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# Don’t judge an orogen by its cover: Kinematics of the Appalachian décollement from seismic anisotropy

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## ABSTRACT

**As North America collided with Africa to form Pangea during the Alleghanian orogeny, crystalline and sedimentary rocks in the southeastern United States were thrust forelandward along the Appalachian décollement. We examined Ps receiver functions to better constrain the kinematics of this prominent subsurface structure. From Southeastern Suture of the Appalachian Margin Experiment (SESAME) and other EarthScope stations on the Blue Ridge–Piedmont crystalline megathrust, we find large arrivals from a 5–10-km-deep converter. We argue that a strong contrast in dipping anisotropic foliation occurs at the subhorizontal Appalachian décollement, and propose that such a geometry may be typical for décollement structures. Conversion polarity flips can be explained by an east-dipping foliation, but this orientation is at odds with the overlying northeast-trending surface tectonic grain. We suggest that prior to late Alleghanian northwest-directed head-on collision, the Appalachian décollement accommodated early Alleghanian west-vergence, independent of the overlying Blue Ridge–Piedmont structural inheritance. The geophysical expression of dipping anisotropic foliation provides a powerful tool for investigating subsurface kinematics, especially where they are obscured by overlying fabric, to disentangle the tectonic complexities that embody oblique collisional orogens.**

## INTRODUCTION

Collisional orogens provide key records of continental construction. Commonly, they evolve through sequential stages and develop repeatedly in the same places through time (e.g., the Variscan and Alpine orogens in Europe, Schmid et al., 2004; the Grenville and Appalachian orogens in North America, Hatcher et al., 2007a). Their characteristic mosaics of rocks and fabrics illuminate how convergent tectonic processes operate and how they may have evolved over Earth’s history (Weller et al., 2021). Structural heterogeneities (e.g., faults, foliations, and other weaknesses) guide prolonged and repetitive deformation yet also contribute to tectonic complexities (Thomas, 2006). A challenge lies in unraveling these overprinted fabrics, and recognizing the conditions and kinematics of each, to better understand collisional orogens.

The southern Appalachians (USA) provide an ideal location for disentangling such collisional complexity (Fig. 1). The surface tectonic grain demonstrates a prolonged history of deformation and reactivation along northeast-trending structures throughout the transpressional Appalachian orogenies (Taconic, Acadian–Neoacadian, and Alleghanian) that formed Pangea (Hatcher, 2010). However, the Appalachian décollement (AD), which transported crystalline terranes of the Blue Ridge–Piedmont (BRP) megathrust and overridden sedimentary rocks along a master thrust in weak pelitic strata, formed only during Alleghanian collision (Cook et al., 1979). Long-lived structural heterogeneities that affected the overlying BRP may not have similarly influenced the underlying AD. Therefore, the BRP and AD may have distinct geometries and kinematics. We examined Ps conversions across the subsurface AD and argue that azimuthal polarity flips are generated from contrasts in dipping anisotropic foliations. Not only do these fabrics help constrain subsurface kinematics in a transpressional orogen, but their misorientations from an overlying tectonic grain also reveal depth-dependent responses to preexisting weaknesses (or lack thereof) during collisional tectonism.

## GEOLOGICAL BACKGROUND

Southern Appalachian crystalline basement formed mostly during the Grenville orogeny to build the supercontinent Rodinia (1.3–0.95 Ga; Whitmeyer and Karlstrom, 2007), which rifted apart in the late Neoproterozoic to early Cambrian (760–530 Ma; Thomas, 2006). A second Wilson cycle (Pangea) initiated as arcs accreted in the Taconic orogeny (462–448 Ma; Merschat et al., 2017), microcontinents collided in the Acadian–Neoacadian (395–340 Ma; Merschat et al., 2005), and Africa collided in the Alleghanian (335–260 Ma; Hatcher, 2002). Finally, Pangea began to rift apart in the Triassic (210 Ma; McHone and Butler, 1984), opening the Atlantic Ocean and setting the stage for modern surface exposure.

Structural inheritance from both Wilson cycles influenced Appalachian deformation. For example, variations in margin sedimentation due to Rodinian rift embayments, and the shapes of subsequently indenting crustal blocks (e.g., BRP; Fig. 1), influenced the geometry and kinematics of the Valley and Ridge fold-thrust belts (Macedo and Marshak; 1999; Thomas, 2006; Hatcher et al., 2007b). During prolonged Appalachian transpressional collision, the Brevard fault zone repeatedly deformed with high-temperature dextral slip during the Neoacadian, greenschist facies dextral reactivation during the early Alleghanian, and southeast-side-up cataclasis during the late Alleghanian (Hatcher, 2001; Merschat et al., 2005).

One of the most elusive tectonic features in the southern Appalachians is the AD. It lies near the base of a multiple-kilometer-thick package

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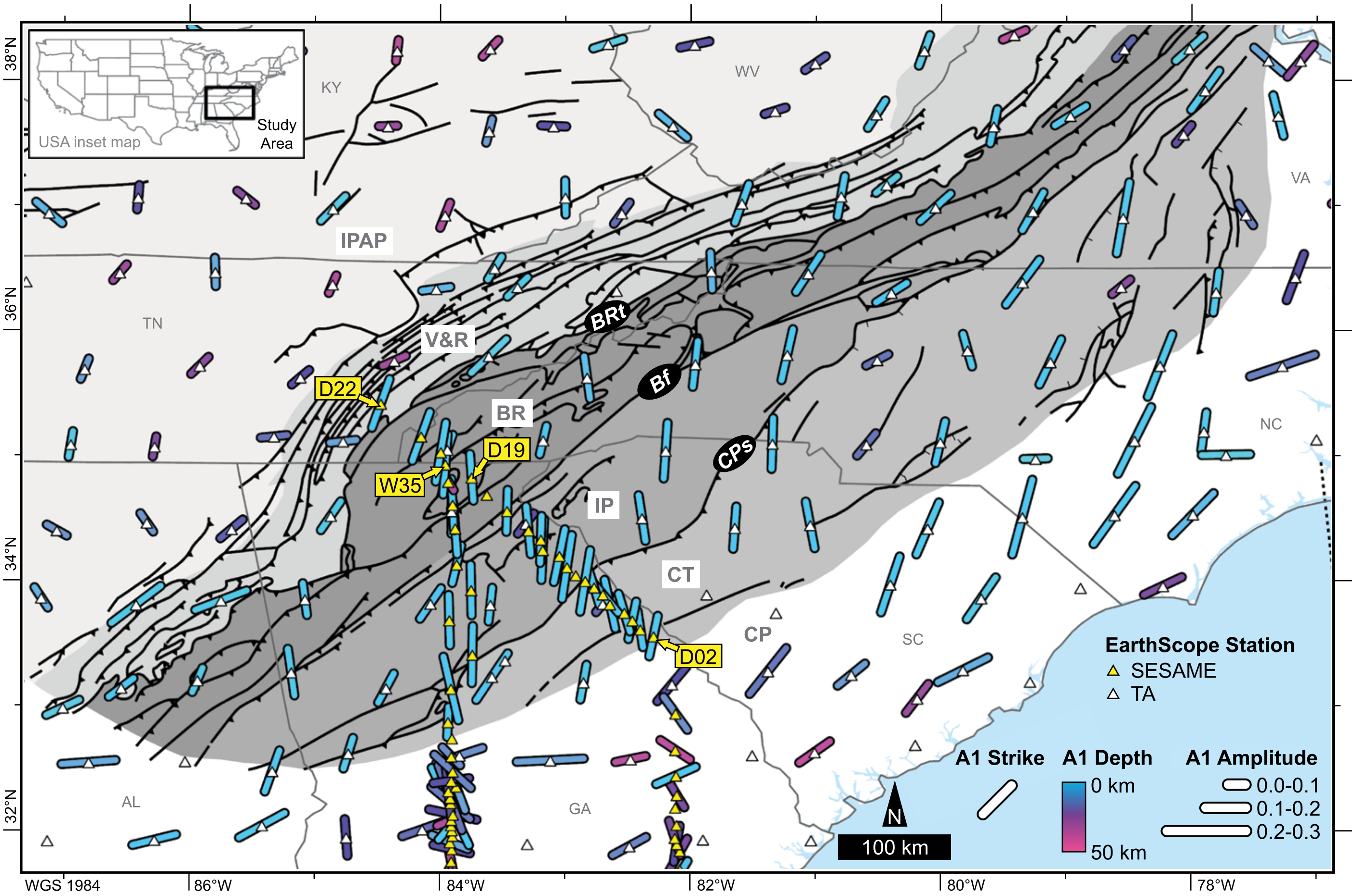

**Figure 1. Simplified map of the southern Appalachians. Tectonic provinces (grays; Hatcher et al., 2007a) include the Interior Plains–Appalachian Plateau (IPAP), Valley and Ridge (V&R), Blue Ridge (BR), Inner Piedmont (IP), Carolina Terrane (CT), and Coastal Plain (CP). Blue Ridge–Piedmont (BRP) = BR + IP + CT. Faults (black lines; Reed et al., 2005) include the Blue Ridge thrust (BRt), Brevard fault zone (Bf), and Central Piedmont suture (CPs). For each station, the largest A1 arrival (bar) is oriented by strike, colored by depth, and sized by amplitude. SESAME—Southeastern Suture of the Appalachian Margin Experiment; TA—Transportable Array; D22 to D02—cross section in Figure 2.**

of Paleozoic shelf strata, is overthrust by the BRP, and accommodated hundreds of kilometers of Alleghanian displacement (Hatcher et al., 2007b). AD geometry has been explored by numerous seismic profiles (e.g., Consortium for Continental Reflection Profiling [COCORP], Cook et al., 1979; McBride et al., 2005; Appalachian Ultradeep Core Hole [ADCOH], Coruh et al., 1987; Southeastern Suture of the Appalachian Margin Experiment [SESAME], Parker et al., 2015; Hopper et al., 2017). However, standard active/passive source experiments do not resolve three-dimensional geometry or anisotropy without specialized approaches, so AD subsurface kinematics and associated fabrics are poorly understood. Therefore, AD deformation and reactivation history remains an enticing target for interdisciplinary structural and geophysical research.

## PS RECEIVER FUNCTIONS

We examined Ps receiver functions from EarthScope Transportable Array and SESAME stations in the southern Appalachians (Fig. 1). Traditional smoothed common conversion point (CCP) stacks along the SESAME profiles show prominent conversions at the Moho (Parker et al., 2013; Hopper et al., 2017); however, some conversions also vary with backazimuth near AD depths (~5–10 km in Fig. 2C; Parker et al., 2015). To investigate these crustal structures, we analyzed conversions in radial and tangential components that reveal azimuthally varying harmonic arrivals with 360°-periodicity (A1; Levin and Park, 1998) following methods outlined by Schulte-Pelkum and Mahan (2014). A1 arrivals are particularly useful for imaging contrasts in dipping anisotropic foliation: strike is constrained at polarity flips between updip versus downdip conversions (red/blue Ps wavefronts in Fig. 2A; see a worked example in Figure S5 in the Supplemental Material[1]; Schulte-Pelkum et al., 2020a). Some conversions exhibit additional azimuthal complexity (e.g., A2; 180°-periodicity; Brownlee et al., 2017), but this paper targets A1 behavior.

The largest A1 arrival per station varies in strike, depth, and amplitude (Fig. 1), but with notable spatial trends. A1 arrivals have small amplitudes across varied crustal depths in the Interior Plains and Appalachian Plateau. Also, A1 strikes and depths are scattered in the Coastal Plain basin strata of southern Georgia and southern South Carolina. However, a prominent concentration of large-amplitude conversions with north-south strikes at ~5–10 km (a similar depth as the AD; Cook et al., 1979) is centered near the junction of North Carolina, South Carolina, and Georgia, including the SESAME D-line. We focus on these large-amplitude A1 arrivals (e.g., Fig. 2B) from stations on the BRP.

## STRUCTURAL COMPARISONS

To test if subsurface features correlate with exposed structure, we compared the orientation of A1 strikes to surface tectonic grain. First, we examined correlations between A1

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[1] Supplemental Material. Digitized structural attitudes from the Greenville 1×2° quadrangle (Nelson et al., 1998) and accompanying stereonets, CCP stacks and accompanying A1 trace profiles from SESAME D-W-lines, as well as a table of receiver function A1 arrivals with accompanying worked example and waveform plots. Please visit https://doi.org/10.1130/GEOL.S.20477700 to access the supplemental material, and contact editing@geosociety.org with any questions.

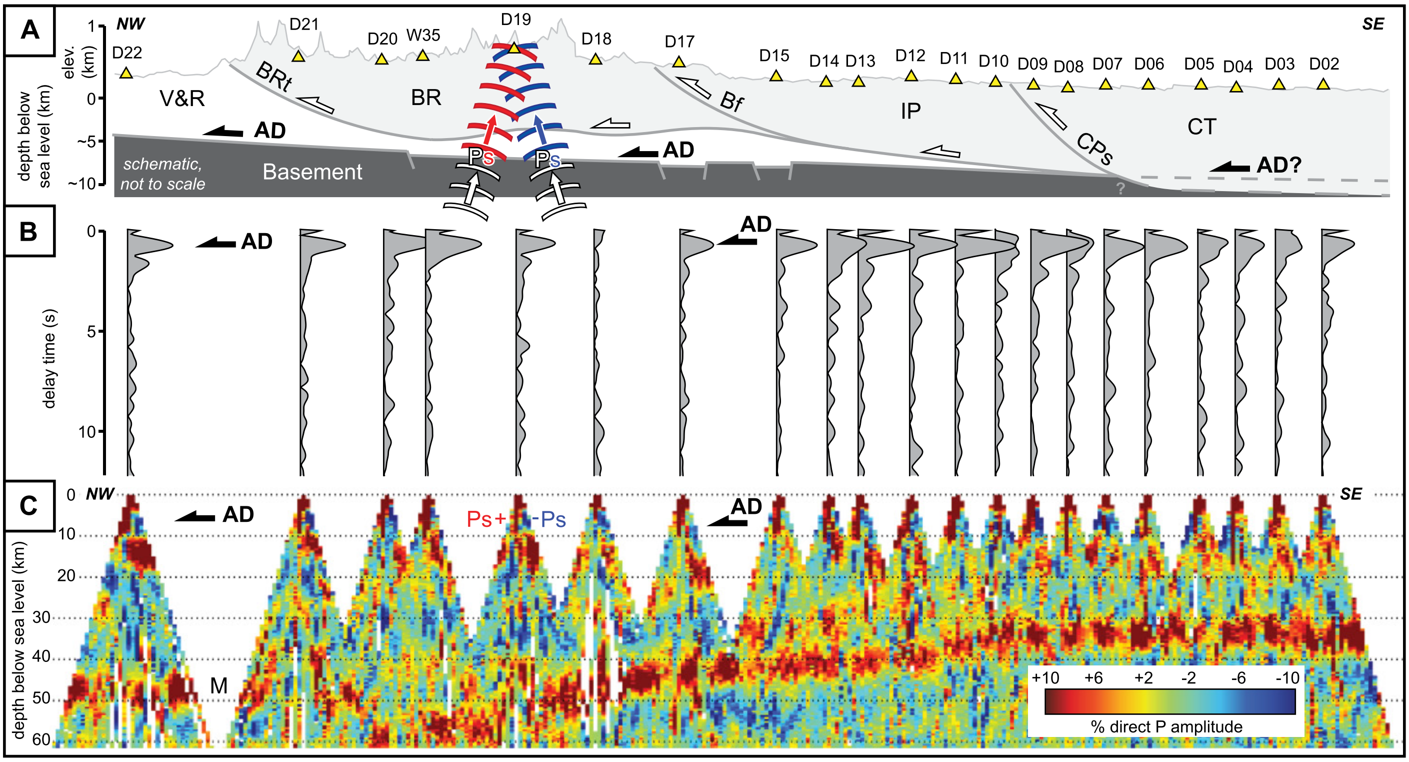

**Figure 2. (A) Southeastern Suture of the Appalachian Margin Experiment (SESAME) D-line and W35 stations overlie a schematic cross section (D22–D02 in Fig. 1); adapted from Coruh et al. (1987), Hatcher et al. (2007a), and Parker et al. (2013). (B) A1 trace profile for stations in A. (C) Radial component, unsmoothed common conversion point (CCP) stack from stations in panel A. P-waves (white wavefronts in A) convert to S-waves (Ps; colored) across the Appalachian décollement (AD), generating A1 arrivals (1 s in B) with positive polarity amplitudes (red) from the west (e.g., D19 in A and C) or northwest (e.g., D22) and negative (blue) from the east or southeast. The Moho (M) also generates conversions (C; Parker et al., 2013) but without an A1 polarity flip as seen in B.**

strikes and regional foliation. Large structural databases do not yet exist (to our knowledge) across the study area, so we digitally georeferenced foliation data from the Greenville 1×2° quadrangle (Nelson et al., 1998; Table S1). Most foliations strike northeast or are subhorizontal, and generally do not align with the north-striking A1 arrivals (Fig. S1). The foliation data set is limited in regional extent, so we made a second comparison with mapped surface fault traces from the 1:5,000,000 scale geologic map of North America (Reed et al., 2005) because the faults seamlessly extend across a much larger region. Faults serve as a proxy for surface tectonic grain in the southern Appalachians because their mapped traces are generally subparallel to foliations, fold traces, and lithologic contacts (Hatcher et al., 2007a). We split fault polylines into line segments and calculated their trends using ESRI ArcGIS Pro software (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview). Within 50 km of each seismic station, we selected all segments and used Orient 3 software (Vollmer, 2015) to calculate their undirected circular axial means (i.e., fault trends ± 180°). To quantify misorientation within each station footprint, we calculated the acute angular difference between A1 strike versus mean fault trend (Frothingham et al., 2022).

In most of the Valley and Ridge as well as the northeastern BRP in central North Carolina and Virginia, A1 strikes closely parallel the surface tectonic grain (Fig. 3). However, a large portion of the BRP shows prominent counterclockwise A1 misorientations. We discuss these north-striking A1 arrivals that are at odds with the northeast-trending tectonic grain.

## DISCUSSION

### East-Dipping Fabrics Above the Appalachian Décollement

Unsmoothed CCP stacks show a prominent contrast from ~5–10 km depth (red/blue in Fig. 2C). While a common assumption is that a shear-related foliation would parallel the boundaries of the AD or similar décollements (e.g., Hopper et al., 2017; Long et al., 2019), such a geometry would not generate A1 polarity flips.

Our results and previously unexplained azimuthal variations across the AD (e.g., Parker et al., 2015) require an inclined foliation (2+ km thickness; Schulte-Pelkum and Mahan, 2014) that terminates at a subhorizontal interface. The observed A1 peak (Fig. 2B) is generated by a contrast of an overlying east-dipping anisotropic foliation against the underlying basement. This anisotropy could be caused by clay alignment (e.g., Johnston and Christensen, 1995) in duplexed shelf strata (Coruh et al., 1987), or by aligned mica in phyllite to schist to mylonite (Godfrey et al., 2000; Ward et al., 2012) in more deeply buried and metamorphosed equivalents near the collisional hinterland (e.g., Dennis, 2007; Merschat et al., 2017). Moreover, an east-*true*-dipping foliation above the AD remains compatible with previous interpretations (Coruh et al., 1987) of imbricate faults and duplexes with southeast *apparent* dips along northwest–southeast ADCOH profiles (Fig. 4A).

A second and structurally higher conversion could theoretically occur at the base of the BRP megathrust (e.g., Parker et al., 2015), but we do not find this second A1 arrival. Therefore, a contrast in dipping fabric anisotropy across this boundary appears minimal compared to the AD. Furthermore, the single prominent A1 arrival cannot originate from the upper contact of east-dipping fabrics because such a geometry would generate an opposite polarity than is observed (Schulte-Pelkum et al., 2020a), and a conversion from the BRP megathrust's lower contact does not explain arrivals at stations outside the BRP (e.g., D22 in Fig. 2).

We propose that azimuthally varying receiver functions can elucidate the AD and other inactive structures (e.g., Frothingham et al., 2022) just as they can for active structures (e.g., Zandt et al., 2004; Schulte-Pelkum et al., 2005). Future seismic imaging of any active or extinct sub-

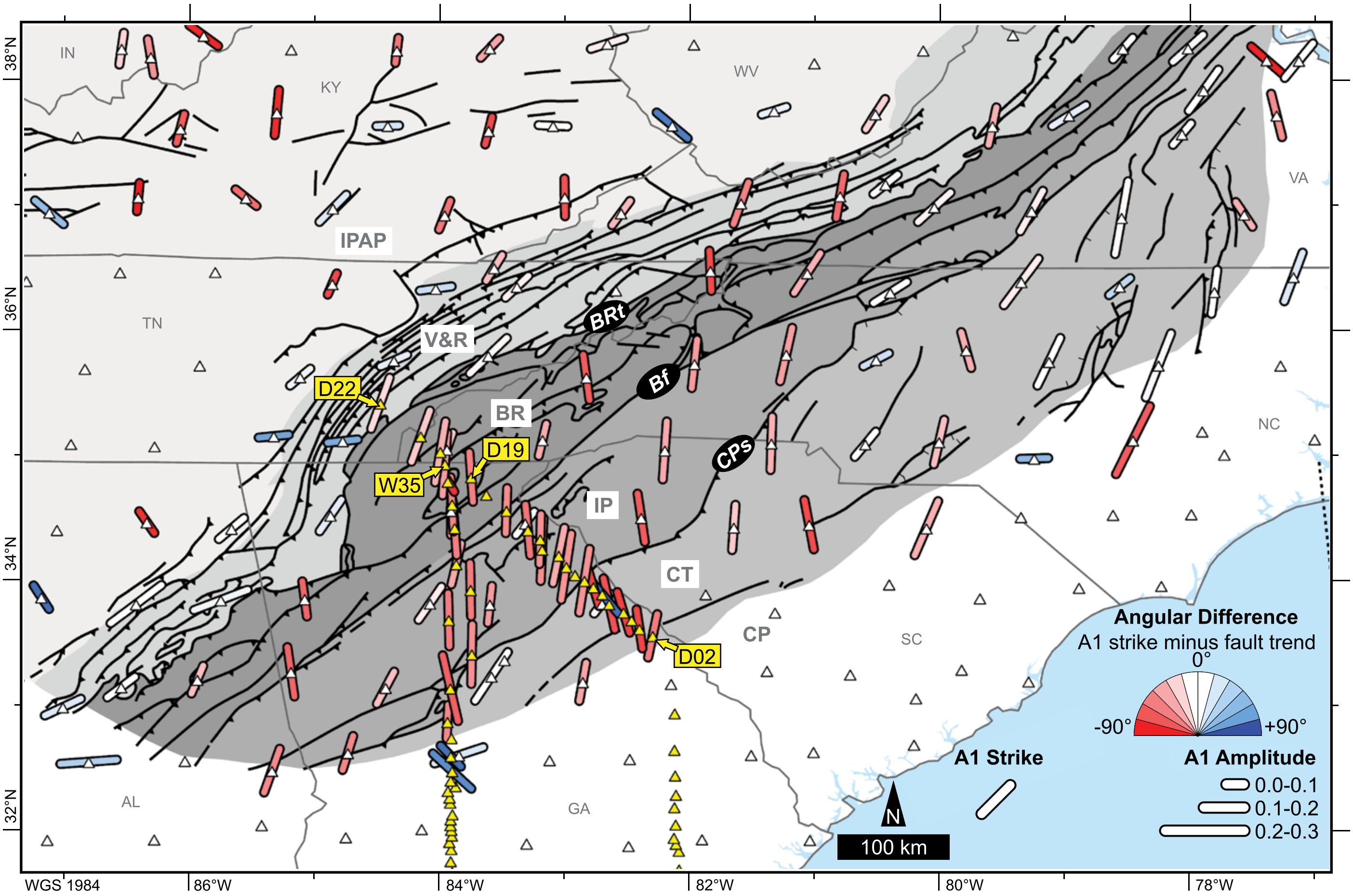

**Figure 3. Comparison map showing A1 strikes versus surface tectonic grain from Figure 1. Each station's largest A1 arrival strike (bar) is colored by its circular angular difference from the mean trend of all faults (black lines) within 50 km. IPAP—Interior Plains–Appalachian Plateau; V&R—Valley and Ridge; BR—Blue Ridge; IP—Inner Piedmont; CT—Carolina Terrane; CPs—Central Piedmont suture; Bf—Brevard fault zone; BRt—Blue Ridge thrust.**

surface structure with dipping fabric anisotropy may also benefit from azimuthal analysis, which could similarly reveal compelling tectonic implications.

## Misorientation Between A1 Strikes and Surface Tectonic Grain

Crustal A1 strikes should generally align with tectonic grain (e.g., white bars in Fig. 3; Schulte-Pelkum et al., 2020b; Frothingham et al., 2022). Therefore, the misorientation between the northeast-trending faults and north-striking A1 arrivals (red bars in Fig. 3) is unexpected. We propose that lithologic and structural variations with crustal depth can explain this discrepancy (e.g., Fig. 4; Cook et al., 1979; Coruh et al., 1987; McBride et al., 2005). However, if structurally overlying and underlying features were each reactivated or deformed at least partly during the Alleghanian orogeny (Hatcher, 2001), then why would they have different geometries?

We interpret a deformation sequence with variable influences of preexisting weaknesses to explain the subsurface fabrics and their misorientations with surface structures (Oldow et al., 1990). Northeast-trending structures in the BRP were the cumulative results of the Taconic, Neoacadian, and Alleghanian orogenies (Hatcher, 2001; Merschat et al., 2017), but the AD is solely Alleghanian (Cook et al., 1979). While the northeast-trending structural inheritance in the BRP influenced subsequent reactivation, the underlying AD should not have had such structures. Instead, preexisting weaknesses above the AD were likely in subhorizontal strata (Coruh et al., 1987). Therefore, imbricate deformation fabrics that sole down to the AD would strike perpendicular to the convergence direction with little influence from the BRP tectonic grain (e.g., Fig. 4; Hatcher et al., 2007b).

Along a SESAME D-line southeast to northwest transect, A1 strikes generally show a clockwise change in orientation as they transition from being orthogonal to nearly parallel to the surface tectonic grain (Fig. 3). We propose two end-member scenarios that could explain these spatial variations. In one case, differently oriented subsurface fabrics formed coevally. Previous work suggests that existing structures (Hatcher, 2001; Merschat et al., 2005) and along-strike variations in promontory/embayment geometries may have deflected local vergence during Appalachian collision (Macedo and Marshak, 1999; Thomas, 2006; Hatcher et al., 2007b). Possibly the Brevard fault zone and other northeast-trending rigid tectonic buttresses also localized Alleghanian AD vergence, simultaneously as southwest-, west-, and northwest-directed, depending on the structural location from hinterland to foreland.

An alternative scenario is that A1 strikes and associated foliations reveal in-sequence (foreland-propagating), spatio-temporal deformation along the AD. Previous work corroborates this second hypothesis. Temporal clockwise rotation of Alleghanian transpressional convergence (from early southwest- to west- to late northwest-directed; Hatcher, 2002; Hatcher et al., 2007a) is compatible with the spatial variations of northwest- to north- to northeast-striking A1 arrivals along the SESAME D-line (Fig. 1). The prominent set of north-striking arrivals also adds evidence for an otherwise cryptic period of west-vergence (e.g., Evans, 2010) on the AD, which may be coeval with early Alleghanian dextral reactivation of the overlying and northeast-striking Brevard fault (Fig. 4; Hatcher, 2001). Perhaps only during late Alleghanian head-on

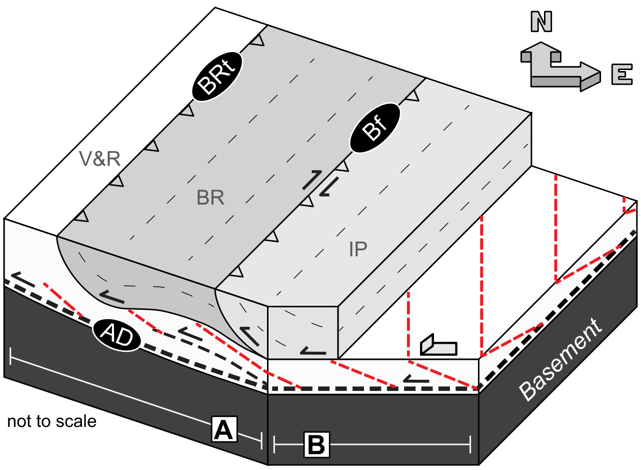

**Figure 4. Schematic block diagram, approximately along the Southeastern Suture of the Appalachian Margin Experiment (SESAME) D-line, illustrates the misorientation between surface and subsurface fabrics (see Figs. 1 and 3); adapted from Oldow et al. (1990). On the surface, faults (lines) and foliations (gray dashes) generally trend northeast. In the subsurface, the Appalachian décollement (AD, black dashes) is overlain by an east-dipping foliation (red dashes). (A) Traditional northwest-southeast profiles (perpendicular to surface tectonic grain) show southeast *apparent* dips above the AD (e.g., Cook et al., 1979; Coruh et al., 1987). However, A1 arrivals indicate that (B) a west-east profile would show east *true* dips. V&R—Valley and Ridge; BR—Blue Ridge; IP—Inner Piedmont; Bf—Brevard fault zone; BRt—Blue Ridge thrust.**

collision did inboard fabrics develop parallel to the strong, northeast-trending tectonic grain (e.g., D22 in Fig. 3; Hatcher et al., 2007b). Recognizing these distinctly oriented fabrics in the subsurface, especially where they are obscured by an oblique tectonic grain on the surface, provides a powerful tool for identifying deviations from simplistic head-on kinematics—whether in the Appalachians or other collisional orogens worldwide.

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## REFERENCES CITED

Brownlee, S.J., Schulte-Pelkum, V., Raju, A., Mahan, K., Condit, C., and Orlandini, O.F., 2017, Characteristics of deep crustal seismic anisotropy from a compilation of rock elasticity tensors and their expression in receiver functions: Tectonics, v. 36, p. 1835–1857, https://doi.org/10.1002/2017TC004625.

Cook, F.A., Albaugh, D.S., Brown, L.D., Kaufman, S., Oliver, J.E., and Hatcher, R.D., Jr., 1979, Thin-skinned tectonics in the crystalline southern Appalachians: COCORP seismic-reflection profiling of the Blue Ridge and Piedmont: Geology, v. 7, p. 563–567, https://doi.org/10.1130/0091-7613(1979)7<563:TTITCS>2.0.CO;2.

Coruh, C., Costain, J.K., Hatcher, R.D., Jr., Pratt, T.L., Williams, R.T., and Phinney, R.A., 1987, Results from regional vibroseis profiling: Appalachian ultra-deep core hole site study: Geophysical Journal International, v. 89, p. 147–156, https://doi.org/10.1111/j.1365-246X.1987.tb04401.x.

Dennis, A.J., 2007, Cat Square basin, Catskill clastic wedge: Silurian–Devonian orogenic events in the central Appalachians and the crystalline southern Appalachians, *in* Sears, J.W., et al., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 313–329, https://doi.org/10.1130/2007.2433(15).

Evans, M.A., 2010, Temporal and spatial changes in deformation conditions during the formation of the Central Appalachian fold-and-thrust belt: Evidence from joints, vein mineral paragenesis, and fluid inclusions, *in* Tollo, R.P., et al., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 477–552, https://doi.org/10.1130/2010.1206(21).

Frothingham, M.G., Mahan, K.H., Schulte-Pelkum, V., Caine, J.S., and Vollmer, F.W., 2022, From crystals to crustal-scale seismic anisotropy: Bridging the gap between rocks and seismic studies with digital geologic map data in Colorado: Tectonics, v. 41, e2021TC006893, https://doi.org/10.1029/2021TC006893.

Godfrey, N.J., Christensen, N.I., and Okaya, D.A., 2000, Anisotropy of schists: Contribution of crustal anisotropy to active source seismic experiments and shear wave splitting observations: Journal of Geophysical Research: Solid Earth, v. 105, p. 27–991, https://doi.org/10.1029/2000JB900286.

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, https://doi.org/10.1144/GSL.SP.2001.186.01.15.

Hatcher, R.D., Jr., 2002, Alleghanian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins, *in* Catalán, J.R.M., et al., eds., Variscan–Appalachian dynamics: The building of the late Paleozoic basement: Geological Society of America Special Paper 364, p. 199–208, https://doi.org/10.1130/0-8137-2364-7.199.

Hatcher, R.D., Jr., 2010, The Appalachian orogen: A brief summary, *in* Tollo, R.P., et al., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 1–21, https://doi.org/10.1130/2010.1206(01).

Hatcher, R.D., Jr., Bream, B.R., and Merschat, A.J., 2007a, Tectonic map of the southern and central Appalachians: A tale of three orogens and a complete Wilson cycle, *in* Hatcher, R.D., Jr., et al., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 1–38, https://doi.org/10.1130/2007.1200(29).

Hatcher, R.D., Jr., Lemiszki, P.J., and Whisner, J.B., 2007b, Character of rigid boundaries and internal deformation of the southern Appalachian foreland fold-thrust belt, *in* Sears, J.W., et al., eds., Whence the Mountains? Inquiries into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 243–276, https://doi.org/10.1130/2007.2433(12).

Hopper, E., Fischer, K.M., Wagner, L.S., and Hawman, R.B., 2017, Reconstructing the end of the Appalachian orogeny: Geology, v. 45, p. 15–18, https://doi.org/10.1130/G38453.1.

Johnston, J.E., and Christensen, N.I., 1995, Seismic anisotropy of shales: Journal of Geophysical Research: Solid Earth, v. 100, p. 5991–6003, https://doi.org/10.1029/95JB00031.

Levin, V., and Park, J., 1998, P-SH conversions in layered media with hexagonally symmetric anisotropy: A cookbook: Pure and Applied Geophysics, v. 151, p. 669–697, https://doi.org/10.1007/s000240050136.

Long, M.D., Benoit, M.H., Aragon, J.C., and King, S.D., 2019, Seismic imaging of mid-crustal structure beneath central and eastern North America: Possibly the elusive Grenville deformation?: Geology, v. 47, p. 371–374, https://doi.org/10.1130/G46077.1.

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, https://doi.org/10.1130/0016-7606(1999)111<1808:COTGOF>2.3.CO;2.

McBride, J.H., Hatcher, R.D., Jr., 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, https://doi.org/10.1130/B25313.1.

McHone, J.G., and Butler, J.R., 1984, Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean: Geological Society of America Bulletin, v. 95, p. 757–765, https://doi.org/10.1130/0016-7606(1984)95<757:MIPONE>2.0.CO;2.

Merschat, A.J., Hatcher, R.D., Jr., and Davis, T.L., 2005, The northern Inner Piedmont, southern Appalachians, USA: Kinematics of transpression and SW-directed mid-crustal flow: Journal of Structural Geology, v. 27, p. 1252–1281, https://doi.org/10.1016/j.jsg.2004.08.005.

Merschat, A.J., Bream, B.R., Huebner, M.T., Hatcher, R.D., Jr., and Miller, C.F., 2017, Temporal and spatial distribution of Paleozoic metamorphism in the southern Appalachian Blue Ridge and Inner Piedmont delimited by ion microprobe U-Pb ages of metamorphic zircon, *in* Law, R.D., et al., eds., Linkages and Feedbacks in Orogenic Systems: Geological Society of America Memoir 213, p. 199–254, https://doi.org/10.1130/2017.1213(10).

Nelson, A.E., Horton, J.W., Jr., and Clarke, J.W., 1998, Geologic map of the Greenville 1 degree by 2 degrees quadrangle, Georgia, South Carolina, and North Carolina: U.S. Geological Survey IMAP 2175, scale 1:250,000, https://doi.org/10.3133/i2175.

Oldow, J.S., Bally, A.W., and Avé Lallemant, H.G., 1990, Transpression, orogenic float, and lithospheric balance: Geology, v. 18, p. 991–994, https://doi.org/10.1130/0091-7613(1990)018<0991:TOFALB>2.3.CO;2.

Owens, T.J., Crotwell, H.P., Groves, C., and Oliver-Paul, P., 2004, SOD: Standing order for data: Seismological Research Letters, v. 75, p. 515–520, https://doi.org/10.1785/gssrl.75.4.515-a.

Parker, E.H., Jr., Hawman, R.B., Fischer, K.M., and Wagner, L.S., 2013, Crustal evolution across the southern Appalachians: Initial results from the SESAME broadband array: Geophysical Research Letters, v. 40, p. 3853–3857, https://doi.org/10.1002/grl.50761.

Parker, E.H., Jr., Hawman, R.B., Fischer, K.M., and Wagner, L.S., 2015, Constraining lithologic variability along the Alleghanian detachment in the southern Appalachians using passive-source seismology: Geology, v. 43, p. 431–434, https://doi.org/10.1130/G36517.1.

Reed, J.C., Jr., Wheeler, J.O., Tucholke, B.E., Stettner, W.R., and Soller, D.R., 2005, Decade of North American Geology Geologic Map of North America–Perspectives and explanation: Geological Society of America Continent-Scale Map 001, scale 1:5,000,000, https://doi.org/10.1130/DNAG-CSMS-v1.

Schmid, S.M., Fügenschuh, B., Kissling, E., and Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen: Eclogae Geologicae Helvetiae, v. 97, p. 93–117, https://doi.org/10.1007/s00015-004-1113-x.

Schulte-Pelkum, V., Monsalve, G., Sheehan, A., Pandey, M.R., Sapkota, S., Bilham, R., and Wu, F., 2005, Imaging the Indian subcontinent beneath the Himalaya: Nature, v. 435, p. 1222–1225, https://doi.org/10.1038/nature03678.

Schulte-Pelkum, V., and Mahan, K.H., 2014, A method for mapping crustal deformation and anisotropy with receiver functions and first results from USArray: Earth and Planetary Science Letters, v. 402, p. 221–233, https://doi.org/10.1016/j.epsl.2014.01.050.

Schulte-Pelkum, V., Ross, Z.E., Mueller, K., and Ben-Zion, Y., 2020a, Tectonic inheritance with dipping faults and deformation fabric in the brittle and ductile Southern California crust: Journal of Geophysical Research: Solid Earth, v. 125, p. 1–15, https://doi.org/10.1029/2020JB019525.

Schulte-Pelkum, V., Caine, J.S., Jones, J.V., III, and Becker, T.W., 2020b, Imaging the tectonic grain of the northern Cordillera orogen using Transportable Array receiver functions: Seismological Research Letters, v. 91, p. 3086–3105, https://doi.org/10.1785/0220200182.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4–11, https://doi.org/10.1130/1052-5173(2006)016[4:TIAACM]2.0.CO;2.

Vollmer, F.W., 2015, Orient 3: A new integrated software program for orientation data analysis, kinematic analysis, spherical projections, and Schmidt plots: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 49, https://gsa.confex.com/gsa/2015AM/webprogram/Paper268707.html.

Ward, D., Mahan, K.H., and Schulte-Pelkum, V., 2012, Roles of quartz and mica in seismic anisotropy of mylonites: Geophysical Journal International, v. 190, p. 1123–1134, https://doi.org/10.1111/j.1365-246X.2012.05528.x.

Weller, O.M., Mottram, C.M., St-Onge, M.R., Möller, C., Strachan, R., Rivers, T., and Copley, A., 2021, The metamorphic and magmatic record of collisional orogens: Nature Reviews: Earth & Environment, v. 2, p. 781–799, https://doi.org/10.1038/s43017-021-00218-z.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220–259, https://doi.org/10.1130/GES00055.1.

Zandt, G., Gilbert, H., Owens, T.J., Ducea, M., Saleeby, J., and Jones, C.H., 2004, Active foundering of a continental arc root beneath the southern Sierra Nevada in California: Nature, v. 431, p. 41–46, https://doi.org/10.1038/nature02847.

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