal, 1988); however, we do not wish to imply similar crustal thickening for the Appalachians. England et al. (1985) used a thin viscous sheet

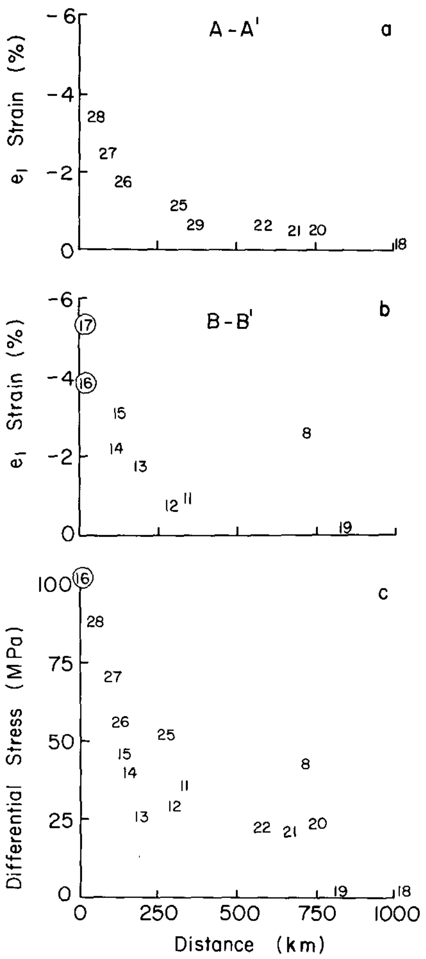

Figure 2. a, b: Maximum shortening strain (e1) magnitude vs. distance from orogenic front along traverses A-A′ and B-B′, respectively. c: Differential stress magnitude vs. distance from orogenic front. Numbers indicate sample locations in Figure 1A; circled numbers are sites within orogenic belt.

and power law rheology to model continental deformation. They showed that the deformation decays exponentially away from the active plate boundary and that the dimension of the continental area with significant deformation perpendicular to the margin is comparable to the dimension of the compressive margin. These geologic and mathematical results compare well with our data on the extent of the deformed area (Fig. 1) as well as the distinct variation in magnitudes of stress and strain in eastern North America (Fig. 2).

Flexural Stresses

Beaumont et al. (1988) have modeled deformation of lithospheric eastern North America in response to loading of the Appalachian-Ouachita margin. In their models, Beaumont and coworkers considered the effect of lithospheric loading to be relatively insignificant in regions that are removed more than several hundred kilometres from the orogenic front (e.g., the Michigan and Illinois basins). Furthermore, at upper crustal levels one expects to find a change from tension (bulge) to compression (basin) as one approaches the orogenic front. Our strain patterns continue well into the craton (>800 km) and, with only two exceptions, show compression perpendicular to the orogenic front (Fig. 2). Thus, loading and plate flexure are an unlikely cause for the observed calcite twinning fabrics.

CONCLUSIONS

Bedding-parallel, subhorizontal shortening fabrics in carbonates that cover the eastern part of cratonic North America are perpendicular to the orogenic fronts of the Appalachians and the Ouachitas and extend up to 800 km into the foreland. The magnitudes of stress and strain show a distinct exponential decrease away from the orogenic fronts. These calcite twinning fabrics were caused by late Paleozoic orogenic stresses that were transmitted more than 1200 km away from the active plate margin.

REFERENCES CITED

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

Bosworth, W., 1984, Foreland deformation in the Appalachian plateau, central New York: The role of small-scale detachment structures in regional overthrusting: Journal of Structural Geology, v. 6, p. 73–81.

Chapple, W.M., 1978, Mechanics of thin-skinned fold-and-thrust belts: Geological Society of America Bulletin, v. 89, p. 1189–1198.

Davis, D., Suppe, J., and Dahlen, F.A., 1983, Mechanics of fold-and-thrust belts and accretionary wedges: Journal of Geophysical Research, v. 88, p. 1153–1172.

Elliott, D.W., 1976, The motion of thrust sheets: Journal of Geophysical Research, v. 81, p. 949–963.

Engelder, T., 1979a, The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York State: Tectonophysics, v. 55, p. 289–310.

—— 1979b, Mechanisms of strain within the Upper Devonian clastic sequence of the Appalachian Plateau, western New York: American Journal of Science, v. 279, p. 527–542.

—— 1982, Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America?: Tectonics, v. 1, p. 161–177.

Engelder, T., and Engelder, R., 1977, Fossil distortion and decollement tectonics of the Appalachian Plateau: Geology, v. 5, p. 457–460.

Engelder, T., and Geiser, P., 1980, On the use of regional joint sets as trajectories of paleostress fields during the development of the Appalachian Plateau, New York: Journal of Geophysical Research, v. 85, p. 6319–6341.

England, P., Houseman, G., and Sonder, L., 1985, Length scales for continental deformation in convergent, divergent and strike-slip environments: Analytical and approximate solutions for a thin viscous sheet model: Journal of Geophysical Research, v. 90, p. 3551–3557.

Gasteiger, C.M., 1980, Strain analysis of a low amplitude fold in north-central Oklahoma using calcite twin lamellae [M.S. thesis]: Norman, University of Oklahoma, 90 p.

Geiser, P., and Engelder, T., 1983, The distribution of layer-parallel shortening fabrics in the Appalachian foreland of New York and Pennsylvania: Evidence for two non-coaxial phases of the Alleghanian orogeny, *in* Hatcher, R.D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 161–176.

Groshong, R.H., Jr., 1972, Strain calculated from twinning in calcite: Geological Society of America Bulletin, v. 83, p. 2025–2038.

Groshong, R.H., Jr., Teufel, L.W., and Gasteiger, C.M., 1984, Precision and accuracy of the calcite strain-gage technique: Geological Society of America Bulletin, v. 95, p. 357–363.

Gwinn, V.E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the central Appalachians: Geological Society of America Bulletin, v. 75, p. 863–899.

Hatcher, R.D., Jr., 1987, Tectonics of the southern and central Appalachian internides: Annual Reviews of Earth and Planetary Sciences, v. 15, p. 337–362.

—— 1989, Tectonic synthesis of the U.S. Appalachians, *in* Hatcher, R.D., Jr., Veely, G.W., and Thomas, W.A., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2 (in press).

Jackson, M., Craddock, J.P., Ballard, M., Van der Voo, R., and McCabe, C., 1988, Anhysteretic remanent magnetic anisotrophy and calcite strains in Devonian carbonates from the Appalachian Plateau, New York: Tectonophysics.

Jamison, W.R., and Spang, J.H., 1976, Use of calcite twin lamellae to infer differential stress: Geological Society of America Bulletin, v. 87, p. 868–872.

Kilsdonk, W., and Wiltschko, D.V., 1988, Deformation mechanisms in the southeastern ramp region of the Pine Mountain block, Tennessee: Geological Society of America Bulletin, v. 100, p. 653–664.

Nickelsen, R.P., 1966, Fossil distortion and penetrative rock deformation in the Appalachian Plateau: Journal of Geology, v. 74, p. 924–931.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037–1053.

Rodgers, J., 1963, Mechanics of Appalachian foreland folding in Pennsylvania and West Virginia: American Association of Petroleum Geologists Bulletin, v. 47, p. 1527–1536.

Tapponnier, P., Peltzer, G., and Armijo, R., 1986, On the mechanics of the collision between India and Asia, *in* Coward, M.P., and Ries, A.C., eds., Collision tectonics: Geological Society of London Special Publication 19, p. 115–157.

van der Pluijm, B.A., and van Staal, C.R., 1988, Characteristics and evolution of the Central Mobile Belt, Canadian Appalachians: Journal of Geology, v. 96, p. 535–547.

Wenk, H.-R., Barber, D.J., and Reeder, R.J., 1983, Microstructures in carbonates, *in* Reeder, R.J., ed., Carbonates: Mineralogy and chemistry: Mineralogical Society of America Reviews in Mineralogy, v. 11, p. 301–367.

Wiltschko, D.V., and Chapple, W.M., 1977, Flow of weak rocks in Appalachian Plateau folds: American Association of Petroleum Geologists Bulletin, v. 65, p. 653–670.

Wiltschko, D.V., Medwedeff, D.A., and Millson, H.E., 1985, Distribution and mechanisms of strain within rocks on the northwest ramp of Pine Mountain block, southern Appalachian foreland: A field test of theory: Geological Society of America Bulletin, v. 96, p. 426–435.

Woodward, N.B., 1987, Geological applicability of critical-wedge thrust-belt models: Geological Society of America Bulletin, v. 99, p. 827–832.

Zoback, M.L., and Zoback, M., 1980, State of stress in the conterminous United States: Journal of Geophysical Research, v. 85, p. 6113–6156.

ACKNOWLEDGMENTS

Supported by the Scott Turner Fund of The University of Michigan and the donors of the Petroleum Research Fund, administered by the American Chemical Society (Grant 20755). Field assistance was provided by J. Cooper, D. Cooper, D. Scharff, C. Inman, C. Craddock, D. Craddock, and P. Craddock. C. McCabe and M. Ballard provided us with oriented samples from New York, and B. Wilkinson made his cratonic thin-section collection available. We thank our colleagues at The University of Michigan for discussions, P. Howell for comments on an early version of the paper, and M. Brandon and an anonymous referee for helpful reviews.

Manuscript received August 31, 1988
Revised manuscript received December 15, 1988
Manuscript accepted January 18, 1989

Reviewer's comment

This paper presents some very provocative data showing that orogenic deformation extends far beyond the Appalachian mountain belt itself.

Mark Brandon
