Tectonic implications drawn from differences in the surface morphology on two joint sets in the Appalachian Valley and Ridge, Virginia

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ABSTRACT

Surface morphology distinguishes two joint sets in the Virginia–West Virginia Appalachians and points to a difference in rupture velocity between the two sets. The earlier joint set, J_1, propagated prior to or during fault-related folding and was subsequently tilted as folds grew to have steeper limb dips. J_1 is characterized by a rougher surface displaying a symmetrical plumose pattern created during the propagation of a simple rupture front. In ceramics, such morphology is the product of a faster rupture under relatively high stress intensity ($K_I > K_{Ic}$, where K_{Ic} indicates critical stress intensity). This relatively fast joint growth is consistent with an effective tensile stress sustained by oblique plate convergence at the onset of the Alleghanian orogeny. The later joint set, J_2, propagated normal to the Allegheny front in a subvertical orientation independent of local bed dip. A multilobed rupture leaves a smooth surface on J_2 joints. By analogy with ceramics, such a surface is indicative of slower propagation by subcritical crack growth ($K_I < K_{Ic}$). This slow joint growth is consistent with the slow generation of effective tensile stress arising from hydrocarbon maturation postdating fold growth during the waning stages of the Alleghanian orogeny.

Keywords: joints, Alleghanian orogeny, subcritical crack propagation, rupture velocity.

INTRODUCTION

When lithospheric plates converge during continental-continental collision, a number of factors control the orientation of the stress field at various locations along the active margin, including the shape of the plate margins and the direction of convergence between the two plates. The stress field can change with time as a function of evolving margin geometry as convergence moves toward final suture. One record of an evolving stress field is the overprinting of joint sets (e.g., Engelder and Geiser, 1980; Gray and Mitra, 1993; Zhao and Jacobi, 1997; Younes and Engelder, 1999). However, a signature indicating the slowing of convergence and concomitant deformation rate toward final suture has yet to be reported. This paper describes an evolution of joint-surface morphology that reflects a switch in joint-driving mechanism leading to a decrease in rupture velocity toward the final stage of Alleghanian deformation in the Appalachian foreland.

The Allegheny structural front from northern Virginia through southern Pennsylvania is straight (029° ± 1°) for >300 km (Fig. 1). This structural front provides a boundary against which a blind duplex of Cambrian–Ordovician carbonates was thrust during the Alleghanian orogeny (Perry, 1978). A linear segment of a mountain belt presents an opportunity to test whether and when cross-fold joints can develop in a roof sequence without the benefit of regional stretching associated with oroclinal bends in mountain belts (e.g., Macedo and Marshak, 1999).

REGIONAL JOINT SETS

Joint development in the roof sequence of the Appalachian Valley and Ridge between the latitudes of 38° and 38°45′N includes two well-developed joint sets (Fig. 2). The regional distribution of these two joint sets was assessed by measuring the orientations of between 5 and 50 of the most prominent joints in each of 76 outcrops along 3 traverses of the mountain belt. When appearing together in the same bed, the two joint sets usually crosscut, meaning that joints of the earlier set were closed when the joints of the later set propagated (Fig. 2A). Vein infilling, a property of the earlier of two joint sets when present, coats some J_1 surfaces (cf. Evans and Battles, 1999). The earlier joint set, J_1, has a regional trend of 082°, thus transecting folds at ~50° (Fig. 3B). The later set, J_2, has a regional trend at 313°, and this is the cross-fold orientation approximately orthogonal to the Allegheny front.

The earlier set, J_1, propagated subnormal to bedding but was tilted to a shallower dip as beds of the roof sequence were folded by the progressive thrusting in the blind duplex below (Fig. 2B). The later set, J_2, propagated and remained subvertical, regardless of the orientation of bedding even when appearing on the nose of folds that have been tilted to dip along strike of the belt (Fig. 2B). Neither set propagated strictly normal to bedding, as indicated by the position of the mean pole to data taken from each set at each outcrop (Figs. 3B, 3D). Yet, the plunge of the mean pole to outcrop-mean poles for all cross-fold (J_2) joints across the region is exactly 0° (Fig. 3D). The plunge of the mean pole to outcrop-mean poles for early (J_1) joints across the region is 6°S, a consequence of the asymmetry of fault-related folding. Even when beds are restored to horizontal, first about plunge and then about dip, many J_1 joints dip < 80°, suggesting that this joint set was not predestined to occupy a position normal to bedding, as is so common for joint propagation during regional extension in gently folded terrain.

Joint sets J_1 and J_2 have a distinguishing surface morphology (Fig. 4). While joints of

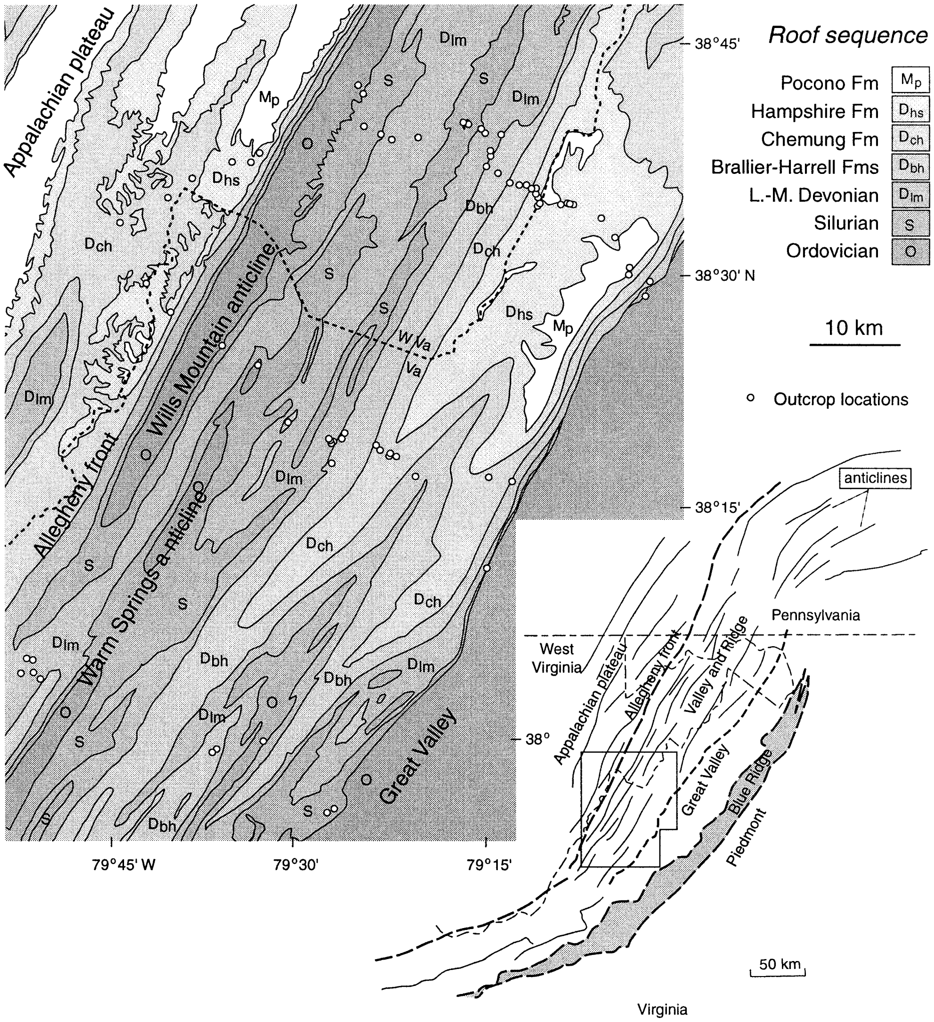

Figure 1. Geologic map of central Appalachian Mountains of Virginia and West Virginia.

both sets are planar, J_1 joints tend to display a rougher, more pronounced morphology, whereas J_2 joints are much smoother (Fig. 2C). Joints in siltstone and fine-grained sandstone beds of at least four formations of the roof sequence (i.e., Oswego, Juniata, Brallier, and Chemung Formations) carry these distinctly different morphologies. J_1 joints rupture through a bed and leave plumes emerging up and down from one major plume axis roughly halfway between bedding surfaces (Figs. 2C and 4). Such ruptures are well organized with one rupture front (Savalli and Engelder, 2004). J_2 joints are more likely to rupture into several lobes with minor plume axes curving into almost any position relative to bedding (Figs. 2C and 4). These latter ruptures are poorly organized and split into multiple rupture fronts. Other J_2 joints high in the roof sequence display the classic cyclic fan pattern of natural hydraulic fractures, where arrest after one cycle is marked by a sudden decrease in surface roughness (Fig. 2D). Finally, J_2 joints in black shale propagate up to but not through concretions, whereas J_1 joints are found to cut concretions (McConaughy and Engelder, 1999).

The distribution of the two joint sets in the roof sequence is noteworthy. With the exception of the Juniata, J_1 joints are most common at the top of the roof sequence, where they were found in 28 of 29 outcrops of the Chemung and Hampshire Formations (Fig. 5). J_2 joints are common deeper in the roof sequence, where they are best developed in the black shale of the Harrell Formation and sandstone beds of the Tuscarora and Juniata Formations.

DISCUSSION

Joint Morphology

Experiments on ceramics show that roughness of fracture surfaces increases with increasing dynamic stress intensity ($K_d > K_{Ic}$ where K_{Ic} is the critical stress intensity) and rupture velocity (v) (Hull, 1999). Because surface roughness varies in the same manner during stable joint propagation, Savalli and Engelder (2004) apply these results to an analysis of surface morphology in the subcritical crack-propagation regime (Fig. 4). By analogy, joints with well-organized rupture fronts and rougher surfaces are characteristic of the upper portion of subcritical region I and into region II. Joints of the J_1 set in the roof sequence of Virginia display a surface roughness consistent with propagation under a driving stress able to sustain a stress intensity (K_I) where $K_I < K_{Ic}$.

Joint driving stress ($\Delta\sigma$) is an effective tensile stress that may arise when pore pressure superimposes on compressive stress from burial, σ_3 ($= S_h$), that is partially relieved by a combination of regional, convergent-normal extension or local stretching associated with folding. Favorable conditions for generating an extension-related $\Delta\sigma$ are most likely at shallow depths, where S_h is low. The predominance of J_1 at the top of the roof sequence is consistent with a scenario where rapid infiltration of hydrostatic pore pressure will provide a loading mechanism that can sustain rupture at $v = 10^{-4}$ to 10^{-1} m/s, as predicted for rupture in sandstone (Segall, 1984).

Lobate, disorganized rupture fronts on smoother surfaces are consistent for propagation in subcritical regime I, where $v < 10^{-6}$ m/s (Savalli and Engelder, 2004). In region I, small ΔK_I can lead to a large Δv and, hence, chaotic advance of individual rupture lodes, giving the pattern observed on J_2 joints (Fig. 4). A scenario for slow rupture in vertical planes occurs during the waning period of orogenic deformation after folding of the roof sequence is nearly complete.

By the Late Carboniferous, burial would have carried the Harrell Formation, a black shale, to thermal maturation, where high fluid pressure evolved slowly. J_2 joints contain characteristics of hydraulic fractures propagating under a fluid-drive mechanism (i.e., McConaughy and Engelder, 1999). The high density of J_2 joints in the Harrell Formation reinforces the fluid drive scenario. Maturation of hydrocarbons led to fluid-driven jointing in black shale elsewhere in the Appalachian basin (Lash et al., 2004). Higher fluid pressures would have been more common in the deeper parts of the sedimentary pile below a seal rock like the shale of the Brallier Formation (Fig. 5).

Regional Tectonics

Dating the propagation of the regional joints in the roof sequence is possible because of their structural position. Generally, prefold-

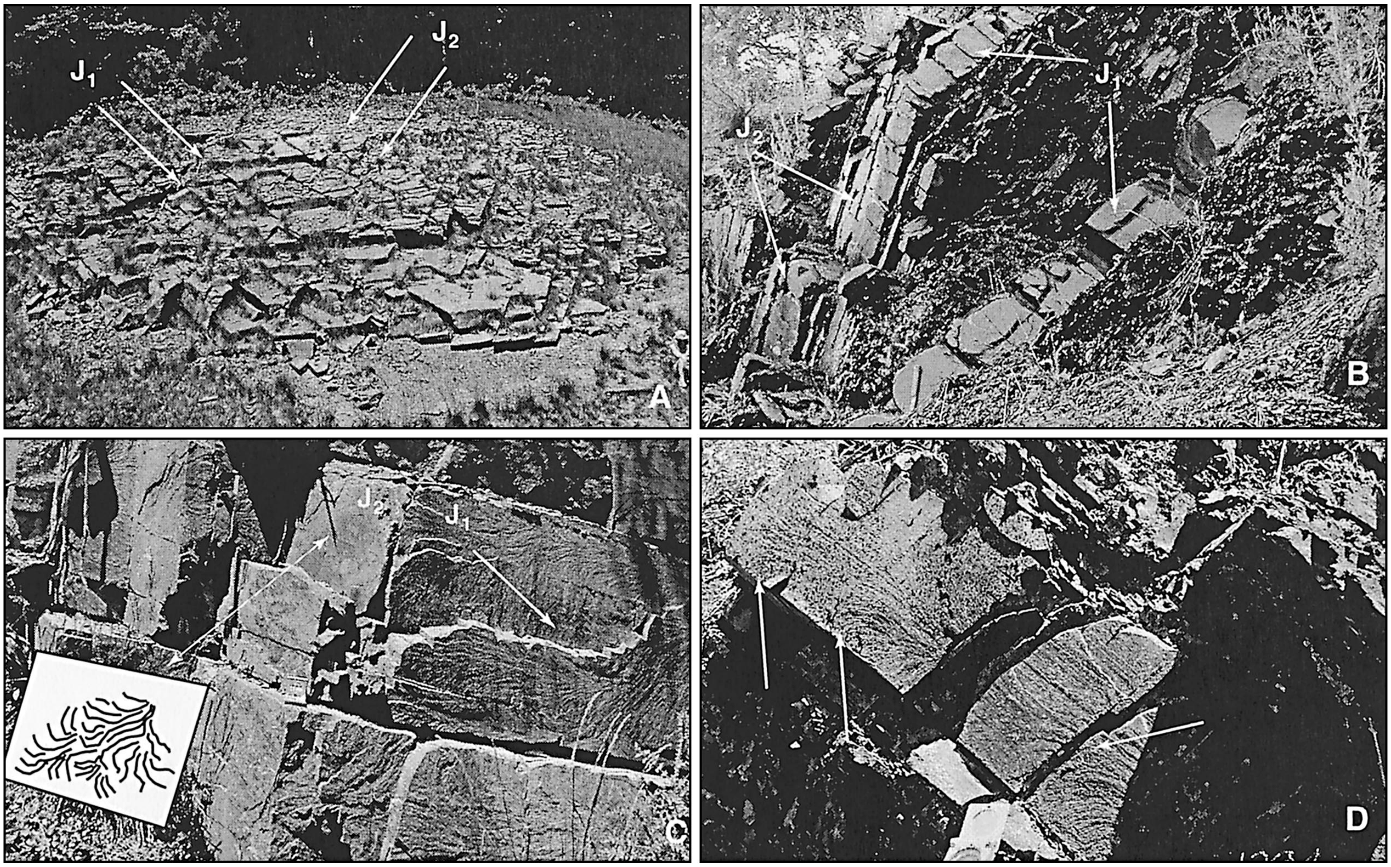

Figure 2. J_1 and J_2 joint sets. A: Chemung Formation. B: Brallier Formation. C: Juniata Formation displaying rough J_1 surfaces and smooth J_2 surfaces; inset shows propagating morphology of one J_2 joint. D: Chemung Formation with arrows pointing to three arrest lines of natural hydraulic fracture on J_2 surface.

ing joints are orthogonal to bedding, whereas J_1 is not strictly orthogonal to bedding, even when sampled in the gently folded rocks of the Appalachian plateau. This finding suggests that folding was under way at the time J_1 propagated.

The strike of J_1 is remarkably uniform (~082°) throughout the roof sequence despite the evidence that it did not propagate normal to bedding in many instances. The uniformly oriented strike for J_1 indicates a well-organized S_h in the roof sequence that is consistent with an oblique convergence between Africa and North America during early stages of the Alleghanian orogeny. The Alleghanian orogeny is characterized by major dextral faulting eastward from the Brevard fault zone and in southeastern New England (Hatcher et al., 1989). Such dextral strike-slip faulting in the southern Appalachians is consistent with a regional stress field at $S_h = 082°$.

Although joints of the later J_2 set are often tilted several degrees relative to vertical, their preferred regional attitude is vertical (Fig. 3D). Such predominately vertical joints indicate that major fold growth was waning by the time of J_2 propagation. By this time oblique

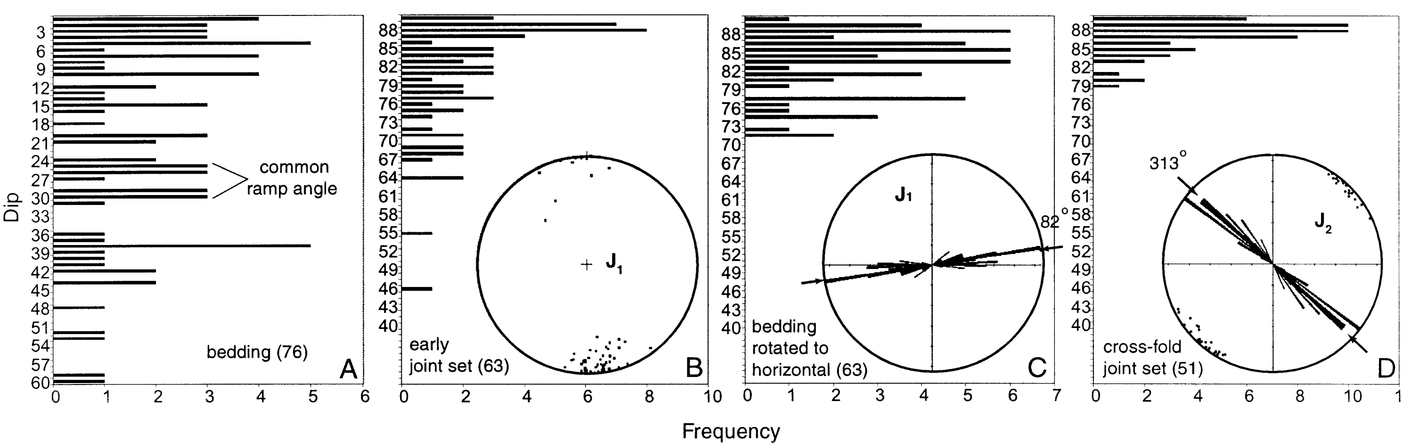

Figure 3. Dip vs. frequency histograms for bedding and two joint sets (J_1, J_2) and lower-hemisphere stereonet projections of poles to mean orientations for joints at each outcrop. Rose diagrams are based on rotated data for J_1 and unrotated data for J_2. Number of outcrops in which each joint set appears is indicated in parenthesis.

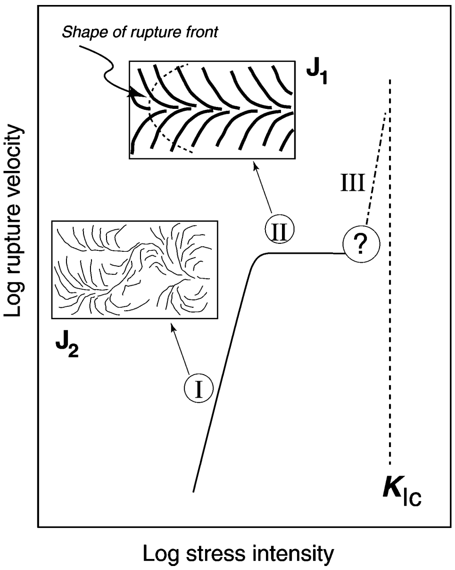

Figure 4. Hypothetical joint-propagation-velocity curve showing three subcritical regimes (adapted from Atkinson and Meredith, 1987). Insets show rough surface morphology for J_1 joints where stress intensity, K_I, approaches critical stress intensity, K_{Ic}, and smooth morphology for J_2, where $K_I \ll K_{Ic}$.

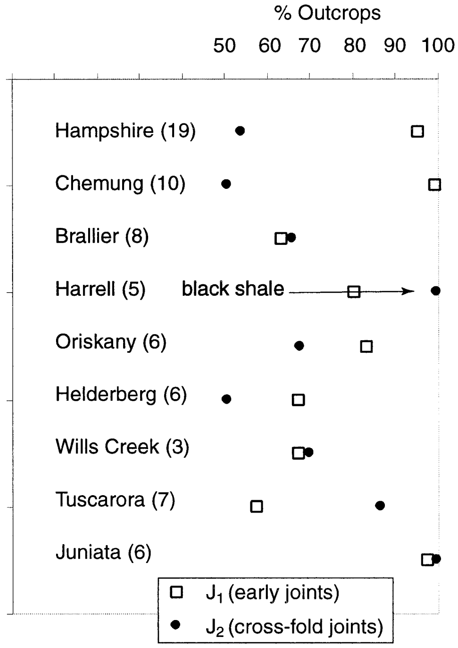

Figure 5. Stratigraphy of roof sequence listing number of outcrops sampled (in parentheses) and percentage of those outcrops with J_1 and J_2 joints.

convergence had ceased to control the regional stress field, which was then homogeneous, with σ_3 (= S_h) nearly coaxial with a straight Allegheny front (033° versus 029°).

In conclusion, the orientation and smooth morphology on J_2 joints indicate the cessation of oblique convergence during the waning phase of the Alleghanian orogeny. In the absence of regional stretching around an oroclinal bend, a pore-pressure–based driving mechanism allows late joint development along the straight 300 km segment of the Virginia–West Virginia Valley and Ridge.

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REFERENCES CITED

Atkinson, B.K., and Meredith, P.G., 1987, Experimental fracture mechanics data for rocks and minerals, *in* Atkinson, B.K., ed., Fracture mechanics of rock: Orlando, Academic Press, p. 111–166.

Engelder, T., and Geiser, P.A., 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.

Evans, M.A., and Battles, D.A., 1999, Fluid inclusion and stable isotope analyses of veins from the central Appalachian Valley and Ridge province: Implications for regional synorogenic hydrologic structure and fluid migration: Geological Society of America Bulletin, v. 111, p. 1441–1460.

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. 435–450.

Hatcher, R.D., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., and Wiltschko, D.V., 1989, Alleghanian orogen, *in* Hatcher, R.D., et al., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 233–318.

Hull, D., 1999, Fractography observing, measuring and interpreting fracture surface topography: Cambridge, Cambridge University Press, 366 p.

Lash, G.G., Loewy, S., and Engelder, T., 2004, Preferential jointing of Upper Devonian black shale, Appalachian plateau, USA: Sorting out the role of organic carbon content, *in* Cosgrove, J., and Engelder, T., eds., The initiation, propagation, and arrest of joints and other fractures: Geological Society [London] Special Publication (in press).

Macedo, J., and Marshak, S., 1999, Controls on the geometry of fold-thrust belt salients: Geological Society of America Bulletin, v. 111, p. 1808–1822.

McConaughy, D.T., and Engelder, T., 1999, Joint interaction with embedded concretions: Joint loading configurations inferred from propagation paths: Journal of Structural Geology, v. 21, p. 1049–1055.

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

Savalli, L., and Engelder, T., 2004, Mechanisms controlling the shape of the rupture front as joints cut through layered clastic sediments: Geological Society of America Bulletin (in press).

Segall, 1984, Rate-dependent extensional deformation resulting from crack-growth in rock: Journal of Geophysical Research, v. 89, p. 4185–4195.

Younes, A., and Engelder, T., 1999, Fringe cracks: Key structures for the interpretation of progressive Alleghanian deformation of the Appalachian plateau: Geological Society of America Bulletin, v. 111, p. 219–239.

Zhao, 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.

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CORRECTION

Tectonic implications drawn from differences in the surface morphology on two joint sets in the Appalachian Valley and Ridge, Virginia: Correction

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An error was found in the following paragraph in the section titled ‘‘Regional Tectonics.’’ In both instances, the subscript to S should have been a capital H. The correct version appears here:

The strike of J_1 is remarkably uniform ($\approx$ 082°) throughout the roof sequence despite the evidence that it did not propagate normal to bedding in many instances. The uniformly oriented strike for J_1 indicates a well-organized S_H in the roof sequence that is consistent with an oblique convergence between Africa and North America during early stages of the Alleghanian orogeny. In fact, the Alleghanian orogeny is characterized by major dextral faulting eastward from the Brevard fault zone and in southeastern New England (Hatcher et al., 1989). Such dextral strike-slip faulting in the southern Appalachians is consistent with a regional stress field at $S_H = 082°$.