Early jointing in coal and black shale: Evidence for an Appalachian-wide stress field as a prelude to the Alleghanian orogeny

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ABSTRACT

Early ENE-striking joints (present coordinates) within both Pennsylvanian coal and Devonian black shale of the Central and Southern Appalachians reflect an approximately rectilinear stress field with a dimension >1500 km. This Appalachian-wide stress field (AWSF) dates from the time of joint propagation, when both the coal and shale were buried to the oil window during the 10–15 m.y. period straddling the Pennsylvanian-Permian boundary. The AWSF was generated during the final assembly of Pangea as a consequence of plate-boundary tractions arising from late-stage oblique convergence, where maximum horizontal stress, S_H, of the AWSF was parallel to the direction of closure between Gondwana and Laurentia. After closure, the AWSF persisted during dextral slip of peri-Gondwanan microcontinents, when S_H appears to have crosscut plate-scale transcurrent faults at ~30°. Following >10 m.y. of dextral slip during tightening of Gondwana against Laurentia, the AWSF was disrupted by local stress fields associated with thrusting on master basement decollements to produce the local orocline-shaped Alleghanian map pattern seen today.

Keywords: joints, coal cleat, Alleghanian orogeny, lithosphere stress field, fault strength, transpressional tectonics.

INTRODUCTION

The map pattern of the Appalachian Valley and Ridge gives the distinct impression that the Alleghanian orogeny was a collision of Gondwana against serrations arising from Late Proterozoic rift-related offsets on the Laurentian margin. Major teeth on the serrated margin include the Alabama, Virginia, and New York promontories (i.e., Rankin, 1976). However, late Paleozoic strike-slip tectonics (e.g., Hylas fault zone [Gates and Glover, 1989], Modoc fault zone [Snoke et al., 1980], and the Brevard fault zone [Hatcher, 2001]) and coeval basins (e.g., the Narragansett of Rhode Island; Mosher, 1983) reflect dextral transcurrent plate motion during the amassing of Pangea (Fig. 1). Large segments of these transcurrent fault systems are more or less straight, indicating that tectonic processes such as the welding of the Taconic and Potomic deformed wedges to irregular basement (i.e., Faill, 1997) acted to smooth the serrated margin of post-Rodinian Laurentia.

The purpose of this paper is to describe evidence for a more or less rectilinear stress field that was transmitted into the smoothed margin of the Laurentian foreland for a period exceeding 10 m.y. during the assembly of Pangea. Because this late Paleozoic stress field was unaffected by the obvious serrations (i.e., promontories and embayments) of the present mountain belt and its predecessor, the post-Rodinian margin of Laurentia, it is an Appalachian-wide stress field (AWSF). The AWSF, a prelude to the Alleghanian orogeny, was disrupted when dextral transpression returned the Appalachian foreland to the shape of the Rodinian margin of Laurentia, by means of stratigraphically controlled decollement tectonics (Gates et al., 1988; Wise, 2004).

FRACTURE EVIDENCE FOR THE AWSF

Along the Appalachian Mountains an ENE joint set is the first to propagate in many outcrops of Devonian through Pennsylvanian rocks (e.g., Nickelsen and Hough, 1967; Nickelsen, 1979; Kulander and Dean, 1993; Pashin and Hinkle, 1997). This early joint set strikes parallel to the orientation of the maximum horizontal stress, S_H, in a stress field that was a prelude to the Alleghanian orogeny. In total, these joint sets appear as one megaset recording a rectilinear stress field extending for >1500 km across three promontories separated by oroclinal embayments of the Central and Southern Appalachians (Fig. 1). This rectilinear stress field is the AWSF.

New Data

Joints in the orientation of the AWSF are found in Late Mississippian through Early Pennsylvanian sandstones near the Virginia

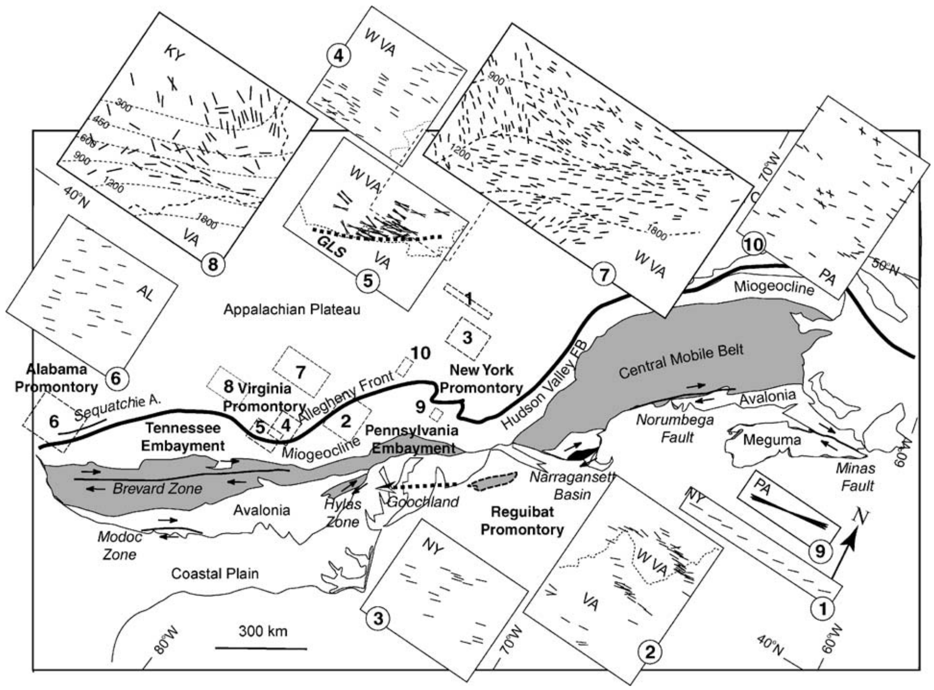

Figure 1. Distribution of ENE joint sets along Appalachian Mountains. References to insets and their map locations (dashed rectangles) are in text. Pennsylvanian isopachs (m) are dashed within insets 7 and 8 (after Colton, 1970).

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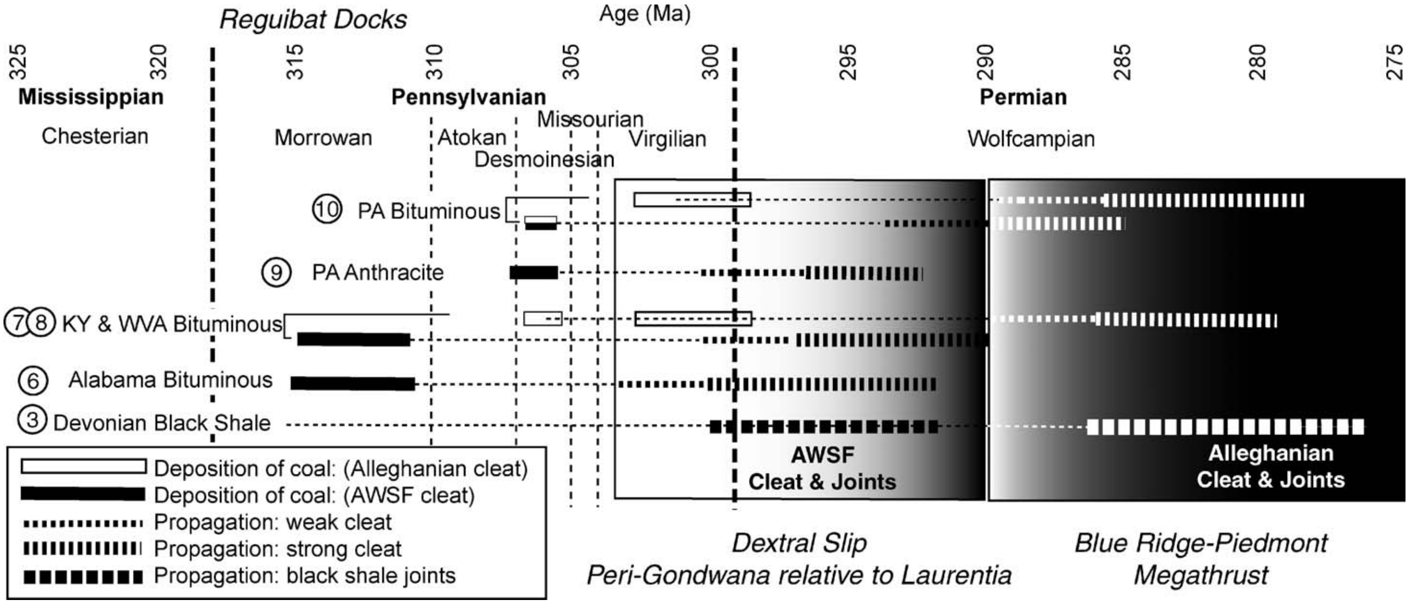

Figure 2. Time line for coal deposition and propagation of Appalachian cleat and joints. Ages are consistent with International Commission on Stratigraphy (www.stratigraphy.org; stage names are North American). AWSF—Appalachian-wide stress field.

promontory, the transition between the Central and Southern Appalachians (inset 5 in Fig. 1). These ENE joints trace continuously from flat-lying beds of the Appalachian Plateau into the folded rocks of the Glen Lyn syncline, the syncline marking the Allegheny Front in Virginia. Within several hundred meters of the Glen Lyn syncline on the plateau side of the front, these joints have slip fibers indicating reactivation during folding. Furthermore, when tilted by folding, ENE joints strike obliquely to the fold axes (mode = 080° for the preferred strike of joints at 47 outcrops). The joints strike obliquely to folds and are present in flat-lying rocks, ruling out outer arc stretching as a mechanism controlling propagation. As such, because they are present in its folded limb, these joints predate the Alleghanian Glen Lyn syncline.

DISCUSSION

The AWSF is dated using the time of joint propagation. In this regard, joints in unfolded Early Pennsylvanian sandstone (inset 5 in Fig. 1) correlate in time with the transition from late-stage Gondwana-Laurentia convergence and dextral transpression along the smoothed-margin of Laurentia to large-scale folding. However, the propagation of face cleat (i.e., joints in coal) gives the tightest constraint.

Dating the AWSF Using Organic-Rich Rocks

A widely spaced (i.e., weak) face cleat initiates in lignite or subbituminous coal during shrinkage of the coal structure by devolatization (Ting, 1977). Closely spaced (i.e., strong) cleat develops later when coal reaches a rank of high volatile A bituminous with a vitrinite reflectance (Rm_o) of 0.8 (Pashin and Hinkle, 1997). A coal rank of high volatile A bituminous is generated by pressure-temperature conditions equivalent to burial just below the top of the oil window. Depending on heat flow this may occur at a depth of 2–3 km (Stach et al., 1982). Propagation of face cleat in the Appalachians is dated using burial curves (e.g., Evans, 1995; Pitman et al., 2003). A regional stress field during coalification controls the orientation of face cleat (Laubach et al., 1998).

A strong ENE face cleat first developed when ca. 315 Ma coal of the Black Warrior Basin (inset 6 in Fig. 1) reached the oil window ca. 300 Ma (Pitman et al., 2003). A weak face cleat developed when these beds metamorphosed from lignite to subbituminous coal ~4 m.y. earlier (Fig. 2). As shallower Morrowan (315–311 Ma) coals of the Black Warrior Basin were metamorphosed within the oil window, they developed a strong face cleat of the same orientation, which means that the AWSF in the Southern Appalachians persisted for several million years starting ca. 304 Ma. A pervasive ENE face cleat throughout the Black Warrior Basin indicates that coalification took place entirely under the influence of the AWSF.

Face cleat in two different geological provinces in Pennsylvania also record an ENE S_H: the anthracite district (inset 9 in Fig. 1) of the eastern Pennsylvania Valley and Ridge (Nickelsen, 1979) and the bituminous district (inset 10) of the western Pennsylvania Plateau (Nickelsen and Hough, 1967). Coal in both districts is Desmoinesian (307–305 Ma) (Fig. 2). Like examples from the Black Warrior Basin, the anthracite coal reached the oil window early enough to record the AWSF throughout. The weakly developed ENE face cleat in bituminous coal of Pennsylvania is found only near the Allegheny Front. Weakly developed ENE face cleat along the Allegheny Front is also found in Kentucky and West Virginia, but only in Morrowan coal (Long, 1979; Kulander and Dean, 1993).

When most of the Pennsylvania Plateau first reached subbituminous rank as late as ca. 290 Ma (i.e., the Evans [1995] burial curve) an orocline-shaped Alleghanian stress field (i.e., S_H = NNW) had supplanted the rectilinear AWSF. Virgilian (304–299 Ma) coals of Pennsylvania record this latter stress field (Nickelsen and Hough, 1967). In West Virginia and Kentucky, both Desmoinesian and Virgilian coals farther into the foreland carry face cleat in the cross-fold Alleghanian orientation (Fig. 1). Burial to the oil window in the Central Appalachians was slower and later than in the Black Warrior Basin (e.g., Colton, 1970). Thus the initiation of ENE face cleat was delayed and in the outer foreland cleat development was not initiated until after the onset of a NNW S_H (Fig. 2).

The earliest joint set in Devonian black shale (inset 3 in Fig. 1) of the Appalachian Plateau, New York, also trends ENE (Engender et al., 2001). The presence of these ENE joints only within or just above black shale suggests that they were driven as a consequence of maturation of hydrocarbons after burial to the oil window (Lash et al., 2004). Although black shale approached the top of the oil window by Late Mississippian time, significant maturation was delayed until ca. 300 Ma or later for two reasons. First, Morrowan-Atokan (317–307 Ma) erosion removed considerable overburden that was replaced starting only after 307 Ma (i.e., Faill, 1997). Second, maturation-related joint propagation probably required more than the initial production at the top of the oil window. In summary, organic-rich rocks in six localities are evidence of the onset of an AWSF no later than ca. 304 Ma and lasting 10–15 m.y. before being supplanted by the orocline-shaped Alleghanian stress fields of the Central and Southern Appalachians (Fig. 2).

AWSF-Consistent Structures in Less Organic-Rich Rocks

In addition to ENE joints in Late Mississippian–Early Pennsylvanian sandstones near the Allegheny Front of Virginia (inset 5 in Fig. 1), earliest joints are ENE in both carbonates and clastics of the same age (inset 4) farther into the West Virginia Plateau (Kulander and Dean, 1993). The same joint set also occurs deep into the Valley and Ridge, Virginia, where it cuts into Devonian sandstone (inset 2) (Engelder, 2004). By passing in the same orientation from the Central to the Southern Appalachians, ENE joints indicate that the orocline-shaped Alleghanian stress fields on either side of the present Virginia promontory postdate the AWSF (Fig. 1).

The E-W shortening direction for fold growth in the W-verging Hudson Valley fold-thrust belt is similar in orientation to a magnetic fabric in Devonian rocks 300 km W of the Hudson Valley (Hirt et al., 1995) and to ENE veins in the Silurian Lockport dolostone (inset 1) of the New York Plateau (Gross et al., 1992). Fault-related folding within the Hudson Valley fold-thrust belt predates the Alleghanian Kittatiny-Shawangunk segment of the Appalachian Valley and Ridge (Marshak and Tabor, 1989). The Hudson Valley fold-thrust may be another manifestation of the same AWSF recorded throughout the Laurentian foreland and, therefore, a prelude to the Alleghanian orogeny rather than Acadian. However, data from rocks other than coal or black shale still permit the presence of the AWSF well before 304 Ma.

Tectonic Context for Development of an AWSF

In some instances, the orientation of S_H in plate-scale stress fields is an outgrowth of plate-boundary tractions that tie closely with the slip vector between plates. Large-scale rectilinear stress fields have an S_H aligned with the relative motions of lithospheric plates. For example, there is a motion-parallel S_H where the Pacific plate is colliding obliquely with the Aleutian arc (Nakamura et al., 1977) and where the eastern portion of the North American plate is moving away from the spreading center at the Mid-Atlantic Ridge (Zoback, 1992). However, in the vicinity of complex transcurrent fault systems such as the San Andreas, the stress field is neither rectilinear nor parallel to relative plate notion (Hardebeck and Hauksson, 2001).

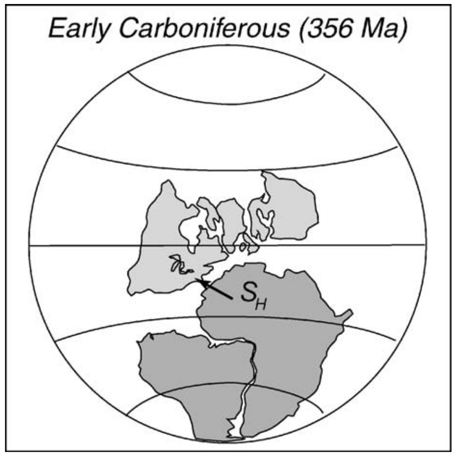

Figure 3. Configuration of continents in early Carboniferous time, when Pangea began to form (Scotese, 2002). S_H—maximum horizontal stress.

In the early Carboniferous, the African portion of Gondwana closed against the southern or Appalachian side of Laurentia obliquely from the ESE, an orientation that would favor dextral transcurrent faulting along the margin of Laurentina (Fig. 3). This is more or less a continuation of the Acadian plate configuration that drove dextral transpression and yielded Devonian synorogenic sedimentary wedges on the edge of Laurentia (Ferrill and Thomas, 1988). The final assembly of Pangea was also marked by a supercontinent-scale dextral strike-slip system extending from the Appalachians to the Urals (Arthaud and Matte, 1977).

Applying the present to the past, the AWSF is a manifestation of tractions accompanying slip at plate boundaries during the assembly of Pangea. By analogy, S_H would have been parallel to the oblique motion of Gondwana toward Laurentia, i.e., from the ENE in modern coordinates. Closure took place ca. 315 Ma with the docking of the Reguibat promontory (i.e., Africa) against peri-Gondwanan microcontinents near the New York promontory (Faill, 1997). A peripheral bulge associated with docking led to the deep Morrowan erosion in the Central Appalachians (Faill, 1997).

After the docking, Gondwana pivoted clockwise around the New York promontory to initiate zipper tectonics (i.e., Hatcher, 2002). Its concomitant rotational transpression constituted a gradual tightening between Gondwana and Laurentia that eventually drove the Blue Ridge–Piedmont megathrust into the foreland along the southern half of the Appalachian chain (McBride et al., 2005). This zipper model is supported by early dextral strike-slip fabrics (ca. 300 Ma) overprinted by brittle dip-slip motion on a number of faults in the southern Appalachian hinterland (Hatcher, 2001).

During rotational transpression, Laurentian fragments and peri-Gondwanan microcontinents were driven dextrally as much as 400 km (Valentino et al., 1994; Bartholomew and Tollo, 2004). Assuming slip rates between 2 and 4 cm per year, dextral displacement lasted 10–20 m.y. (Fig. 1). During this 400 km translation, a clastic wedge from a transpressional-related highland buried Morrowan coals from Alabama to West Virginia and Desmoinesian coals in Pennsylvania through subbituminous rank to high volatile A bituminous and beyond (e.g., Pitman et al., 2003). This post-Virgilian burial lead to conditions favoring the propagation of coal cleat and black shale joints in a stress field that parallels the track of Gondwana closing against Laurentia (Fig. 3).

Strength of the Dextral Transcurrent System

Joints and coal cleat reflect a rectilinear stress field lasting >10 m.y. with an along-strike dimension >1500 km. Given such duration and dimension, it is reasonable to presume that this Laurentian stress field arose from tractions at its Alleghanian boundary with Gondwana. The strength of this conjecture rests with trajectories of the AWSF pointing in the direction of the oblique convergence between African Gondwana and Laurentia (Fig. 3). Several dextral transcurrent sutures within Avalonian and peri-Gondwanan terranes were caught within this Laurentian-Gondwana stress field; S_H crosscut the dextral fault systems at ~30°. If dextral transcurrent systems were strong, the friction angle on these faults would have been S_H ~30°. Weaker faults would have caused S_H trajectories to curve and crosscut the fault system at a higher angle, like the situation along the San Andreas (Hardebeck and Michal, 2004). It is noteworthy that no evidence of weak-fault curving of S_H is seen along the 1500 km with the AWSF. Evidence, however circumstantial, suggests that transcurrent sutures at the edge of Laurentia were strong during assembly of Pangea. Later transpression (ca. 270 Ma) gave rise to a master decollement under the southern Appalachian hinterland that truncated the strike-slip faults and drove the Blue Ridge–Piedmont megathrust sheet (McBride et al., 2005). Local thrusting set up the succeeding orocline-shaped stress fields that overprinted the AWSF (e.g., Wise, 2004).

Geological Coincidence

The post-Paleozoic counterclockwise rotation of Laurentia realigned Morrowan-Wolfcampian coal cleat and other joints with the ENE S_H of the contemporary tectonic stress field. This coincidence led to the erroneous interpretation that ENE joints of New York (e.g., Engelder, 1982) and coal cleat of

West Virginia (e.g., Kulander and Dean, 1993) were late neotectonic joints. Other ENE joints of the Appalachian Basin appear to be neotectonic (e.g., Hancock and Engelder, 1989).

CONCLUSIONS

Early ENE face cleat development in coal is a manifestation of an AWSF at the time that burial initiated coalification throughout the Central and Southern Appalachians. Coalification was concurrent with dextral slip that displaced peri-Gondwanan microcontinents as much as 400 km along the smoothed margin of Laurentia during the Alleghanian assembly of Pangea.

While coal cleat development is unambiguously late Virgilian to early Wolfcampian, the sets of ENE joints in clastics and carbonates of the Virginia promontory may reflect either an AWSF set up by tractions during Chesterian-Morrowan convergence and docking or later dextral slip in the same stress field. Together these data suggest that an AWSF crossed the Appalachians obliquely with a duration of as much as 25 m.y. After ca. 290 Ma rotational transpression initiated several master basement decollements (e.g., Wise, 2004) that led to the development of local orocline-shaped stress fields in the Central and Southern Appalachians. The delay between docking of Gondwana (ca. 315 Ma) and basement thrusting more than 25 m.y. later is a manifestation of the oblique tightening between Gondwana and Laurentia that would have been much faster in a head-on collision of the India-Asia type.

ACKNOWLEDGMENTS

Support came from National Science Foundation grant EAR-04-40233 and Penn State's SEC. We thank Alex Gates, Don Wise, and Steve Wojtal for thoughtful, time-consuming reviews.

REFERENCES CITED

Arthaud, F., and Matte, P., 1977, Late Paleozoic strike-slip faulting in southern Europe and northern Africa; result of a right-lateral shear zone between the Appalachians and the Urals: Geological Society of America Bulletin, v. 88, p. 1305–1320, doi: 10.1130/0016-7606(1977)88<1305:LPSFIS>2.0.CO;2.

Bartholomew, M.J., and Tollo, R.P., 2004, Northern ancestry for the Goochland terrane as a displaced fragment of Laurentia: Geology, v. 32, p. 669–672, doi: 10.1130/G20520.1.

Colton, G.W., 1970, The Appalachian Basin—Its depositional sequences and their geologic relationships, *in* Fisher, G.W., et al., eds., Studies of Appalachian geology: Central and southern: New York, John Wiley, p. 5–47.

Engelder, T., 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, 2004, Tectonic implications drawn from differences in the surface morphology on two joint sets in the Appalachian Valley and Ridge, Virginia: Geology, v. 32, p. 413–416, doi: 10.1130/G20216.1.

Engelder, T., Haith, B.F., and Younes, A., 2001, Horizontal slip along Alleghanian joints of the Appalachian Plateau: Evidence showing that mild penetrative strain does little to change the pristine appearance of early joints: Tectonophysics, v. 336, p. 31–41, doi: 10.1016/S0040-1951(01)00092-0.

Evans, M.A., 1995, Fluid inclusions in veins from the Middle Devonian shales: A record of deformation conditions and fluid evolution in the Appalachian Plateau: Geological Society of America Bulletin, v. 107, p. 327–339, doi: 10.1130/0016-7606(1995)107<0327:FIIVFT>2.3.CO;2.

Faill, R.T., 1997, A geologic history of the north-central Appalachians, Part 2, The Appalachian basin from the Silurian through the Carboniferous: American Journal of Science, v. 297, p. 729–761.

Ferrill, B.A., and Thomas, W.A., 1988, Acadian dextral transpression and synorogenic sedimentary successions in the Appalachians: Geology, v. 16, p. 604–608, doi: 10.1130/0091-7613(1988)016<0604:ADTASS>2.3.CO;2.

Gates, A.E., and Glover, L., 1989, Alleghanian tectonothermal evolution of the dextral transcurrent Hylas zone, Virginia: Journal of Structural Geology, v. 11, p. 407–419, doi: 10.1016/0191-8141(89)90018-7.

Gates, A.E., Speer, J.A., and Pratt, T.L., 1988, The Alleghanian southern Appalachian Piedmont: A transpressional model: Tectonics, v. 7, p. 1307–1324.

Gross, M.R., Engelder, T., and Poulson, S., 1992, Veins in the Lockport Dolomite: Evidence for an Acadian fluid circulation system: Geology, v. 20, p. 971–974, doi: 10.1130/0091-7613(1992)020<0971:VITLDE>2.3.CO;2.

Hancock, P.L., and Engelder, T., 1989, Neotectonic joints: Geological Society of America Bulletin, v. 101, p. 1197–1208, doi: 10.1130/0016-7606(1989)101<1197:NJ>2.3.CO;2.

Hardebeck, J.L., and Hauksson, E., 2001, Crustal stress field in southern California and its implications for fault mechanics: Journal of Geophysical Research, v. 106, p. 21,859–21,882, doi: 10.1029/2001JB000292.

Hardebeck, J.L., and Michael, A.J., 2004, Stress orientations at intermediate angles to the San Andreas fault, California: Journal of Geophysical Research, v. 109, no. B11, doi: 10.1029/2004JB003239.

Hatcher, R.D., 2001, Rheological partitioning during multiple reactivation of the Palaeozoic Brevard fault zone, Southern Appalachians, USA, *in* Holdsworth, R.E., et al., eds., The nature and tectonic significance of fault zone weakening: Geological Society [London] Special Publication 186, p. 257–271.

Hatcher, R.D., 2002, Alleghanian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins, *in* Martinez Catalan, J.R., et al., eds., Variscan-Appalachian dynamics: The building of the late Paleozoic basement: Geological Society of America Special Paper 364, p. 199–208.

Hirt, A.M., Evans, K.F., and Engelder, T., 1995, Correlation between magnetic anisotropy and fabric for Devonian shales on the Appalachian Plateau: Tectonophysics, v. 247, p. 121–132, doi: 10.1016/0040-1951(94)00176-A.

Kulander, B.R., and Dean, S.L., 1993, Coal-cleat domains and domain boundaries in the Allegheny Plateau of West Virginia: American Association of Petroleum Geologists Bulletin, v. 77, p. 1374–1388.

Lash, G.G., Loewy, S., and Engelder, T., 2004, Preferential jointing of Upper Devonian black shale, Appalachian Plateau, USA: Evidence supporting hydrocarbon generation as a joint driving mechanism, *in* Cosgrove, J., and Engelder, T., eds., The initiation, propagation, and arrest of joints and other fractures: Geological Society [London] Special Publication 231, p. 129–151.

Laubach, S.E., Marrett, R.A., Olson, J.E., and Scott, A.R., 1998, Characteristics and origins of coal cleat: A review: International Journal of Coal Geology, v. 35, p. 175–207, doi: 10.1016/S0166-5162(97)00012-8.

Long, B.R., 1979, Regional survey of surface joints in eastern Kentucky [M.S. thesis]: Morgantown, West Virginia University, 68 p.

Marshak, S., and Tabor, J.R., 1989, Structure of the Kingston orocline in the Appalachian fold-thrust belt, New York: Geological Society of America Bulletin, v. 101, p. 683–701, doi: 10.1130/0016-7606(1989)101<0683:SOTKOI>2.3.CO;2.

McBride, J.H., Hatcher, R.D., Stephenson, W.J., and Hooper, R.J., 2005, Integrating seismic reflection and geological data and interpretations across an internal basement massif: The southern Appalachian Pine Mountain window, USA: Geological Society of America Bulletin, v. 117, p. 669–686, doi: 10.1130/B25313.1.

Mosher, S., 1983, Kinematic history of the Narragansett basin, Massachusetts and Rhode Island: Constraints on late Paleozoic plate reconstructions: Tectonics, v. 2, p. 327–344.

Nakamura, K., Jacob, K.H., and Davies, J.N., 1977, Volcanoes as possible indicators of tectonic stress orientation—Aleutians and Alaska: Pure and Applied Geophysics, v. 115, p. 87–112, doi: 10.1007/BF01637099.

Nickelsen, R.P., 1979, Sequence of structural stages of the Allegheny orogeny at the Bear Valley Strip Mine, Shamokin, Pennsylvania: American Journal of Science, v. 279, p. 225–271.

Nickelsen, R.P., and Hough, V.D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609–630.

Pashin, J.C., and Hinkle, F., 1997, Coalbed methane in Alabama: Circular: Geological Survey of Alabama Report 192, 71 p.

Pitman, J.K., Pashin, J.C., Hatch, J.R., and Goldhaber, M.B., 2003, Origin of minerals in joint cleat systems of the Pottsville Formation, Black Warrior basin, Alabama: Implications for coalbed methane generation and production: American Association of Petroleum Geologists Bulletin, v. 87, p. 713–731.

Rankin, D.W., 1976, Appalachian salients and recesses: Late Precambrian continental breakup and the opening of the Iapetus Ocean: Journal of Geophysical Research, v. 81, p. 5605–5619.

Scotese, C.R., 2002, PALEOMAP Project: http://www.scotese.com (March 2003).

Snoke, A.W., Kish, S.A., and Secor, D.T., Jr., 1980, Deformed Hercynian granitic rocks from the Piedmont of South Carolina: American Journal of Science, v. 280, p. 1018–1034.

Stach, E., Mackowsky, M.T., Teichmueller, M., Taylor, G.H., Chandra, D., and Teichmueller, R., 1982, Stach's textbook of coal petrology (third edition; translation and English revision by Murchison, D.G., et al.): Berlin, Borntraeger, 535 p.

Ting, R.T.C., 1977, Origin and spacing of cleats in coal beds: Journal of Pressure Vessel Technology, v. 99, p. 624–626.

Valentino, D.W., Gates, A.E., and Glover, L., III, 1994, Late Paleozoic transcurrent tectonic assembly of the central Appalachians: Tectonics, v. 13, p. 111–126, doi: 10.1029/93TC02313.

Wise, D.U., 2004, Pennsylvania salient of the Appalachians: A two-azimuth transport model based on new compilations of Piedmont data: Geology, v. 32, p. 777–780, doi: 10.1130/G20547.1.

Zoback, M.L., 1992, First and second order patterns of stress in the lithosphere: The World Stress Map Project, *in* Zoback, M.L., ed., The World Stress Map Project: Journal of Geophysical Research, v. 97, p. 11,703–11,728.

Manuscript received 26 October 2005
Revised manuscript received 21 February 2006
Manuscript accepted 1 March 2006

Printed in USA