New model for evolution of fold and thrust belt curvature based on integrated structural and paleomagnetic results from the Pennsylvania salient

Mary Beth Gray
Department of Geology, Bucknell University, Lewisburg, Pennsylvania 17837
John Stamatakos
Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute, San Antonio, Texas 78228-0510

ABSTRACT

In a number of curved fold and thrust belts worldwide, such as the Cantabrian arc and the Wyoming-Idaho salient, paleomagnetic data indicate vertical axis rotations inconsistent with structural findings. This apparent conflict is especially pronounced in the Pennsylvania salient, where the paleomagnetically defined vertical axis rotations are opposite of the rotation sense indicated by structural studies. We resolve this apparent disparity by developing an integrated and kinematically admissible model that has implications for other curved mountain belts. The curvature of the Pennsylvania salient may be explained by deformation partitioning in an initially laterally tapered basin between the Cambrian-Ordovician carbonates and the overlying siliciclastic rocks. Earliest deformation occurred in the lowest strata and progressed toward the foreland and up section with time. Lateral differences in initial layer-parallel shortening in the Cambrian-Ordovician carbonates caused differential translation and rotations about a vertical axis in the cover sequence. Because of initial basin geometry, the orogenic wedge developed a lateral taper. With further shortening in the wedge and involvement of the cover rocks in the fold and thrust deformation, gravitational driving forces became more important, and the paleostress trajectories diverged in opposite directions on the two arms of the salient in response to the lateral taper.

INTRODUCTION

Structural and paleomagnetic studies in curved fold and thrust belts often produce divergent interpretations of the nature and timing of thrust belt curvature. Notable examples include the Cantabrian arc in northwestern Spain (Van der Voo et al., 1997; Alvarez-Marrón, 1995), the Wyoming-Idaho salient in the western Cordillera (Grubbs and Van der Voo, 1976; Beutner, 1977), and the Pennsylvania salient in the central Appalachians (Kent, 1988; Geiser and Engelder, 1983). In particular, paleomagnetic data from Pennsylvania and Wyoming appear to document substantial vertical axis rotations associated with bending of an originally more linear fold and thrust belt. In contrast, structural data from these same areas indicate that curvature is primarily due to differential translation between and within thrust sheets.

In this paper we develop a kinematically admissible model for the development of the Pennsylvania salient within the tight constraints of structural and paleomagnetic results and in light of the theoretical constraints and the tectonic framework established by the aforementioned studies. Discussion of the evolution of the salient is primarily restricted to the evidence gathered from the deformed Appalachian foreland basin. We limit our discussion in this way because nearly all the prior structural and paleomagnetic data were conducted within the Valley and Ridge and Plateau Provinces, and most, if not all, of the deformation is the result of late Paleozoic (Alleghanian) tectonism (Faill, 1985).

GEOLOGIC SETTING

Paleozoic rocks within the central Appalachians consist of a nearly continuous section of miogeoclinal carbonate and clastic sedimentary rocks deposited on a rifted margin of Grenville-age metamorphic basement (Thomas, 1977). Alleghanian deformation in the foreland basin created a two-tier thrust system composed of a lower thrust sheet of Cambrian-Ordovician carbonates and flysch and an upper thrust sheet of Silurian through Pennsylvanian siliciclastics (Herman, 1982). The lower sheet primarily shortened by displacements on map-scale thrust faults that sole into the regional basal Cambrian décollement and tie into a roof thrust in the Middle to Upper Ordovician flysch deposits (Perry, 1978). The upper sheet was internally shortened by small-scale faulting, high-order folding, and grain-scale deformation. Internal faulting in the lower sheet has created passive, low-order folds in the upper sheet and both sheets are transected by late-breaking thrust faults that sole into the basal Cambrian décollement (Nickelsen, 1996). The Pennsylvania salient of the Valley and Ridge is composed of three roughly linear segments of different trend, here recognized as the southern (020°–025°), central (055°–060°), and northern segments (065°–085°) (Fig. 1). The Juniata Culmination in the central segment reflects differences in map scale shortening in the salient. Rocks have been shortened ~30% to 38% in the south (Kulander and Dean, 1986; Hatcher et al, 1989) and ~38% to 39% in the north (Gray, 1991; Hatcher et al., 1989), and the central salient has been shortened 46% (Herman, 1982; Hatcher et al., 1989).

Structural Data

Nickelsen (1979) defined a sequence of deformation in the upper sheet that can be simplified into three main stages: (1) layer-parallel shortening, (2) folding, and (3) later fold modification. Each segment of the salient underwent additional stages of progressive deformation that are unique; however, Nickelsen's sequence is common to all segments of the salient. Regional shortening directions record as much as 30° clockwise rotation in the northern segment (Nickelsen, 1979; Geiser and Engelder, 1983; Gray and Mitra, 1993) and a similar rotation sense in the New York Appalachian Plateau (Geiser and Engelder, 1983; Zhou and Jacobi, 1997; Younes and Engelder, 1997). The opposite rotation sense is observed in the southern segment. Nickelsen (1988, 1996) demonstrated a temporal 15° to 45° counterclockwise rotation in regional shortening directions. This sense of rotation is also observed farther to the south, in western Maryland (Markley and Wojtal, 1996; Evans, 1994). Maximum shorten-

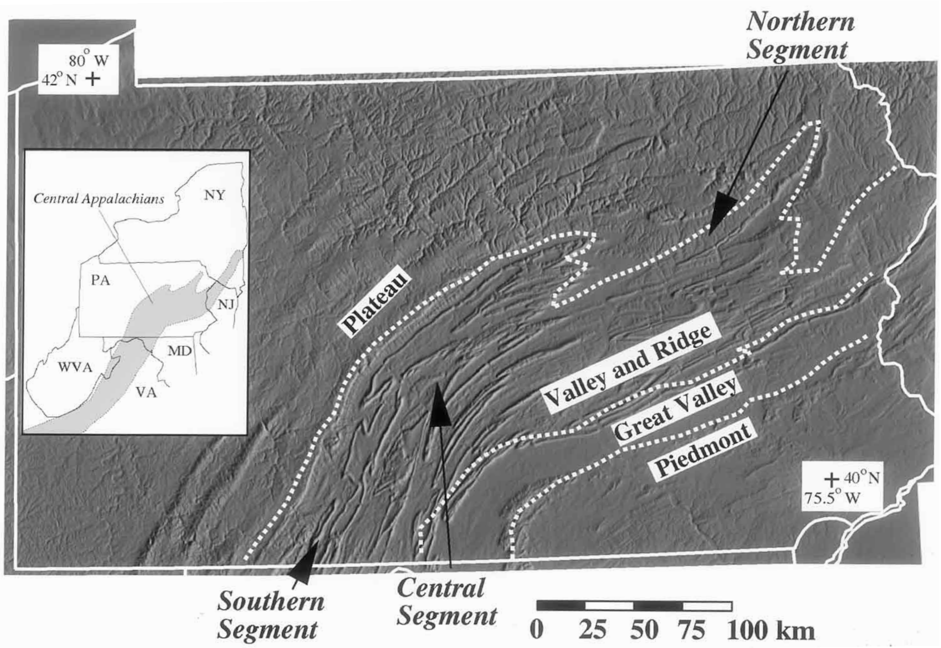

Figure 1. Digital elevation model (based on U.S. Geological Survey Digital elevation data) illustrates curvature and geologic context of Pennsylvania salient. NY—New York, PA—Pennsylvania, NJ—New Jersey, WVA—West Virginia, MD—Maryland, VA—Virginia.

ing directions in the Juniata Culmination apparently remain constant (Spiker and Gray, 1997).

The regional shortening directions on both limbs of the salient were initially subparallel and trended ~320°–340° (Fig. 2A). After the initial onset of layer-parallel shortening, the shortening directions began to diverge. The final stages of deformation exhibit maximum shortening directions of 280°–290° in the southern segment (Nickelsen, 1988, 1996) and 010° in the northern segment (Gray and Mitra, 1993).

Paleomagnetic Data

Paleomagnetic results summarized in Stamatakos and Hirt (1994) and Stamatakos et al. (1996) reveal the following spatial and temporal relationships: (1) All folding in the salient occurred in the Permian with no evidence for multiple discrete phases (Mississippian Lackawanna phase and Permian Main phase) of Alleghanian deformation as proposed by Geiser and Engelder (1983). (2) The temporal progression of thrusting and folding is toward the foreland (normal sequence), as indicated by structural data (Gray and Mitra, 1993) and individual fold-test results. (3) Either prior to or during the earliest stages of Alleghanian deformation, rocks within the salient were rotated about a vertical axis between 20° and 30° (Fig. 3). It remains unclear whether all of the rotation took place on one limb of the salient or whether the rotations were evenly distributed on the limbs of the salient. If both limbs of the salient rotated to achieve the overall 30° tightening of the salient, each limb must have rotated 15° in opposite directions during the earliest phase of the Alleghanian orogeny. (4) Since the onset of folding and thrusting, vertical axis rotations around the salient have been negligible (Fig. 3). Thus, the curved trends of thrusts and folds are an original feature of shortening and did not result from oroclinal bending of an originally more linear fold and thrust belt despite evidence for early vertical axis rotations. This conclusion is further supported by the shortening directions that rotated in an opposite sense to those predicted for an orocline (Fig. 2B) (cf. fig. 13, Zhou and Jacobi, 1997) and precludes tectonic models for the Alleghanian orogeny that explain the curvature of the orogen solely in terms of impact by rigid indentors on the opposing African margin (e.g., Faure et al., 1996).

BOUNDARY CONDITIONS

An admissible model for the evolution of the Pennsylvania salient must take into account several inherited architectural features. The cover rocks stratigraphically thin laterally away from the center of the salient (Wagner, 1966; Colton, 1970). The basement-cover contact, along which the sole thrust of the fold and thrust belt approximately resides, was initially concave to the southeast (e.g., Thomas, 1977). Deformation was continuous during a single phase of Alleghanian deformation in the Permian. The model must also reconcile apparently conflicting paleomagnetic and structural data. The present orientation of the characteristic magnetizations in these rocks requires as much as 30° of vertical-axis rotation of the limbs of the salient prior to recorded deformation in these areas, with negligible vertical-axis rotations since the onset of folding and thrusting. Maximum shortening directions (related to paleostress trajectories) rotated 30° clockwise in the northern salient and as much as 40° counterclockwise in the southern salient as Alleghanian deformation progressed.

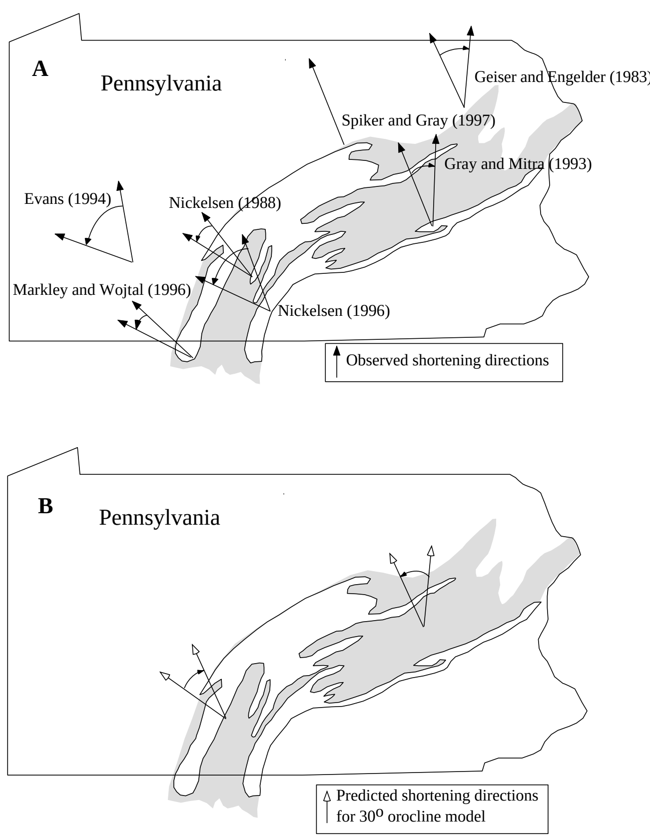

Figure 2. A: Sketch map of Pennsylvania salient in Valley and Ridge, with arrows showing orientations of Alleghanian shortening directions with time as established by progressive deformation studies in region. B: Illustration of sequential shortening directions expected for orocline model for Pennsylvania salient. Earliest shortening direction would be subparallel on either end of originally linear mountain belt. As limbs of orocline rotated, earlier structures, recording early shortening directions, would also rotate clockwise on northern limb and counterclockwise on southern limb. New structures, superimposed on older, rotated structures, would record sequential counterclockwise relative rotation in shortening directions of northern limb and sequential clockwise rotation on southern limb. These relationships are opposite of those actually observed in Pennsylvania salient (A).

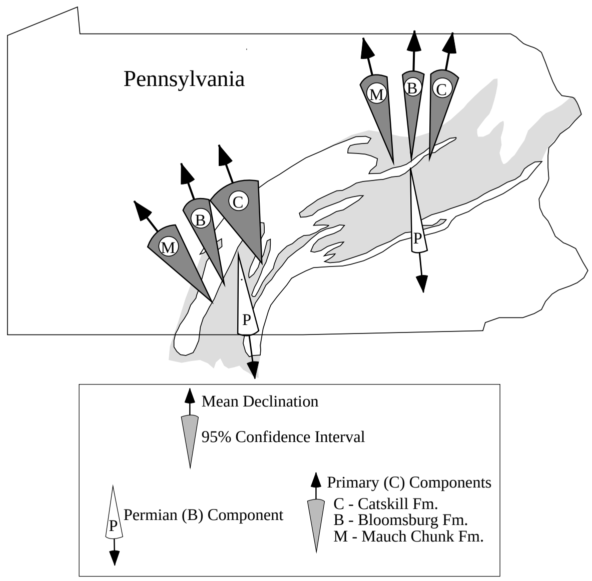

Figure 3. Distribution of characteristic and secondary magnetizations around salient. Data reflect 30° relative dispersion of characteristic directions around salient. Orientation of secondary magnetization is nearly uniform around salient. Secondary magnetization was acquired during Alleghanian deformation.

MODEL

The first increment of deformation in the central Appalachian foreland basin involved layer-parallel shortening by grain-scale deformation mechanisms (such as pressure solution and deformation twinning) as well as by the development of mesoscopic structures (such as small-scale conjugate contraction fault arrays and high-order folds) (Nickelsen, 1979, 1988; Gray and Mitra, 1993). The first increment of deformation, as established by analog models and field relations, occurs at the rear of the wedge and proceeds from hinterland to foreland. Deformation fronts, instantaneous boundaries that divide rocks that are undergoing different stages of deformation, are predicted to be instantaneously inclined toward the foreland in most cases, due to factors such as thermal structure, topography, and stress distributions within the wedge (e.g., Evans and Dunne, 1991; Gray, 1991). Thus, at a given instant in time, rocks near the surface have undergone typically less advanced stages of deformation than those directly beneath. As the orogen develops, deformation fronts are predicted and observed to migrate toward the foreland until they reach a terminal position within the belt.

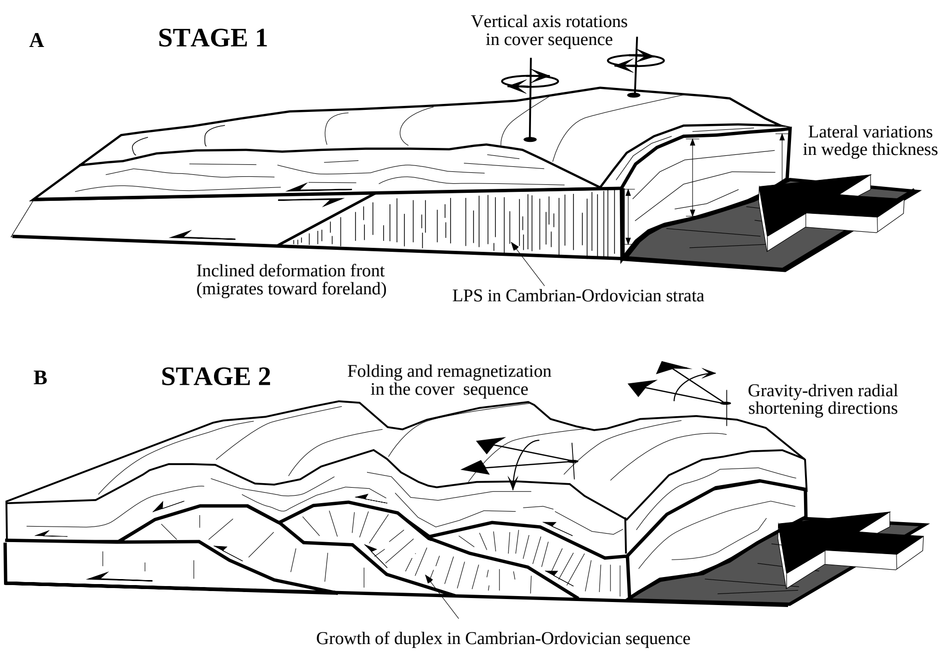

Figure 4. Kinematics of deformation in our model for the evolution of salient. A: Earliest phase of deformation in foreland composed of layer-parallel shortening (LPS) in lower sheet and detachment and simple, differential translation of upper sheet toward foreland. B: In advanced phases of deformation internal faulting in lower sheet increased taper in deformed, laterally tapering wedge, causing progressive radial dispersion of stress trajectories with time.

Our model uses the concept of inclined deformation fronts to explain the mechanism of vertical axis rotations in the upper sheet prior to recorded Alleghanian deformation in these rocks. During the earliest increment of deformation, an inclined deformation front marking the boundary between undeformed rocks and those undergoing layer-parallel shortening would permit layer-parallel shortening in the lower sheet while the upper sheet underwent no bulk-rock deformation (Fig. 4A). Rocks in the cover would undergo translation toward the foreland as layer-parallel shortening strains accumulated in the rocks below. If the initial sedimentary wedge exhibited no lateral variations in thickness, one could expect laterally constant layer-parallel shortening strains and commensurate uniform translations toward the foreland in the upper sheet. However, the starting condition of a laterally tapering wedge and concave basal detachment causes lateral variations in shortening of the wedge. Marshak and Wilkerson (1992) showed that the thickest portions of an initially laterally tapered sedimentary wedge produce the widest portions of the belt. Deformation of a laterally tapered wedge produces a curved thrust wedge from an initially linear basin geometry. In addition, thicker portions of the belt are expected to accumulate higher layer-parallel shortening strains with commensurate longitudinal strains (Ferrill and Groshong, 1993). This would help to explain the relatively large map scale shortening and width of the central segment.

The earliest increment of development of the salient involved initial layer-parallel shortening of the lower sheet, causing differential translations in the cover and subsequent rotations of the characteristic component on the limbs of the salient. Differential translation in the upper sheet could explain the rotations about a vertical axis that must have occurred prior to bulk rock deformation of the upper sheet. As the lower sheet in the center of the salient underwent more layer-parallel shortening than the limbs, a relative clockwise rotation in the northern segment and counterclockwise rotation in the southern segment would have occurred. The detailed mechanism of differential translation in the upper sheet remains unknown. Rotation of the characteristic component must have preceded layer-parallel shortening in the upper sheet because the secondary magnetization shows no evidence of rotation about a vertical axis and was, in some cases, synchronous with layer-parallel shortening (i.e., prefolding). There are no ubiquitous structures in the Valley and Ridge that we can attribute to differential foreland shear in the upper sheet prior to folding. Perhaps strain rates during the early orogeny permitted the upper sheet to undergo differential movement on prefolding strike-slip faults common throughout the salient (e.g., Nickelsen, 1996) or differential flow at the grain scale by difficult to detect mechanisms such as grain-boundary sliding.

As the layer-parallel shortening deformation front migrated toward the foreland, bulk-rock deformation of the cover sequence at the rear of the wedge commenced. The orientations of earliest layer-parallel shortening vary as little as 10° around the salient, perhaps indicating that the differential translations and rotations about a vertical axis that had already occurred in the upper sheet had only a minor effect on the curvature of the belt, and therefore the distribution of paleostress trajectories.

With increased convergence between Laurentia and Gondwana, the thrust wedge increased in size. Fold and thrust deformation fronts migrated through the wedge and as they did, the wedge thickened (Fig. 4B) to produce a three-dimensional, laterally tapering tectonic wedge. Gravitational forces overwhelm inertial forces at the scale of the wedge and therefore propagation of the wedge is largely controlled by factors such as topography and wedge thickness (Elliott, 1976; Chapple, 1978). Because gravity acts to drive thrusting in the direction of the surface slope, an evolving, laterally tapering tectonic wedge will generate radiating paleostress trajectories (Platt et al., 1989). With time, the curvature, lateral thickness gradient, and degree of radial dispersion of paleostress trajectories will increase. In the Pennsylvania salient, this is manifested by clockwise rotations of maximum shortening directions in the northern salient and counterclockwise rotations of paleostress trajectories in the southern salient as the thrust wedge increased in size.

CONCLUSIONS

We have developed a kinematically admissible model that takes into account the available paleomagnetic and structural data from the Pennsylvania salient. Lateral differences in the amount of layer-parallel shortening in the lower thrust sheet (due to preexisting basin geometry) produced vertical axis rotations in the upper thrust sheet. Imbrication of the lens-shaped lower sheet eventually led to the development of a three-dimensionally tapered wedge. Gravitational spreading of the tapered wedge generated progressively radiating paleostress trajectories (and concordant maximum shortening directions within the wedge) while it inhibited further vertical axis rock rotations. This model simultaneously explains the observed moderate vertical axis rotations of the primary magnetization component and the spatially uniform declination of syn-folding secondary magnetizations in the upper sheet, and the initially subparallel maximum shortening directions that temporally radiate through the salient. Deformation partitioning of the kind described in this paper may help explain the complex evolution of curvature in other fold and thrust belts that also do not fit a simple oroclinal model.

ACKNOWLEDGMENTS

We wish to thank D. Davis, M. Evans, D. Ferrill, and R. Nickelsen for providing helpful comments on the manuscript.

REFERENCES CITED

Alvarez-Marrón, J., 1995, Three-dimensional geometry and interference of fault-bend folds: Examples from the Ponga Unit, Variscan Belt, NW Spain: Journal of Structural Geology, v. 17, p. 549–560.

Beutner, E. C., 1977, Causes and consequences of curvature in the Sevier orogenic belt, Utah to Montana: Wyoming Geological Association 19th Annual Field Conference Guidebook, p. 353–365.

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

Colton, G. W., 1970, The Appalachian basin—Its depositional sequences and their geologic relationships, *in* Fisher, G. W., Pettijohn, F. J., Read, J. C., Jr., and Weaver, K. N., eds., Studies of Appalachian geology: Central and southern: New York, Wiley-Interscience, p. 5–47.

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

Evans, M. A., 1994, Joints and décollement zones in Middle Devonian shales: Evidence for multiple deformation events in the central Appalachian Plateau: Geological Society of America Bulletin, v. 106, p. 447–460.

Evans, M. A., and Dunne, W. M., 1991, Strain factorization and partitioning in the North Mountain thrust sheet, central Appalachians, U.S.A.: Journal of Structural Geology, v. 13, p. 21–35.

Faill, R. T., 1985, The Acadian orogeny and the Catskill delta, *in* Woodrow, D. L., and Sevon, W. D., eds., The Catskill Delta: Geological Society of America Special Paper 201, p. 15–37.

Faure, S., Tremblay, A., and Angelier, J., 1996, Alleghanian paleostress reconstruction in the northern Appalachians: Intraplate deformation between Laurentia and Gondwana: Geological Society of America Bulletin, v. 108, p. 1467–1480.

Ferrill, D. A., and Groshong, R. H., Jr., 1993, Kinematic model for the curvature of the northern Subalpine Chain, France: Journal of Structural Geology, v. 15, p. 523–541.

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: Geological Society of America Memoir 158, p. 161–175.

Gray, M. B., 1991, Progressive deformation and structural evolution of the Southern Anthracite region, Pennsylvania, [Ph.D. thesis]: Rochester, New York, University of Rochester, 277 p.

Gray, M. B., and Mitra, G., 1993, Migration of deformation fronts during progressive deformation: Evidence from detailed structural studies in the Pennsylvania Anthracite region, U.S.A.: Journal of Structural Geology, v. 15, p. 435–449.

Grubbs, K. L., and Van der Voo, R., 1976, Structural deformation of the Idaho-Wyoming overthrust belt (U.S.A.), as determined by Triassic paleomagnetism: Tectonophysics, v. 33, p. 312–336.

Hatcher, R. D., Jr., Thomas, W. A., Geiser, P. A., Snoke, A. W., Mosher, S., and Wiltschko, D. V., 1989, Alleghanian orogen, *in* Hatcher, R. D., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 233–319.

Herman, G., 1982, A structural analysis of a portion of the Valley and Ridge Province of Pennsylvania, [M.S. thesis]: Storrs, Connecticut, University of Connecticut, 107 p.

Kent, D. V., 1988, Further paleomagnetic evidence for oroclinal rotation in the central folded Appalachians from the Bloomsburg and the Mauch Chunk Formations: Tectonics, v. 7, p. 749–759.

Kulander, B. R., and Dean, S. L., 1986, Structure and tectonics of the central and southern Appalachian Valley and Ridge and Plateau provinces, West Virginia and Virginia: American Association of Petroleum Geologists Bulletin, v. 70, p. 1674–1684.

Markley, M., and Wojtal, S., 1996, Mesoscopic structure, strain, and volume loss in folded cover strata, Valley and Ridge Province, Maryland: American Journal of Science, v. 296, p. 23–57.

Marshak, S., and Wilkerson, M. S., 1992, Effects of overburden thickness on thrust belt geometry and development: Tectonics, v. 11, p. 560–567.

Nickelsen, R. P., 1979, Sequence of structural stages of the Alleghany orogeny, Bear Valley strip mine, Shamokin, Pa.: American Journal of Science, v. 279, p. 225–271.

Nickelsen, R. P., 1988, Structural evolution of folded thrusts and duplexes on a first-order anticlinorium in the Valley and Ridge Province of Pennsylvania, *in* Mitra, G., and Wojtal, S., eds., Geometries and mechanisms of thrusting, with special reference to the Appalachians: Geological Society of America Special Paper 222, p. 89–106.

Nickelsen, R. P., 1996, Alleghanian sequential deformation on the SW limb of the Pennsylvania salient in Fulton and Franklin Counties, south-central Pennsylvania: Pennsylvania Geological Survey, 61st Annual Field Conference of Pennsylvania Geologists Guidebook, 108 p.

Perry, W. J., Jr., 1978, Sequential deformation in the central Appalachians: American Journal of Science, v. 278, p. 518–542.

Platt, J. P., Behrmann, J. H., Cunningham, P. C., Dewey, J. F., Helman, M., Parrish, M., Shepley, M., Wallis, S., and Weston, P., 1989, Kinematics of the Alpine arc and the motion history of Adria: Nature, v. 337, p. 158–161.

Spiker, E. C., and Gray, M. B., 1997, A study of progressive deformation at the Allegheny Front, Lycoming County, PA.: Geological Society of America Abstracts with Programs, v. 29, p. 82.

Stamatakos, J., and Hirt, A. M., 1994, Paleomagnetic considerations of the development of the Pennsylvania salient in the central Appalachians: Tectonophysics, v. 231, p. 237–255.

Stamatakos, J., Hirt, A. M., and Lowrie, W., 1996, The age and timing of folding in the central Appalachians from paleomagnetic results: Geological Society of America Bulletin, v. 108, p. 815–829.

Thomas, W. A., 1977, Evolution of Appalachian salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233–1278.

Van der Voo, R., Stamatakos, J. A., and Parés, J. M., 1997, Kinematic constraints on thrust-belt curvature from syndeformational magnetizations in the Lagos del Valle Syncline in the Cantabrian Arc, Spain: Journal of Geophysical Research, v. 102, p. 10105–10119.

Wagner, W. R., 1966, Stratigraphy of the Cambrian to Middle Ordovician rocks of central and western Pennsylvania: Pennsylvania Geological Survey General Geology Report G49, 156 p.

Younes, A., and Engelder, T., 1997, Fringe cracks: A key data set for the interpretation of progressive Alleghanian deformation of the Appalachian Plateau: Geological Society of America Bulletin (in press).

Zhou, M., and Jacobi, R. D., 1997, Formation of regional cross-fold joints in the northern Appalachian Plateau: Journal of Structural Geology, v. 19, p. 817–834.

Manuscript received April 14, 1997
Revised manuscript received August 25, 1997
Manuscript accepted September 10, 1997