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Detrital zircon geothermochronology reveals pre-Alleghanian exhumation of regional Mississippian sediment sources in the southern Appalachian Valley and Ridge Province

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ABSTRACT

The Black Warrior foreland basin records sedimentation associated with the development of intersecting Ouachita and Alleghanian thrust belts along the southern margin of Laurentia. Mississippian–Pennsylvanian units in the Black Warrior basin are interpreted to be sourced from either the northern Appalachians and mid-continent or more regionally from the southern Appalachians or nearby Ouachita thrust belt. We present detrital zircon U-Pb ages and Th/U values from Paleozoic units that indicate zircon from the Mississippian Hartselle Sandstone are temporally and chemically compatible with being sourced from the southern Appalachians. Zircon mixing models suggest sediment was primarily recycled from Cambrian, Ordovician, and Devonian strata in the Appalachian Valley and Ridge, with minor influx from Piedmont units. A ca. 415 Ma zircon population requires additional input from the Maya Block of the Yucatan Peninsula or similar outboard terranes. We present zircon (U-Th)/He analysis and thermal history modeling of Paleozoic units, which detail pre-Alleghanian exhumation in the Appalachian Valley and Ridge. Both the Cambrian Chilhowee Group and Pennsylvanian Pottsville Formation exhibit (U-Th)/He dates ranging from 507 to 263 Ma with a Mississippian subset (353–329 Ma, n = 4), which indicates rapid cooling and inferred exhumation during Late Devonian–Early Mississippian Neoacadian tectonism. We propose a Mississippian drainage system that transported material along southern Appalachian structural fabrics to the juncture between Appalachian and Ouachita thrust belts followed by a sediment-routing rotation toward the Black Warrior foreland. This interpretation honors chemical-age zircon data, accounts for metamorphic grains in thin section petrography, and matches Mississippian–Pennsylvanian Black Warrior foreland lithostratigraphic relationships.

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1. INTRODUCTION

Detrital zircon geochronology provides insight to ancient drainage networks for interpreting sedimentary provenance (Dickinson and Gehrels, 2009; Gehrels et al., 2011; Thomas, 2011; Blum et al., 2017). In synorogenic sedimentary systems, the detrital zircon record can resolve the rerouting of drainage systems, uplift and burial of potential sediment sources, and changes in magmatism (DeCelles et al., 2007; Thomas et al., 2015; Bhattacharya et al., 2020). However, challenges remain for deciphering multigenerational sediment recycling from first-generation strata that exhibit similar zircon age spectra. Sediment sources with similar zircon ages but varying differences in relative proportions also prove difficult to interpret without additional context or information.

Analytical geochemical techniques have improved the ability to collect trace-element compositions to complement mineral age data (i.e., petrochronology; Kylander-Clark et al., 2013). The application of igneous petrochronology (e.g., Grimes et al., 2007, 2015) to the detrital record provides opportunities to interpret sedimentary sources that include similar aged source rocks or when age populations are ubiquitous and otherwise indistinguishable (Degraff Surpless et al., 2019). Unfortunately, these new approaches are difficult to apply to existing data sets without the collection of new trace-element analyses, limiting the application of detrital petrochronology to future data sets. Because thorium (Th) and uranium (U) concentrations are collected and reported as part of standard zircon U-Pb analysis by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS), coupling Th/U information with U-Pb ages provides a bridge for correlating new and existing petrochronology data sets. Magmatic and metamorphic processes control Th and U in zircons (Kirkland et al., 2015). In the western United States and southern Gondwana, lower Th/U (<0.75) in zircon is linked to cycles of convergent arc magmatism, whereas variable Th/U zircon that include elevated Th/U (>1.0) zircon populations are associated with slab rollback extension (McKay et al., 2018a). Yakymchuk et al. (2018) use a global data set to show that metamorphic zircons commonly contain Th/U <0.10, while igneous zircon Th/U values are dominantly >0.20.

The Black Warrior foreland basin, at the juncture between the southernmost Appalachian and easternmost Ouachita thrust belts, provides a record of Mississippian through Pennsylvanian flexural subsidence and sedimentation of the Ouachita-Appalachian orogeny. Due to differences in source rocks and paleogeographic reconstructions between the Ouachita and Appalachian orogenic systems (Thomas, 1988, 2010), clastic units in the

Black Warrior basin represent a natural laboratory to utilize detrital zircon chemical-age relationships. The provenance of the Upper Mississippian Hartselle Sandstone unit has been debated for more than 40 years. Original lithostratigraphic relationships and thin section petrography promote a sediment source from the southwest associated with the Ouachita thrust belt (Graham et al., 1976; Mack et al., 1981; Thomas and Mack, 1982). Recent U-Pb detrital zircon studies of the Hartselle Sandstone interpret a sediment source to the northwest based on the presence of zircon age populations at ca. 415, 1300–1500, and >2500 Ma (Xie et al., 2016; Gifford et al., 2020). A third provenance hypothesis for the Hartselle Sandstone, which has received less attention, involves sourcing material from the southern Appalachians to the southeast.

To test these models, we present detrital zircon U-Pb ages with their corresponding Th/U ratios, as well as zircon (U-Th)/He data from potential Paleozoic source rocks in the southern Appalachian thrust belt. The objective of this study is to determine whether Paleozoic, Proterozoic, and Archean zircon populations, used to interpret a northern Appalachian and Mid-Continent sediment source, can be found in the southern Appalachians. We aim to evaluate the timing of exhumation and availability of Paleozoic strata prior to and during the Mississippian–Pennsylvanian, because potential source rocks must be exposed at the surface during deposition of the unit to which they are supplying material. This study provides an example of how to resolve inconsistencies in sediment source interpretations based on U-Pb ages by requiring zircon sediment sources to match basin deposits in both age and composition. Our results also highlight the complexity of sediment recycling for interpreting detrital geochronology data sets and the ability for zircon chemical (Th/U) and zircon-helium data to aid in correlating sediment source rocks to subsequent deposits.

2. GEOLOGIC BACKGROUND

The Appalachian Mountains record four major tectonic phases of mountain building over the past 1.3 billion years. The Meso- to Neoproterozoic Grenville orogeny (1.3–1.0 Ga) records the amalgamation of various continental blocks to form the supercontinent Rodinia (Tollo et al., 2004). Subsequent, extensional collapse in the Grenville orogenic belt (Streepey et al., 2004) and pulses of regional extension occurred from ca. 760–615 Ma until 570–550 Ma, culminating in the opening of the Iapetus Ocean (Aleinikoff et al., 1991, 1995; Cawood et al., 2001; O'Brien and van der Pluijm, 2012). A Cambrian–Ordovician passive margin then developed where sedimentation mixed recycled Grenville-sourced detritus with lesser amounts of local, synrift and mid-continental, Granite Rhyolite province (1.5–1.3 Ga)–derived sediment (Bream et al., 2004; Thomas, 2011; Thomas et al., 2017).

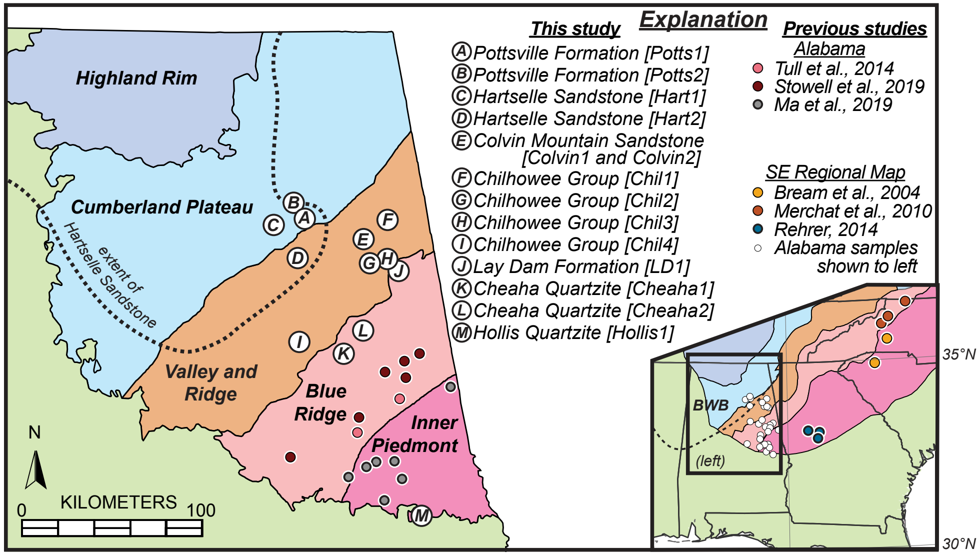
In the Early Ordovician, subduction initiated outboard of the Laurentian passive margin resulting in a series of volcanic arcs (Hatcher, 2010). In the southernmost Appalachians, backarc extension may have separated the Laurentian craton from outboard arcs (Tull et al., 2014; Barineau et al., 2015). Accretion of these arcs defines the Taconic orogeny (490–420 Ma), which led to mid-crustal metamorphism throughout the Appalachian Mountains and sedimentation into an Ordovician foreland basin system (Bayona and Thomas, 2003). Taconic magmatism in the Southern Appalachians (Tennessee, North Carolina, Georgia, and Alabama) is recorded by ca. 460 Ma plutons in the Piedmont province (Miller et al., 2000; Hatcher et al., 2007; Hatcher, 2010). In Alabama, evidence for Taconic metamorphism is not readily recognized (Stowell et al., 2019), but Ordovician clastic sedimentary sequences in the foreland have been correlated with erosion of the rising Taconic highlands of Tennessee and North Carolina (Bayona and Thomas, 2003). Continued subduction along the Laurentian margin resulted in accretion of exotic terranes defining the Acadian orogeny (420–350 Ma), which is recorded by (1) mid- to lower-crustal metamorphism in the southern Appalachians within the Blue Ridge province of the Appalachian Piedmont (Stowell et al., 2019) and (2) Devonian–Mississippian clastic wedges in the northern, central, and southern Appalachians (Osberg et al., 1989). In the southernmost Appalachians, Late Acadian (also known as the Neoacadian; 370–350 Ma) metamorphism and magmatism temporally grade into the start of the Alleghanian orogeny at ca. 325 Ma (Osberg et al., 1989; Stowell et al., 2019).

2.1 Alleghanian-Ouachita Orogeny

The Alleghanian-Ouachita orogeny (330–270? Ma) resulted from a continent-continent collision between Gondwana and Laurentia that folded and faulted Cambrian through Pennsylvanian–Permian strata. Unmetamorphosed strata that are deformed by Appalachian folds and faults extend from eastern Canada to Alabama and define the Appalachian Valley and Ridge province (Fig. 1; Secor et al., 1986; Becker et al., 2005). In the southern Appalachian Valley and Ridge, the Pennsylvanian Pottsville Formation is the youngest unit within fold and thrust belt structures; however, exposures of Permian strata in the central Appalachian Mountains of West Virginia are present within Valley and Ridge structures, bracketing deformation in the central Appalachian foreland basin to Permian or later (Becker et al., 2005; Schneider et al., 2013). Permian deformation of the Valley and Ridge is consistent with thermochronology estimates for uplift and exhumation in portions of the Appalachian Piedmont (288–268 Ma hornblende and biotite-argon cooling ages; Dallmeyer et al., 1986; Secor et al., 1986; Steltenpohl et al., 2008, and references therein). The northeast-southwest–striking Appalachian Mountains transition in the subsurface to the Ouachita Mountain belt in the Alabama Promontory in west-central Alabama and continue to the northwest and west before being exposed in central Arkansas and eastern Oklahoma.

2.2 Black Warrior Foreland Basin

The Black Warrior basin represents the easternmost foreland of the Ouachita system and is located at the juncture between Ouachita and Appalachian thrust belts (Thomas, 1977, 1991, 2010). The eastern Ouachita thrust front trends in a northwest-southeast direction across the southwestward side of the Black Warrior basin (Thomas, 1988). Flexural



[Samples from the Ouachita Mountains to the west not shown]

Figure 1. Physiographic provinces of Alabama (left) with sample locations. Samples from Ma et al. (2019) and Bream et al. (2004) are shown and included for discussion. Extent of the Hartselle Sandstone from the zero isopach line from Thomas (1972). Black Warrior basin (BWB) shown in inset map.

subsidence associated with Ouachita loading predates Appalachian flexural loading (Thomas, 1988; Whiting and Thomas, 1994) and subsurface Ouachita structures are cut by later Appalachian (Alleghanian) structures (Robinson et al., 2012), suggesting deformation in the Ouachita belt predates deformation in the southern Appalachian Mountains to the east (Thomas, 2010). Unlike the Appalachian thrust belt to the east, the Ouachita thrust belt lacks the exposure of adjacent hinterland assemblages due to Jurassic rifting, extensional subsidence, and burial under southeastern Coastal Plain sediments related to opening of the Gulf of Mexico (Thomas, 2010) and the easternmost extent in eastern Arkansas and Mississippi is buried beneath Coastal Plain sediments in the Mississippi Embayment.

The Black Warrior basin consists of Cambrian through Pennsylvanian carbonate and clastic strata. Cambrian through Mississippian strata record deposition on a Paleozoic passive margin that developed in response to Rodinia rifting and removal of the Argentina precordillera along the Alabama-Oklahoma transform (Thomas and Astini, 1996, 2003; Thomas et al., 2004). Passive-margin sedimentation persisted into the Mississippian along the southwestern side of the Alabama Promontory, unlike in the southeast, which records sedimentation associated with the Taconic and Acadian/Neoacadian tectonism (Ferrill and Thomas, 1988; Haynes and Goggin, 2011). Mississippian and lower Pennsylvanian strata in the Black Warrior basin record sedimentation associated with Ouachita tectonism to the southwest (Thomas, 1976; Viele and Thomas, 1989; Pashin and Rindsberg, 1993), which ultimately transitions to Appalachian/Alleghanian–derived sedimentation in the Pennsylvanian (Graham et al., 1976; Liu and Gastaldo, 1992).

2.3 Mississippian Hartselle Sandstone

The Mississippian Hartselle Sandstone (Fig. 2) is a light-gray to white-colored, well-sorted, fine-grained quartzose sandstone that generally exhibits massive bedding (Thomas, 1972). The Hartselle Sandstone overlies the Mississippian Pride Mountain Formation and Mississippian Monteagle Limestone and is beneath the Mississippian Bangor Limestone. The Hartselle Sandstone outcrops in the northern part of the Black Warrior foreland basin and is included within some Alleghenian thrust sheets in the southern Appalachian Valley and Ridge province. The Hartselle Sandstone unit continues to the southwest in the subsurface of the Black Warrior basin, where it reaches a maximum stratigraphic thickness of ~50 m (Thomas, 1972; Hills et al., 2016). The overall trend of the Hartselle Sandstone is northwest-southeast, laterally grading into the Floyd Shale to the southwest, the Monteagle Limestone to the northeast (Thomas, 1972), and the Golconda Formation in the Illinois basin to the north (Driese et al., 1994). Thomas and Mack (1982) observe horizontally laminated, well-sorted sand facies, multiple cross-bed sets, rippled sandstone, interbedded cross-bed and ripple sand facies, and interbedded fine-grained sand with ripples and massive mudstone facies. These sedimentological observations, coupled with the spatial and thickness distribution, suggest barrier-island, shelf bar, and lagoon depositional environments for the Hartselle Sandstone (Thomas and Mack, 1982). The Hartselle Sandstone represents one of the initial influxes of clastic material associated with flexural subsidence and Ouachita tectonism; thus, it is important to evaluate the provenance of this unit within the foreland strata of the Black Warrior basin.

3. SEDIMENTARY SOURCE INTERPRETATION OF THE HARTSELLE SANDSTONE

3.1 Ouachita Source

The Black Warrior and Ouachita foreland basins have long been hypothesized to share a common sedimentary source because of the similarity in Carboniferous sandstone compositions from both basins (Graham et al., 1976). Sandstone

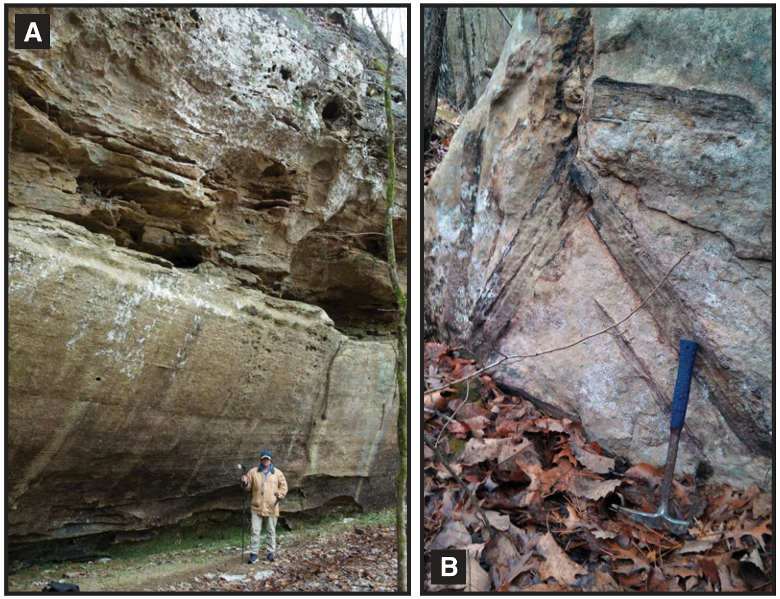


Figure 2. Field photographs of the Hartselle Sandstone from (A) outcrop near Rattlesnake Saloon, Barton, Alabama; (B) fossil logs in the Hartselle Sandstone near Attala, Alabama (eastern Alabama).

compositions are defined by the abundance of recycled metamorphic lithic grains alongside few igneous grains. The lack of igneous grains and presence of metamorphic grains suggests a proximal, mixed metamorphic and sedimentary rock source (Graham et al., 1975; Mack et al., 1981, 1983). Mississippian and early Pennsylvanian sediment in the Black Warrior foreland is interpreted to be sourced from the Ouachita thrust belt to the southwest due to a lack of known Mississippian deformation in the southern Appalachian thrust belt, documented flexural subsidence related to an Ouachita tectonic load, and southwest to northeast thinning of a prograding, synorogenic clastic wedge (Mack et al., 1981; Thomas and Mack, 1982; Mack et al., 1983). Thomas et al. (2003) demonstrate that Alleghanian-aged, syn-orogenic sediment is notably missing from Mississippian–Pennsylvanian sandstone units in the Black Warrior basin, suggesting that Alleghanian crystalline rocks are not integrated into the Carboniferous foreland basin drainage, possibly because the crystalline suites have not been unroofed at that time.

During Mississippian and early Pennsylvanian time, the southern Appalachian foreland basin was dominated by carbonate facies to the northeast (in northeast Alabama, eastern Tennessee, and northern Georgia), north (central Tennessee), and northwest (Ozarks), where Mississippian limestone is hundreds of feet thick (Thomas, 1972; Pashin and Gastaldo, 2009), precluding sediment transport from those directions and also suggests minimal subsidence. In comparison, in the southwestern Black Warrior basin, sequences of Carboniferous clastic strata thicken toward the southwest to in excess of 300 m (Thomas, 1972) and thin toward the northeast. These observations further complement the interpretation of linking the Black Warrior basin with Ouachita tectonism, since earlier Ouachita tectonism would, therefore, be responsible for subsidence and sediment generation that may predate major uplift in the Appalachian Mountains. However, the inability to directly compare Ouachita thrust belt rocks to foreland Black Warrior basin deposits has limited confirmation or exclusion of a Ouachita source. Absence of identifiable Mississippian clastic feeder systems (deltaic and fluvial deposits) also represents a major unresolved issue for determining the Hartselle Sandstone provenance (Thomas and Mack, 1982).

3.2 Northern Appalachian and Mid-Continent Source

Driese et al. (1994) interpret the Hartselle Sandstone to be sourced from the north-northwest based on a regional unconformity in the underlying Mississippian Monteagle Limestone. Sediment drainages for the Hartselle Sandstone have been reinterpreted using U-Pb detrital zircon. Zircon populations associated with the Granite Rhyolite (1.3–1.5 Ga), Yavapai–Mazatzal (1.6–1.8 Ga), and Superior (>2.5 Ga) ages motivate interpretations that include a drainage system that transported intra-cratonic sediment from the northern Midwest/Great Lakes region (Xie et al., 2016; Gifford et al., 2020). The Hartselle Sandstone also contains a ca. 415 Ma zircon population that is best documented within early Acadian-age rocks in the Northern Appalachian Mountains (Xie et al., 2016; Gifford et al., 2020). Gifford et al. (2020) interpret the presence of sillimanite in thin-section petrography to reflect a metamorphic source, which would be compatible with a northern Appalachian provenance. Thus, this inferred drainage mixed Paleozoic grains from the northern Appalachians with mid-continental sources and can substantiate a compositionally mature Hartselle Sandstone that includes lithic metamorphic detritus.

Thomas and Mack (1985) note that a north-northwest sediment source for the Hartselle is inconsistent with lithostratigraphic relationships, discriminatory thin-section petrography, and sedimentological field observations. Similar to a southwest source problem, outcrop evidence for clastic input via Mississippian feeder systems to the northwest is absent. Driese et al. (1994) suggest large Mississippian fluvial feeder channels that transported material to the south-southeast similar to Pennsylvanian channel deposits in Missouri and southern Illinois that disconformably overlie carbonate facies. This interpretation requires Mississippian channels to be subsequently removed by erosion. However, the subsequent erosion and removal of large fluvial channels is more likely to the southwest because of the folding and faulting (and presumable exhumation) of the Ouachita foreland thrust belt. North-northwest channels would be located in regions dominated by Paleozoic carbonate deposits that remain largely undeformed. A continental-scale drainage system during the Upper Mississippian is also difficult to integrate into paleo-geographic reconstructions. The mixing of northern Appalachian and Mid-Continent material requires sediment transport around and or through multiple active depositional centers (Appalachian foreland, Michigan Basin, and Illinois Basin). Finally, the presence of sillimanite is a non-unique provenance indicator, in that it only substantiates a metamorphic sediment source component. Sillimanite is present in the southern Appalachian Piedmont of Alabama and Georgia (Rheams, 1986) and presumably would be present in metamorphic sequences in the Ouachita thrust belt.

3.3 Southern Appalachian Source

Pennsylvanian Pottsville sandstone and conglomerate layers in the Cahaba synclinorium are interpreted to be sourced from the southern Appalachian thrust belt to the southeast (Pashin, 1999; Greb et al., 2008). Uddin et al. (2016) report detrital biotite $^{40}Ar/^{39}Ar$ and thin-section petrography that correlates Pottsville Formation detritus to the southern Appalachian metamorphic hinterland. Influx of sediment from the southeast is interpreted to be associated with late-stage exhumation into the synorogenic foreland system, onlapping the two merging clastic wedges from the southwest and northeast (Greb et al., 2008).

Flexural subsidence analysis suggests sediment influx from the southeast did not initiate until the Pennsylvanian (Whiting and Thomas, 1994; Pashin, 1999). The timing of flexure and the southwest to northeast trends in the clastic wedge have excluded a southern Appalachian thrust belt sediment source for Mississippian strata in the Black Warrior basin. In addition, timing of deformation in the southern Appalachian thrust belt has excluded Paleozoic strata in the Valley and Ridge from being considered viable sediment sources. However, Paleozoic clastic units in the southern Appalachians were deposited in a passive-margin setting (Cambrian Chilhowee Group) and distal forelands (Ordovician Colvin Mountain and Devonian Frog Mountain sandstones) and therefore have the ability to include sediment from numerous North American lithotectonic terranes (Thomas, 2011). Recycling Paleozoic clastic units could also explain the mature composition for the Hartselle Sandstone unit; however, limited U-Pb detrital zircon data are available from the underlying Valley and Ridge strata to assess this potential source for the Hartselle Sandstone.

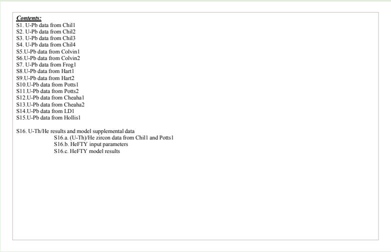
4. U-Pb AND Th/U IN ZIRCON

4.1 Methods

We present U-Pb detrital zircon ages from 11 Paleozoic sandstone units in the southern Appalachian Valley and Ridge and Cumberland Plateau, three metasedimentary rocks from the Talladega Belt (western Blue Ridge province), and one quartzite from the Pine Mountain window within the Inner Piedmont. Sandstone units include samples from the Cambrian Chilhowee Group (*Chil1–Chil4*); the Ordovician Colvin Mountain Sandstone (*Colvin1* and *Colvin2*); the Devonian Frog Mountain Formation (*Frog1*); the Mississippian Hartselle Sandstone (*Hart1* and *Hart2*); and the Pennsylvanian Pottsville Formation (*Potts1* and *Potts2*). Cambrian Chilhowee Group samples were collected in the hanging wall of the Jacksonville thrust fault (Osborne and Szabo, 1988) and Coosa deformed belt (Thomas and Drahovzal, 1988; Thomas et al., 2016), which represent the easternmost, highest structural position in the Valley and Ridge province. Ordovician Colvin Mountain Sandstone (*Colvin1* and *Colvin2*) samples are from the Helena thrust sheet. The Devonian Frog Mountain sandstone sample is from the frontal tier of the Coosa deformed belt (Bearce et al., 2004). Mississippian Hartselle Sandstone samples are from outcrops along the southeastern limb of the Murphrees Valley anticline (*Hart1*) and in the hanging wall of the Dunaway Mountain thrust fault (Irvin et al., 2018; *Hart2*). Pennsylvanian Pottsville Formation samples are from the southeastern limb of the Blount Mountain syncline (*Potts1*) and northwestern limb of the Blue Mountain syncline and southeastern limb of the Murphrees Valley anticline (*Potts2*). Metasedimentary samples from the Lay Dam Formation, including the Cheaha Quartzite (N = 3; n = 347; Fig. 3E), were selected to characterize the detrital zircon signal of the Appalachian western Blue Ridge in Alabama. A sandstone from the Hollis Quartzite (*Hollis1*) was sampled to add to published age controls for the zircon signature of the Inner Piedmont.

Zircon grains were extracted using standard mineral extraction techniques at Missouri State University, and U-Pb analyses were conducted at the University of Arkansas Trace Element and Radiogenic Isotope Laboratory. Grains were ablated with a 20–25 mm spot using an ESI NWR 193 nm Excimer laser and analyzed with a Thermo-Scientific iCapQ quadrupole mass spectrometer (results included in Tables S1–S15 in the Supplemental Material[1]). Analyses that yielded ^{238}U-^{206}U and ^{207}Pb-^{206}Pb ages that were >20% discordant were excluded from further consideration. Best age is reported using the $^{238}U/^{206}Pb$ for ages <1200 Ma and $^{207}Pb/^{206}Pb$ ages for analyses >1200 Ma (Puetz et al., 2018; Sundell et al., 2020).

Additional samples from the southern Appalachian Blue Ridge and Inner Piedmont provinces, including metasedimentary and igneous rocks within the Ashland-Wedowee Groups (Tull et al., 2014; Stowell et al., 2019) of eastern Alabama, Dadeville Complex of eastern Alabama (Ma et al., 2019), Cat Square terrane of North Carolina, Tennessee, and Georgia (Bream et al., 2004; Merschat et al., 2010; Rehrer, 2014), are included in our evaluations. Samples were selected if (1) the U-Pb analyses reported U and Th (ppm) concentrations; (2) the zircon age spectra contained Paleozoic populations; and (3) multi-sample data sets contain >100


Contents:
S1. U-Pb data from Chil1
S2. U-Pb data from Chil2
S3. U-Pb data from Chil3
S4. U-Pb data from Chil4
S5.U-Pb data from Colvin1
S6.U-Pb data from Colvin2
S7. U-Pb data from Frog1
S8.U-Pb data from Hart1
S9.U-Pb data from Hart2
S10.U-Pb data from Potts1
S11.U-Pb data from Potts2
S12.U-Pb data from Cheaha1
S13.U-Pb data from Cheaha2
S14.U-Pb data from LD1
S15.U-Pb data from Hollis1

S16. U-Th/He results and model supplemental data
S16.a. (U-Th)/He zircon data from Chil1 and Potts1
S16.b. HeFTY input parameters
S16.c. HeFTY model results

[1]Supplemental Materials. U-Pb zircon data, U-Th/He data, and HeFTy models. Please visit **https://doi.org/10.1130/GEOS.S.14992341** to access the supplemental material, and contact editing@geosociety.org with any questions.

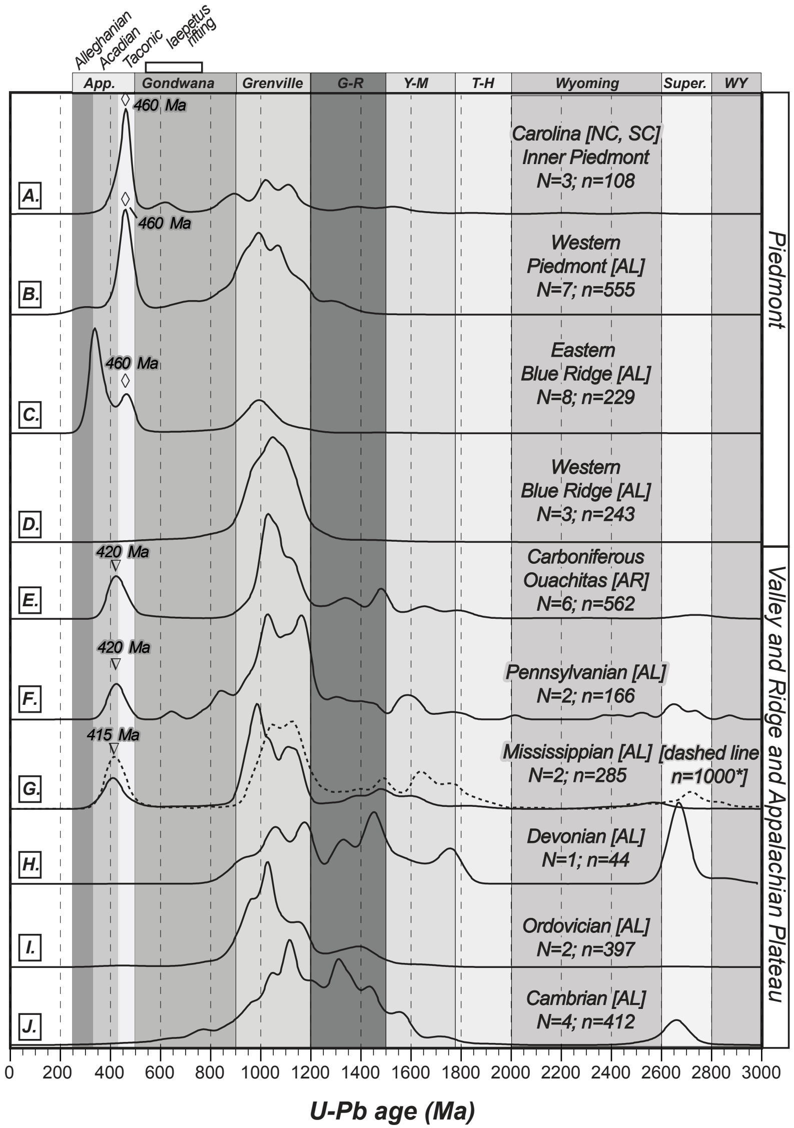


Figure 3. Kernel density estimates for samples (sources specified in Figures 1 and 4): (A) North/South Carolina Inner Piedmont; (B) Alabama western Piedmont; (C) Alabama eastern Blue Ridge; (D) Alabama western Blue Ridge; (E) Arkansas Carboniferous Ouachitas; (F) Alabama Pennsylvanian Valley and Ridge; (G) Mississippian Alabama Valley and Ridge; (H) Alabama Devonian Valley and Ridge; (I) Alabama Ordovician Valley and Ridge; and (J) Alabama Cambrian Valley and Ridge.

n-values, if available. U-Pb zircon ages from Carboniferous strata within the Arkoma basin along the Ouachita thrust front in Arkansas and Oklahoma (Prines, 2020) are also included to provide a comparison with strata in the Ouachita foreland basin. A summary of U-Pb ages, compiled from lithotectonic units in the Appalachian Piedmont is provided in Table 1.

4.2 U-Pb Detrital Zircon Ages

4.2.1 Paleozoic Sandstone Samples

Detrital zircon ages from the Cambrian Chilhowee Group (N = 4; n = 412; Fig. 3J) span from 348 to 3380 Ma. Zircon ages are within the age ranges for the Grenville orogeny (0.9–1.2 Ga) and Granite-Rhyolite province (1.2–1.5 Ga). A small population of ca. 2.7 Ga zircon is present in two of four samples, being absent in sample *Chil3*, which only yielded 32 concordant zircon ages, and *Chil4*. The depositional age of the Chilhowee Group is Cambrian (Mack, 1980), and samples yielded five zircon ages that are Cambrian or younger. Of the five analyses younger than the depositional age, three produced U concentrations of >3000 ppm, suggesting these ages are related to Pb loss.

Detrital zircon from the Colvin Mountain Sandstone (N = 2; n = 397; Fig. 3I) contain grains that are between 416 and 2674 Ma in age. A Grenville population (0.9–1.2 Ga) dominates the sample, with a secondary peak of Granite-Rhyolite province grains. Post-Grenville grains include nine grains <800 Ma, with four grains that yield a weighted mean age of 440 ± 5 Ma (mean square of weighted deviates [MSWD] = 2.2).

Detrital zircon from the Frog Mountain Formation (N = 1; n = 44; Fig. 3H) span from 897 to 2863 Ma. Populations of Grenville (0.9–1.2 Ga), Granite-Rhyolite (1.2–1.5 Ga), and Yavapai–Mazatzal (1.6–1.8 Ga) age are in relatively comparable proportions. A ca. 2.7 Ga zircon population (n = 9) forms the largest peak and a weighted mean of 2695 ± 14.7 Ma (MSWD = 1.78).

Detrital zircon ages from the Mississippian Hartselle Sandstone (N = 2; n = 285; Fig. 3G) span

TABLE 1. U-Pb ZIRCON SAMPLES INCLUDED AS POTENTIAL APPALACHIAN SOURCE ROCKS

Reference	Sample ID	Lithotectonic unit	Approximate age populations
Bream et al., 2004	BCTF (n=39)	Cat Square terrane gneisses (Fig. 3A)	450 Ma, 1.0 Ga
	GR1 (n=30)		450 Ma, 1.1 Ga
Merschat et al., 2010	EL2 (n=40)	Cat Square terrane gneisses (Fig. 3A)	450 Ma, 1.1, 1.4, 1.6 Ga
Tull et al., 2014	AZ1a (n=36)	Emuckfaw Group (Josie Leg Fm) (Fig. 3D)	450 Ma, 1.1 Ga
	AZ5 (n=64)	Wedowee Group (Fig. 3D)	530-400 Ma
Ma et al., 2019	AG1-14 (n=160)		900 Ma, 1.1 Ga
	CM-AL3 (n=24)	Agricola Schist (Fig. 3C)	394 Ma
	CM-AL4 (n=144)		700, 950 Ma, 1.1 Ga
	CH-1 (n=20)	Camp Hill Gneiss (Fig. 3C)	480 Ma
	RCA-FL6 (n=39)	Ropes Creek Amphibolite (Fig. 3C)	458 Ma
	WA-1 (n=36)	Waverly Gneiss (Fig. 3C)	454, 402 Ma
	WS-1 (n=20)	Waresville Formation (Fig. 3C)	465 Ma
	cmtbc (n=32)	Emuckfaw Group (Fig. 3D)	408 Ma, 1.0, 1.2 Ga
Stowell et al., 2019	ALMOND1 (n=23)	Almond trondhjemite (Fig. 3D)	347 Ma
	ALMOND2 (n=21)	Almond trondhjemite (Fig. 3D)	324, 349 Ma
	ROCK1 (n=12)	Rockford granite (Fig. 3D)	377, 390 Ma
	WP1 (n=9)	Wedowee pluton (Fig. 3D)	335 Ma
	BSG1 (n=9)	Bluff Springs granite (Fig. 3D)	366 Ma
	BF09 (n=23)	Blakes Ferry pluton (Fig. 3D)	346 Ma

from 349 and 2844 Ma. Grenville-age zircons create peaks in the kernel density estimate (KDE) at 900 and 1100 Ma. A secondary peak of ca. 425 Ma is present, with lesser distinct populations of Granite-Rhyolite province and older zircon grains. The ten youngest grains (<400 Ma) produce a weighted mean age of 374 ± 2.7 Ma (MSWD = 4.6).

Detrital zircons from the Pennsylvanian Pottsville Formation (N = 2; n = 166; Fig. 3F) yield ages from 386 to 2,875 Ma. Two major Grenville-age peaks are present in the Pennsylvanian samples, occurring at 1150 and 1050 Ma, with a small, diffuse peak of Granite-Rhyolite-age grains and a ca. 386–473 Ma population composed of 12 grains.

4.2.2 Piedmont Metasedimentary Samples

Zircon ages from the Cheaha Quartzite (N = 3; n = 243; Fig. 3D: Western Blue Ridge) range from 439 to 2734 Ma, with a near-bimodal distribution of ages between ca. 1100 Ma Grenville-age and ca. 1300 Ma Granite-Rhyolite province as peaks. Only three Paleozoic grains (439, 496, and 554 Ma) were present in the Lay Dam Formation samples. Additional data from Ma et al. (2019) and Bream et al. (2004) are presented (Fig. 3C; Eastern Blue Ridge) to augment the sample distribution of this study. To the southeast, zircons from the Hollis Quartzite (N = 1; n = 133; Fig. 3B), within the Pine Mountain structural window, yield ages from 267 Ma to 1442 Ma. The spectrum of ages from the Hollis Quartzite contains a large Grenville population, with a smaller Alleghanian peak that includes 15 Mississippian through Permian grains.

4.3 Th/U in Zircon

Th/U in zircon is presented for potential local sources in the southeastern United States in the Valley and Ridge and Piedmont provinces (Fig. 4). To differentiate between high and low Th/U populations that may correlate to extensional versus convergent-style magmatism (McKay et al., 2018a), we use a Th/U cutoff of 0.75. Normalized kernel density estimates (KDEs) were created with each sample (Fig. 3); then high and low KDEs were created for each sample (Fig. 5). As shown, the KDEs denote high Th/U and low Th/U signatures simultaneously, and we used both signatures to qualitatively evaluate the compatibility between potential sediment sources. The majority of zircons are low Th/U (<0.75); however, increasing Th/U values are noted in late Grenville-age zircon populations, particularly after ca. 975 Ma; these populations are visually discernable (Figs. 4 and 5) in Cambrian Chilhowee (this study) and Cat Square terrane samples (see Table 1 for data sources). High Th/U values are also present in Paleozoic zircons from the Eastern Blue Ridge and Inner Piedmont (see Table 1 for data sources) and in smaller quantities in the Pennsylvanian Pottsville Formation and Mississippian Hartselle Sandstone units.

4.4 Detrital Mixing Models Using DZmix

To test the potential of Black Warrior basin sediment being locally sourced and to quantify the required contribution from the proposed sedimentary sources, mixing models using DZmix (Sundell and Saylor, 2017) were generated by inputting zircon age data from the Chicxulub basement rocks (as an analogue for the sub-Coastal Plain, Gondwanan-affinity, Ouachita basement rocks), Cambrian and Ordovician Appalachian fold and thrust belt strata, and the Alabama Blue Ridge to assess whether those age populations can account for the observed detrital zircon spectra in Carboniferous Black Warrior sedimentary rocks. The Chicxulub impact samples record post-Paleozoic events; thus all grains younger than ca. 350 Ma, the youngest grain in the Carboniferous strata, are not considered for modeling purposes.

Mixing models were created after the instructions of Sundell and Saylor (2017) using a Monte Carlo modeling protocol followed by an optimization routine.

Cross-correlation plots of the kernel density estimates and cumulative density function suggest that the zircon spectrum of the Mississippian Black Warrior strata (Fig. 6) can be statistically replicated

Figure 4 is interactive. Hover over each sample set (right) to see stacked on composition-age fields (left) (A) 250–500 Ma and (B) 800–1200 Ma. Layers may be viewed separately or in combination using the capabilities of the Acrobat (PDF) layering function (click "Layers" icon along vertical bar on left side of window for display of available layers; turn layers on or off by clicking the box to the left of the layer name). If the interactivity does not work in the version of the paper you are reading, please visit https://doi.org/10.1130/GEOS.S.16905034.

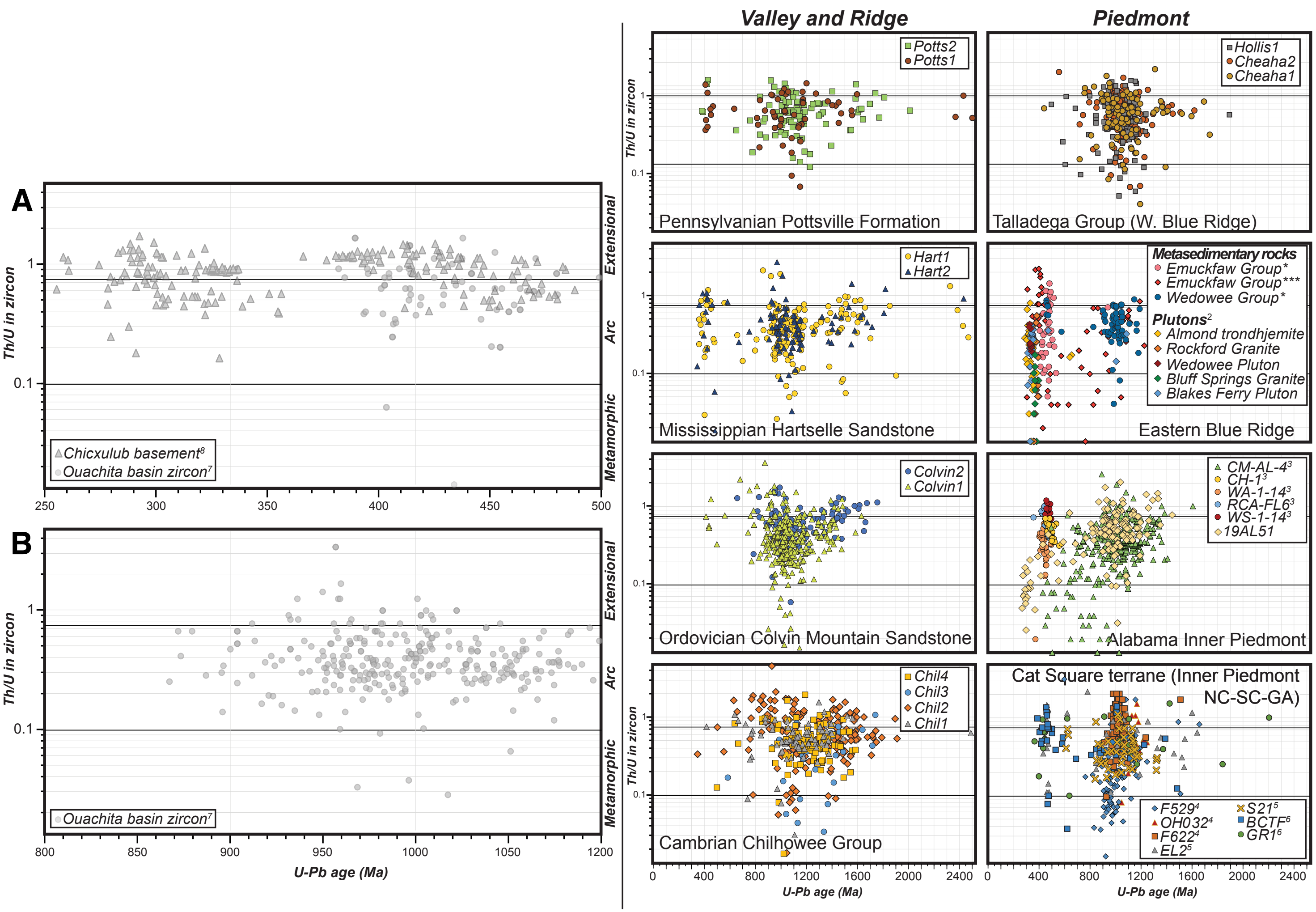


Figure 4. U-Pb versus Th/U: Mississippian and Pennsylvanian strata contain distinct populations of zircon based on Th/U and U-Pb age, where Ordovician through Devonian zircon are elevated Th/U ~0.75, and no high Th/U (>0.75) Ordovician population, as observed in the western Inner Piedmont. Parts of the Eastern Blue Ridge contain the appropriate populations, but the assemblages were at mid-crustal conditions during deposition. References footnoted on figure as follows: 1—Tull et al. (2014); 2—Stowell et al. (2019); 3—Ma et al. (2019); 4—Rehrer (2014); 5—Merschat et al. (2010); 6—Bream et al. (2004); 7—Prines (2020) (Ouachita). Figure 4 is interactive. Hover over each sample set (right) to see stacked on composition-age fields (left) (A) 250–500 Ma and (B) 800–1200 Ma. Layers may be viewed separately or in combination using the capabilities of the Acrobat (PDF) layering function (click "Layers" icon along vertical bar on left side of window for display of available layers; turn layers on or off by clicking the box to the left of the layer name). If the interactivity does not work in the version of the paper you are reading, please visit https://doi.org/10.1130/GEOS.S.16905034.

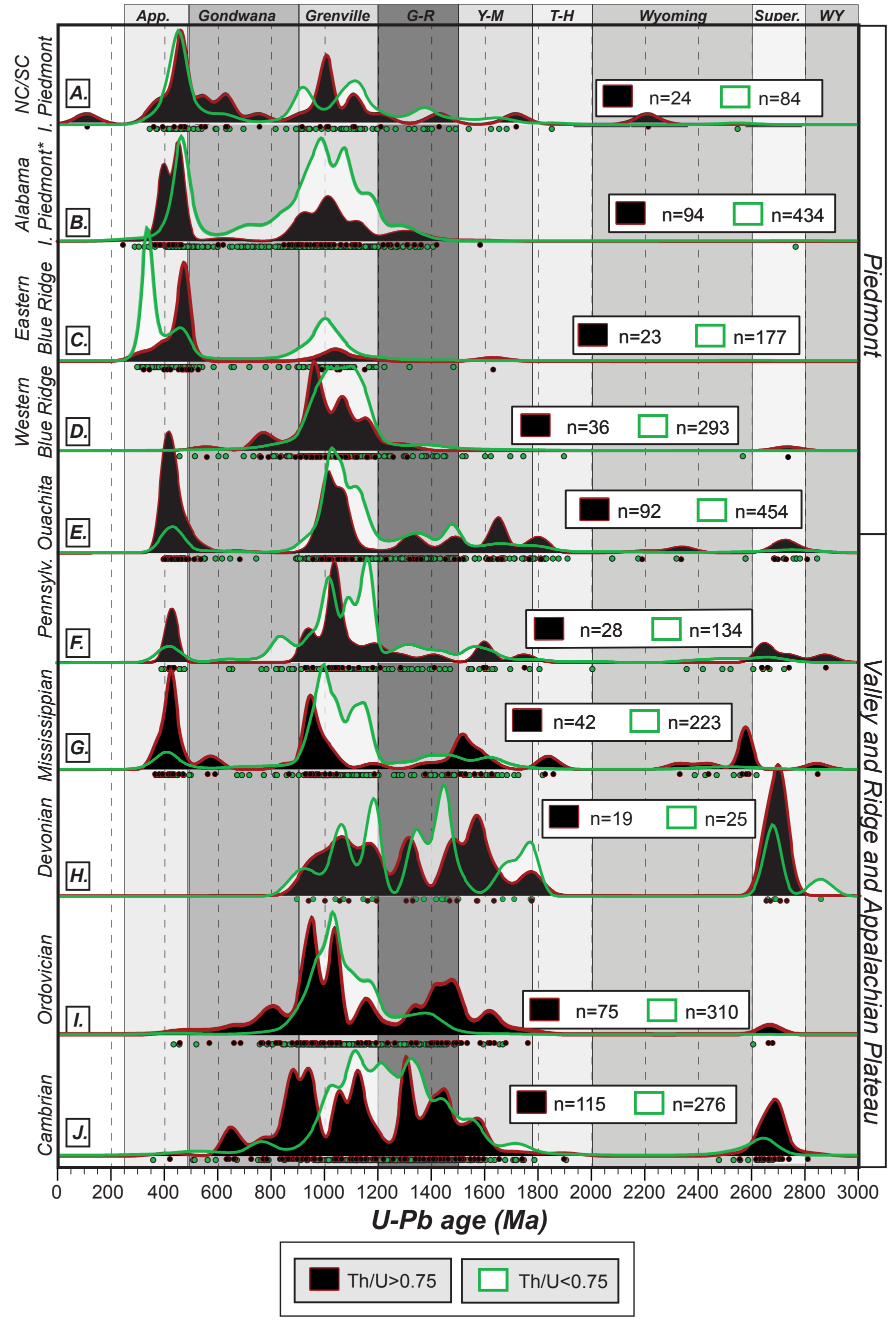


Figure 5. Kernel density estimates (KDEs) of zircon populations divided by Th/U values. High Th/U zircon (>0.75) shown in black-red compared to low Th/U zircon (<0.75) shown in green demonstrate different chemical-age trends that can be correlated between samples. The divided KDEs allow for differentiation of coeval zircon U-Pb ages. Figure 5 is interactive. Hover over the Th/U>75 (black-red) box and Th/U<75 (green) box in the lower part of the figure to view subset KDEs of each sample. Layers may be viewed separately or in combination using the capabilities of the Acrobat (PDF) layering function (click "Layers" icon along vertical bar on left side of window for display of available layers; turn layers on or off by clicking the box to the left of the layer name). If the interactivity does not work in the version of the paper you are reading, please visit https://doi.org/10.1130/GEOS.S.16905034.

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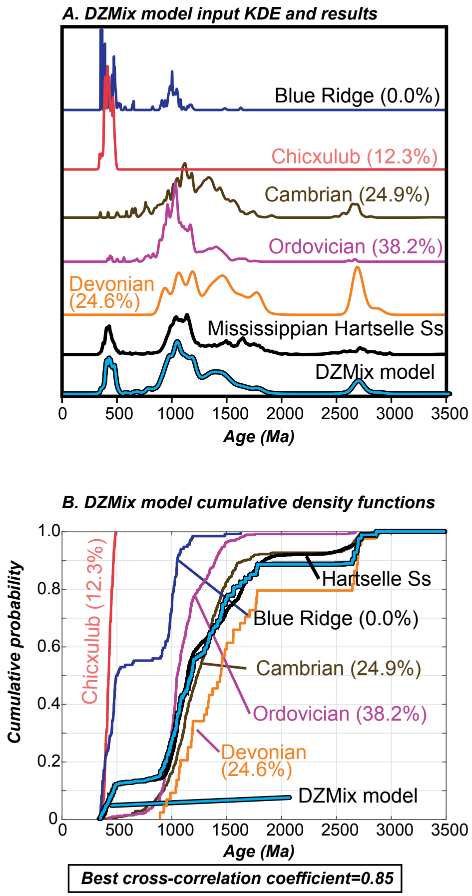

Figure 6. Input kernel density estimates (KDEs) for DZ-Mix models: Blue Ridge, Chicxulub, Cambrian, Ordovician, Devonian, and Mississippian. Mixed sample input: Mississippian Hartselle Sandstone, including data from this study and Gifford et al. (2020). Output percentages based on best cross-correlation coefficient optimization results. Other data sources from Table 1.

by mixing local, lower Paleozoic strata with minor amounts of Yucatan or similar-affinity basement rocks. Maximized cross-correlation models (Table 2) producing a R^2 value of 0.85 contain zircon contribution in the proportions below.

A second model minimizing the D statistic ("distance" between cumulative density function and model) within a K-S test produced a Best D value of 0.057, suggesting different proportions of zircon contributions from the potential sources (Table 3). This correlation suggests a strong linkage between Mississippian and Cambrian strata, albeit requiring the addition of some other sediment source to explain Paleozoic zircon.

5. ZIRCON (U-Th)/He THERMOCHRONOLOGY

5.1 Zircon (U-Th)/He Methods and Results

To document the thermal history of the foreland basin sediment and thrust belt in southern Appalachian Paleozoic strata, zircon grains were selected for (U-Th)/He thermochronological analysis in the Basin Analysis and Helium Thermochronology Laboratory (BAHTL) at the University of Connecticut. Two samples, one from the Pennsylvanian Pottsville Formation (*Potts1*) and one from the Cambrian Chilhowee Group (*Chil1*), were selected to evaluate the magnitude and timing of burial and subsequent unroofing of the foreland thrust belt.

The Chilhowee Group sample (*Chil1*) represents rocks exposed along Weisner Mountain. Weisner Mountain has been historically interpreted as a klippe, possibly linked to the thrust sheets to the southeast in the hanging walls of the Jacksonville, Indian Mountain, or Duggar Mountain thrust faults (Cloud, 1967). More recent geologic mapping places the Chilhowee Group rocks near Weisner Mountain in a stand-alone thrust sheet and represents a section in stratigraphic continuity with the overlying Cambrian strata (Cloud, 1967; B.S. Cook, 2018, personal commun.). In either interpretation, the Chilhowee Group rocks at Weisner Mountain are the farthest northwest (foreland) exposures of the lower Cambrian section in the Valley and Ridge Province. Because the Chilhowee Group represents the oldest stratigraphic and structurally lowest unit in the southern Appalachians, its postdepositional thermochronological record provides an important time control for the earliest possible onset of cooling and inferred unroofing of the thrust belt toward the surface.

TABLE 2. DZmix R^2 MAXIMIZED MIXING RESULTS FROM POTENTIAL SOURCE ROCKS COMPARED TO THE HARTSELLE SANDSTONE

R^2 maximized models	$R^2 = 0.85$
Valley and Ridge Devonian strata	24.60%
Valley and Ridge Ordovician strata	38.20%
Valley and Ridge Cambrian strata	24.90%
Total Valley and Ridge	87.70%
Chicxulub basement	12.30%
Alabama Blue Ridge	0.00%

TABLE 3. DZmix D-VALUE MINIMIZATION MIXING RESULTS FROM POTENTIAL SOURCE ROCKS COMPARED TO THE HARTSELLE SANDSTONE

Best D value models	D statistic = 0.057
Valley and Ridge Devonian strata	50.20%
Valley and Ridge Ordovician strata	17.80%
Valley and Ridge Cambrian strata	13.60%
Total Valley and Ridge	81.60%
Chicxulub basement	4.80%
Alabama Blue Ridge	13.60%

The Pottsville Formation sample (*Potts1*) was collected in the lower Pottsville Formation along the southeast limb of the Blount Mountain syncline and in the footwall of the Wills Valley fault, west of Gadsden, Alabama. The youngest stratigraphic unit in the southern Appalachians, the Pottsville Formation, provides an important thermochronological control on the potential extent of postdepositional basin burial heating and thermal resetting of the underlying Mississippian strata under investigation.

For each sample, we selected four to five individual grains based on crystal quality, size, shape, and the absence of excessive inclusions or internal fractures. Grains from the Chilhowee Group sample (*Chil1*) were plucked from a tape mount, and grains from the Pottsville Formation (*Potts1*) were picked from loose grains. Samples from the Mississippian Hartselle Sandstone (Hart1 and Hart2) did not contain grains sufficiently large for analysis. Zircon crystals from samples were hand-picked, screened, and photographed under ethyl alcohol at 120× magnification and cross-polarized light using a Leica M165 binocular microscope equipped with a calibrated digital camera. Crystal size measurements of selected grains are collected from these high-resolution images to calculate crystal mass and alpha-ejection correction factors following procedures after Ketcham et al. (2011) to calculate (U-Th)/He dates. Individual crystals were then transferred into 1-mm-diameter Nb foil packets for stable heating during gas extraction. Nb packets containing the mineral aliquots were loaded into the He gas extraction line and pumped down to high vacuum (<10^{-8} torr). Packets were then heated with a diode laser at 1250 °C for 15 min to extract radiogenic ^{4}He. Sample gas was spiked with ~7 ncc of pure ^{3}He, cleaned using two SAES getters and cryogenic purification, and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. This gas extraction and measurement procedure was repeated on each aliquot at least once to ensure complete mineral degassing to <1% re-extract gas volume. Aliquot ^{4}He gas concentrations were calculated from these data.

Degassed aliquots were shipped to the University of Colorado Thermochronology Research and Instrumentation Laboratory for chemical dissolution and U-Th-Sm measurement. At the Thermochronology Research and Instrumentation Laboratory, aliquots were dissolved using Parr large-capacity dissolution vessels in a multi-step acid-vapor dissolution process. Grains (including the Nb tube) were placed in Ludwig-style Savillex vials, spiked with a ^{235}U-^{230}Th tracer, and mixed with 200 µl of Optima grade HF. The vials were then capped, stacked in a 125 mL Teflon liner, placed in a Parr dissolution vessel, and baked at 220 °C for 72 h. After cooling, the vials were uncapped and dried down on a ~90 °C hot plate until dry. The vials then underwent a second round of acid-vapor dissolution, this time with 200 µl of Optima grade HCl in each vial baked at 200 °C for 24 h. Vials were then dried down a second time on a hot plate. Once dry, 200 µl of a 7:1 HNO_3:HF mixture were added to each vial, the vial was capped and heated on the hot plate at ~90 °C for 4 h. Once the minerals were dissolved, they were diluted with 1–3 mL of doubly-deionized water, and taken to the ICP-MS lab for analysis. Sample solutions, along with normal solutions and blanks, were analyzed for U and Th content using a Thermo Element 2 magnetic sector mass spectrometer equipped with a Teflon spray chamber and platinum cones.

U and Th measurements from the Thermochronology Research and Instrumentation Laboratory were combined with blank-corrected He concentrations and associated grain morphometric data to calculate (U-Th)/He dates (herein zircon He dates) using a custom in-house data reduction MATLAB code based on the methods described in Ketcham et al. (2011). Procedural blanks and the laboratory standard Fish Canyon Tuff zircon were analyzed with each planchette.

Zircon He dates from the Chilhowee Group (*Chil1*) span ca. 296–507 Ma (n = 5) and exhibit a positive correlation between date and grain size (Table S16.a [footnote 1]). Zircon He dates from the from ca. 264–502 Ma (n = 4) and exhibit a negative correlation between date and effective uranium concentration (defined as [U ppm] + (0.234*[Th ppm]) and serves as a useful proxy for extent of radiation damage, Shuster et al., 2006). Both of these factors, grain size and eU, may influence the dispersion of single-grain dates in zircon (e.g., Guenthner et al., 2013).

5.2 Thermal History Modeling

Thermochronometric data from samples *Potts1* (Pottsville Formation) and *Chil1* (ed to explore the range of plausible thermal histories of these units using the Monte Carlo inverse modeling algorithms in HeFTy software v. 1.9.3 (Ketcham, 2005). For each sample, model simulations were performed concurrently on the youngest late Paleozoic zircon He dates (Fig. 7). Preliminary modeling attempts to simulate all grains in a given sample (e.g., n = 4 or n = 5) were unsuccessful, given the large age dispersion in the data set (table in Supplemental File S16.a [footnote 1]) that is likely a function of inherited He from pre-depositional sediment source unroofing (e.g., Fosdick et al., 2015). Thus, the first-order modeling focuses on aspects of postdepositional reheating and the timing of late Paleozoic cooling compatible with these data. Model parameters include the zircon radiation damage and annealing model of Guenthner et al. (2013) and Ft alpha-correction of Ketcham et al. (2011). Inverse models generated thermal history paths compatible with (U-Th)/He zircon data and the calibration by Guenthner et al. (2013). Input parameters for both samples were as discussed below.

An additional constraint was input for the Pennsylvanian Pottsville Formation sample, such that the model assumed temperatures of 15 °C ± 10 °C at 315 Ma ± 10 Ma based on the depositional age of Pottsville Formation strata (Pashin and Gastaldo, 2009, and references therein). Models were created (inputs in Table 4; additional detail in Table S16.b [footnote 1]) to allow the most freedom to calculate potential thermal history paths, while honoring known inputs, such as modern surface temperature and depositional ages. The Chilhowee Group is estimated to not have exceeded burial temperatures of ~240 °C based on ~5 km of Paleozoic overburden (from cross sections from Bearce et al., 2003; Bearce and Irvin, 2005; Irvin et al., 2018) and an average geothermal gradient of ~45 °C/km in the southern Appalachians (Thomas et al., 2008).

Three models were created (results in Supplemental Table S16.c): Model A: including two Mississippian grains from the Chilhowee Group; Model B: two Mississippian grains from the Pottsville Formation, assuming no known thermal history prior to the Carboniferous; Model C: two Mississippian grains from the Pottsville Formation assuming a similar thermal history as the Chilhowee Group to test thermal compatibility between grains in the Pottsville Formation and the Chilhowee Group as a potential sediment source. Modeling results for the Chilhowee Group predict burial from surficial conditions in the Cambrian to peak conditions during the Silurian–Devonian. Post-peak paths (all three models) for both the Pottsville and Chilhowee samples *Potts1* and *Chil1* show rapid cooling trends (Figs. 7A and 7B; Models A and B shown in Figs. 7A and 7B, respectively; Model C not shown due to similarity with Model B) through the zircon He closure window (160–200 °C, Reiners, 2005) between ca. 380 and 350 Ma. The rate of cooling varies throughout the models, but no model of either sample predicts cooling through zircon He closure after ca. 350 Ma.

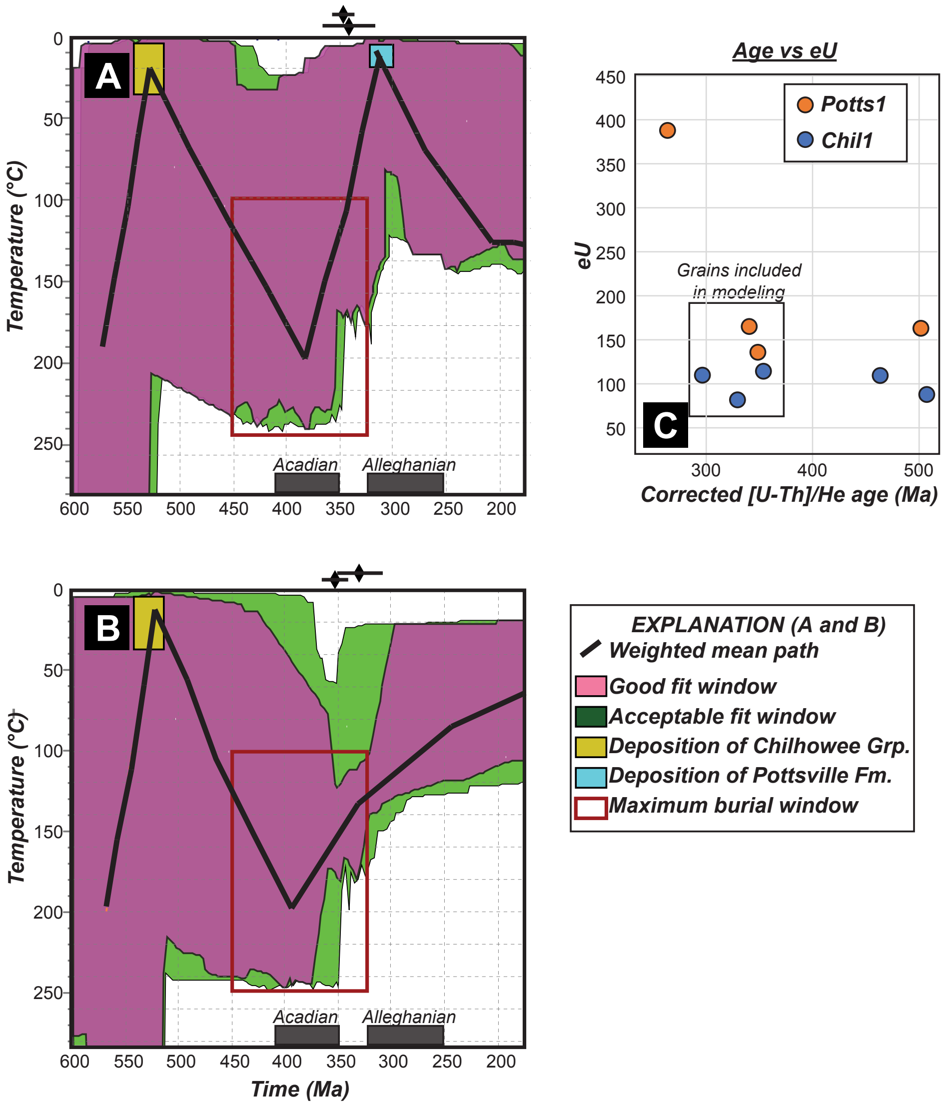

Figure 7. HeFTY models for the time-temperature (T-t) histories of sediment from the (A) Pottsville Formation and (B) Cambrian Chilhowee Group demonstrate shared cooling paths for their zircon grains. Thermal models predict cooling between 370 and 350 Ma in both Pennsylvanian and Cambrian strata, suggesting exhumation prior to documented Alleghanian deformation that may have provided an Appalachian sediment source for synorogenic Mississippian strata in the Black Warrior basin.

6. DISCUSSSION: SEDIMENTARY PROVENANCE OF MISSISSIPPIAN STRATA IN THE SOUTHEASTERN UNITED STATES

6.1 The Source of Precambrian Zircon Populations in Mississippian Strata

A visual test between U-Pb zircon age spectra, plotted as kernel density estimations (Fig. 3), demonstrates most samples from the eastern United States contain a dominant ca. 1.1 Ga zircon population associated with the Grenville orogeny. Pre-Grenville zircons are restricted to small populations of mid-continental (1.3–1.5 Ga) and minor late Paleoproterozoic western U.S. grains (1.6–1.8 Ga) in Cambrian, Ordovician, Devonian, and Carboniferous samples from the Appalachian Valley and Ridge. A distinct 2.7 Ga zircon population is present in Cambrian and Devonian strata, which only reappears in significant quantities in Pennsylvanian strata. A ca. 2.7 Ga population in southeastern Mississippian strata has been used to infer a Great Lakes/Superior Craton sedimentary provenance (Xie et al., 2016; Gifford et al., 2020). The presence and resolution of late Archean grains in the southern Appalachian Valley and Ridge Cambrian Chilhowee Group eliminate the need to directly source grains from the Superior craton during the Mississippian. Late Archean grains in Cambrian strata were originally sourced from the Superior craton during Cambrian passive-margin sedimentation and could be subsequently recycled into the Black Warrior basin during uplift of Cambrian clastic sequences during Mississippian tectonism. Our Mississippian samples contain few Archean grains (n = 9); however, other studies (Gifford et al., 2020) report Mississippian samples from northwest Alabama containing up to 20% of late Archean grains in detrital spectra, suggesting variability in Superior age grains in the Hartselle Sandstone. Gifford et al. (2020) interpreted larger Archean populations to reflect higher sediment influx into the eastern Black Warrior basin from the Superior craton. This trend in Archean grain abundance could alternatively be explained by variability of Superior age

TABLE 4. HeFTY MODEL INPUTS

Parameter	Value	Justification
Model start time (Ma)	600	Predates most known exposures in southern Appalachians.
Model end time (Ma)	0	
Maximum temperature (°C)	240	Lacks metamorphic mineral assemblages; chlorite (<400°); temperature estimates of nearby metamorphic rocks in overlying thrust sheet >280°C; assuming thickness of ~5 km overlying strata and 45 °C/km geotherm + 15°C deposition. Temperature = 240 °C.
Maximum burial age (Ma) (Chilhowee Group)	440–320	Assumes peak burial postdates deposition of overlying Ordovician section and predates deposition of the Pottsville Formation.
Depositional age of Pottsville Formation (Ma)	320–300	
Depositional age of Chilhowee Group (Ma)	541–520	

Note: HeFTy software v. 1.9.3 (Ketcham, 2005).

zircon in recycled lower Paleozoic sedimentary sources, which also contain late Archean grains, as shown by our data. Several ca. 2.7 Ga grains are also present in Carboniferous strata of the Ouachita/Arkoma foreland basin, suggesting detritus from Cambrian rocks may have been recycled into the Ouachita foreland as well.

Mid-Continent and/or Granite-Rhyolite age spectra are also present and in numerous quantities in Cambrian, Ordovician, and Devonian strata. Because Cambrian strata record passive-margin sedimentation sourced from Laurentia, and Ordovician strata likely record erosion of the Taconic orogen along the Laurentian margin, these two types of strata have distinct age spectra. If Paleozoic clastic sequences were exhumed during or prior to the early Mississippian, mixing of these sources is a reasonable explanation for the resulting U-Pb age spectra present for the Hartselle Sandstone. In summary, all Precambrian age populations observed in the Mississippian Hartselle Sandstone are also present in local Cambrian–Devonian southern Appalachian strata, and therefore sedimentary recycling of Paleozoic units offers a simpler solution for reproducing Precambrian age spectra grains than a transcontinental drainage system.

6.2 Late Silurian–Early Devonian Zircon Source

Ordovician through Devonian grains are present in both Mississippian and Pennsylvanian sandstone units, with a pronounced 410–420 Ma peak. Southeastern Piedmont rocks (Figs. 3–5) contain Paleozoic zircon populations are present in southeastern Piedmont Rocks (Figs. 3–5), but either (1) span a much wider age spectra or (2) are chemically incompatible with Early Silurian zircons in Black Warrior Carboniferous strata. Carboniferous zircon grains (Fig. 4) are within 490–375 Ma and have Th/U ranging from <0.01 to >1.0. The majority of zircon grains are ~0.75, which is distinctly higher than documented arc magmatism in Acadian/Neoacadian rocks of the southern Appalachian Piedmont of Alabama (Eastern Blue Ridge on Figs. 4 and 5). The Paleozoic age spectra in Mississippian–Pennsylvanian strata predate Eastern Blue Ridge magmatism (370–350 Ma), suggesting an alternate source. Zircon grains from Carboniferous Black Warrior strata are more similar in composition and age to grains found within the Alabama Inner Piedmont associated with the late stages of the Dadeville backarc complex (Alabama Inner Piedmont of Figs. 4 and 5). The Dadeville complex developed in an Ordovician backarc basin setting along the southeastern Laurentian margin (Barineau et al., 2015). However, Alabama Inner Piedmont rocks contain a much larger Ordovician component than the Carboniferous Black Warrior strata, early Ordovician zircon are significantly enriched in Th/U compared to Black Warrior strata grains, and Black Warrior strata age spectra span into the Devonian–Early Mississippian.

Th/U in zircon from continental arc systems are dominated by low (<0.75) Th/U zircons, whereas zircons from extensional magmatism contain values that are highly variable (McKay et al., 2018a), with large populations of high and low Th/U. The zircon Th/U composition in the Black Warrior Mississippian samples is unlikely to have been sourced from a traditional volcanic arc, due to the proportions of high Th/U (>0.75) grains mixed with low Th/U grains (<0.75). These compositions are comparable to late stages of extension in the Dadeville complex but do not match observed age ranges. Inner Piedmont rocks to the north in the Cat Square terrane, however, appear to be similar in age and compositional ranges. Upon inspection (Fig. 5), the Cat Square terrane zircon does contain compatible age-composition populations (intermediate Th/U ca. 420 Ma). Cat Square terrane rocks, however, are dominated by a ca. 460 Ma zircon population, with the late Silurian–early Devonian population representing the youngest extent. Because ca. 460 Ma grains are rare in the Black Warrior strata, which are dominated by the ca. 420 Ma population, this correlation cannot account for the Paleozoic grains observed in the Hartselle Sandstone, and the Inner Piedmont rocks of North Carolina are unlikely to have contributed significant sediment to the Mississippian Black Warrior basin. In an attempt to visualize chemical-age populations, Figure 5 displays cumulative KDEs for each physiographic province, divided by populations of high and low Th/U zircon. High Th/U (>0.75) are displayed in black-red, while low Th/U zircon (<0.75) are shown in white-green. When age spectra are divided based on compositions, tectonic trends can be observed. During times of orogenesis and arc-dominated magmatism, low Th/U peaks are higher in magnitude than high Th/U peaks (360 Ma peak in Eastern Blue Ridge, Fig. 5C; ca. 1.2–0.9 Ga Grenville orogeny,

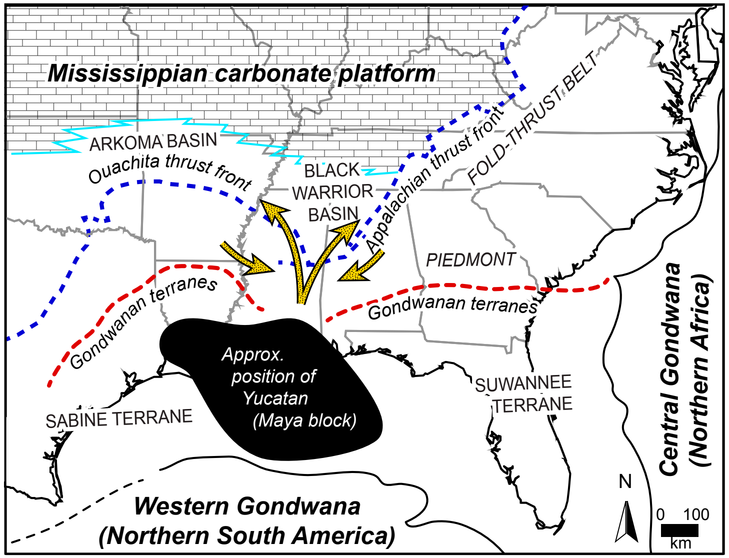

Figure 8. Model for syn-orogenic sediment pathways (yellow arrows) with (1) along-strike transport of recycled sediment from the southern Appalachians and Ouachita Mountains; (2) minor mixing of southern terrane-sourced material redirection through the Alabama Promontory; and (3) redirection through the Alabama Promontory orocline. Approximate position of the Maya block (Scotese, 2016).

Figs. 5A–5I). Post-orogenic magmatism (0.9 Ga in Cambrian strata, Fig. 5I), rifting, and backarc magmatism (480 Ma in Eastern Blue Ridge, AL-NC-SC Inner Piedmont, Figs. 5A–5C) appear to correlate to higher Th/U peaks. Divided KDEs of Carboniferous strata of the Black Warrior basin (Figs. 5F and 5G) and Ouachita basin (Fig. 5E) contain distinct ca. 415 Ma peaks that are dominated by high Th/U zircon. These trends in zircon Th/U suggest an extensional magmatic source, not a traditional subduction-related arc system as observed in the southern Appalachian Piedmont.

Dissection of southern Laurentia during the breakup of Pangea and opening of the Gulf of Mexico resulted in tectonic dispersion of potential source terranes and burial by southeastern Coastal Plain sediments in the sector of the Appalachian-Ouachita orogen currently occupied by westernmost Alabama, Mississippi, Louisiana, and western Arkansas. Since a crystalline source in the Piedmont is elusive, we must explore terranes to the southwest. Paleogeographic reconstructions of Laurentia and Gondwana place the Maya block that currently underlies the Yucatan peninsula to the southwest of (Fig. 8) the Black Warrior basin (Pindell, 1985). Crystalline basement of the Maya block is exposed in the Chicxulub impact crater and contains high Th/U zircons that are late Silurian and early Devonian, similar in both composition and age to the ca. 420–410 Ma population observed in the Black Warrior basin. The Maya Mountains also expose Late Silurian plutons of compatible age (Steiner and Walker, 1996; Martens et al., 2010), and the Maya block has been interpreted to be located near bi-modal rift-drift, backarc, and arc tectonism (Casas-Peña et al., 2021) that is compatible with the variable Th/U values observed in Black Warrior strata. The Yucatan/Maya block has been proposed as a source of ca. 415 Ma grains in the Paleozoic Marathon basin to the west (Thomas et al., 2019), therefore it is reasonable to postulate the Mississippian Black Warrior drainage systems may have also tapped into this sedimentary source during the Appalachian-Ouachita orogeny. While there is variability in paleogeographic reconstructions, some models have the Maya block approaching the position shown on Figure 8 as early as the latest Devonian and remaining there until the Jurassic (Pindell, 1985; Scotese, 2016). Therefore, the most proximal sources for ca. 415 Ma zircon grains in the Mississippian Black Warrior are outboard terranes currently located in Central America. Late Silurian grains are present in both Mississippian and Pennsylvanian Black Warrior strata, suggesting a sustained sedimentary link between outboard terranes and foreland basins, and these grains even appear in Late Jurassic strata of the Gulf of Mexico, which are interpreted to be sourced directly from Yucatan rocks (Weislogel et al., 2015).

6.3 A Mississippian, Southern Appalachian Valley and Ridge Source

In the Pennsylvanian, sedimentation in Alabama and the Black Warrior basin became dominated by a northwestward-prograding clastic wedge from the rising Appalachian Mountains (Thomas et al., 2017), suggesting a transition from Ouachita-influenced sedimentation to Appalachian-sourced sediment. The uppermost Mississippian and Pennsylvanian sedimentary systems include a southwestward-prograding clastic wedge to the northeast of the Black Warrior basin that merges with the northeastward-thinning clastic wedge to the southwest (Ettensohn and Pashin, 1993; Thomas et al., 2004; Thomas et al., 2017). The Pennsylvanian Pottsville Formation has been linked with both the Ouachita (Mack et al., 1983) and the uplifting southern Appalachians (Uddin et al., 2016). Recent provenance analyses identified evidence for local transport of metamorphic clasts (Haque and Uddin, 2017), supporting a sediment source to the southeast during the Pennsylvanian. Both Pennsylvanian and Mississippian samples presented here (Figs. 3F and 3G) contain similar zircon age spectra including (1) late Silurian–early Devonian populations with few other Paleozoic grains; (2) dominant Grenville and Mid-Continental Granite Rhyolite age populations; and (3) variable populations of ca. 2.5 Ga grains. With resolution of lower Paleozoic detrital zircon spectra presented here, the source for both the Mississippian and Pennsylvanian detrital zircon populations can be accounted for by localized drainages from the southern Appalachian Valley and Ridge strata or perhaps correlative strata in the now-covered section of the eastern Ouachita Mountains. Evidence from the western United States suggests sediment from the Appalachian Mountains may have covered large portions of the southern United States, including the central plains and southwestern United States along the ancient continental shelf (Chapman and Laskowski, 2019). Similar age spectra in the Ouachita foreland basin suggest the widespread transport of southern Appalachian sediment during the Mississippian.

6.4 Integrated Source to Sink Model

Both modeling results from DZMix predict a high (>87%) zircon contribution locally derived from source rocks in the southern Appalachians (Valley and Ridge and Blue Ridge provinces). Sourcing of Mississippian strata in the Black Warrior basin from the adjacent Neoacadian thrust belt would imply influx of sediment from the southeast (present-day spatial relationship), which is difficult to integrate into the synorogenic, southwest- to northeast-prograding clastic wedge (Graham et al., 1975; Mack et al., 1981; Thomas, 1982; Mack et al., 1983). We envision two possible scenarios for sourcing sediment from the southwest, as detailed from field-based stratigraphic data (Thomas and Mack, 1982; Thomas, 1991), and through recycling of Paleozoic (Cambrian, Ordovician, and Devonian clastic units) strata, with lesser amounts of material from Ouachita-Chicxulub-Gondwanan basement rock and Blue Ridge metamorphic and igneous rock. In scenario one, zircons are sourced directly from Paleozoic strata and Blue Ridge rocks in the southern Appalachians and subsequently transported along-strike within NE-SW–striking (present-day configuration) structural fabrics associated with developing thrust sheets. Along-strike sediment transport in trellis drainages are well documented in orogenic systems (e.g., Apennines fold-thrust belt; Alvarez, 1999), and oroclinal bends are known to focus sedimentary systems (e.g., modern Bhahmaputra drainage from the Himalaya; Permo-Triassic drainage in South Africa; McKay et al., 2018b). Along-strike sediment transport during the Neoacadian and earliest Alleghanian rectifies inconsistencies by transporting sediment out of the Neoacadian thrust belt toward the southwest. The Alabama Promontory orocline, the basement-controlled oroclinal bend in the Appalachian–Ouachita orogen that serves as the junction between the Appalachian and Ouachita orogenic fronts, formed prior to Cambrian time (Thomas, 1977, 1985; Thomas and Whiting, 1995; Groshong et al., 2010) and would, therefore, likely reroute sediment from the southwest near the Alabama Promontory toward the north-northeast, compatible with stratigraphic observations of thickening strata toward the southwest (Fig. 8). As material was being rerouted at the orogenic bend some subsequent sediment from the west-southwest (Ouachita-Chicxulub) would be incorporated to the overall sediment input. This style of syn-orogenic drainage is analogous to the Brahmaputra River in eastern Asia, which transports Himalayan sediment to the Bengal fan and flows parallel to the orogenic front before re-routing transport directions. Because Paleozoic clastic units largely exhibit a sub-arkose and/or lithic arenite to quartz-arenite composition, recycling these units provides a compositional match for the quartzose nature of the Mississippian Hartselle Sandstone. The presence of metamorphic lithics and minerals (e.g., sillimanite) are also compatible with this model, since they could have been sourced locally from the Alabama Blue Ridge (Rheams, 1986) and/or Maya block-comparable terranes (Weber et al., 2008). The presence of ca. 415 Ma zircon, if sourced from Maya block, or comparable terranes such as the Sabine terrane, requires sedimentary linkage between Gondwanan-affinity rocks and the early developing Appalachian–Ouachita orogen. These small populations mixed with locally sourced, recycled Paleozoic clastic rocks, which include 90% of the zircon ages, account for (1) the age populations observed, (2) relative proportions, (3) the compositional maturity, (4) presence of metamorphic grains and/or lithics, and (5) the well-constrained stratigraphic relationships of thickening toward the southwest clastic sequences, without extraneous drainages that extend across Laurentia.

The second conceptual model is that sediment may have originated to the southwest, within the now-covered Mississippi sector of the Ouachita orogeny, but would require the presence of Paleozoic correlative strata. While it is unclear the lower Paleozoic stratigraphy that would have been exposed in the eastern Ouachita Mountains in the Carboniferous, extrapolating our understanding of regional Appalachian facies may provide some insight. Given that the Cambrian Chilhowee Group is a passive-margin clastic sequence and laterally present from Alabama into Virginia (King, 1949; Mack, 1980; Simpson and Sundberg, 1987; Park et al., 2010), it is reasonable to infer that it was likely present to the southwest and/or may be present in the modern subsurface. However, Ordovician and Devonian clastic units are harder to correlate, because clastic Ordovician and Devonian strata are not traceable over large areas and pinch out laterally and between structures. Therefore it is unclear what Ordovician and Devonian clastic units may have been exposed in the eastern Ouachita Mountains in the Carboniferous. This interpretation relies on inferences about possible subsurface rocks; therefore, we prefer scenario one. However, this second scenario provides a testable hypothesis for future studies.

6.5 Thermal History (Temperature-Time [T-t]) Correlation between Source and Sink

With Mississippian sediment containing signatures of orogenic influence, sourcing material from the Ouachita Mountains would seem more likely than the southern Appalachian because of the estimated ages of deformation. Ouachita deformation is documented in the Upper Mississippian, coeval with deposition of the Pride Mountain Formation and the Hartselle Sandstone (Whiting and Thomas, 1994; Thomas, 2010). In contrast, the southern Appalachian foreland thrust belt is thought to develop in the Early Pennsylvanian (Thomas, 1977; Thomas and Schenk, 1988). Recent estimates for the age of metamorphism in the Alabama Blue Ridge (Dallmeyer, 1988; Stowell et al., 2019) seem to lessen the gap between the Devonian–Mississippian Neoacadian and Pennsylvanian–Permian Alleghanian orogenies such that the two orogenies may have temporally overlapped. Blue Ridge hornblende $^{40}Ar/^{39}Ar$ cooling ages range from 362 to 322 Ma (Dallmeyer, 1988) overlap with late Blue Ridge garnet growth between 331 and 320 Ma (Stowell et al., 2019). HeFTy thermal models from (U-Th)/He zircon data from the Pennsylvanian Pottsville Formation and the and Cambrian Chilhowee Group of the Alabama Valley and Ridge allow us to assess the hypothesis that Black Warrior basin sediment could have been sourced from Mississippian structures within the southern Appalachian fold and thrust belt.

HeFTy models for cooling two (of four) detrital zircons (U-Th)/He from the Pennsylvanian Pottsville Formation predict cooling through zircon He closure temperature (~200 °C) between ca. 375 (weighted mean) and 350 Ma (youngest predicted cooling by any model paths). Cooling at 375–350 Ma predates any known Valley and Ridge deformation in the southern Appalachian Mountains but is within error of Neoacadian tectonism. Thermal history modeling results from Pennsylvanian strata likely represent cooling and exhumation of the sediment source. These findings also seem to indicate that Pottsville grains underwent postdepositional reheating, but not sufficient to thermally reset most of the grains during burial, and therefore can be used as a sediment provenance indicator.

HeFTy thermal history models for late Paleozoic grains (two of four) from the Chilhowee Group yield cooling paths that overlap and may even predate cooling estimates in the Pottsville Formation, ranging from 385 Ma (weighted mean path) to 350 Ma (youngest predicted model cooling paths), suggesting Cambrian clastic strata in the Valley and Ridge were undergoing cooling during the Devonian. Since Cambrian strata are thrust-fault–bounded blocks, we interpret that cooling as thrust fault exhumation during structural uplift. Therefore, Paleozoic (Cambrian through Devonian?) strata experienced exhumation prior to deposition of Mississippian strata, allowing them to be available as a sediment source. The similar cooling paths in zircon from Pennsylvanian and Cambrian strata are compatible with Black Warrior sediment being sourced directly from Appalachian sources, even if subsidence was driven by uplift of the Ouachita Mountains to the southwest.

Thermal models of the Chilhowee Group and Pottsville Formation share evidence for pre–350 Ma tectonic inversion in the Appalachian Valley and Ridge, suggesting a reevaluation of the timeline for Appalachian mountain building. Devonian cooling ages in unmetamorphosed Cambrian strata within the Valley and Ridge suggest Acadian–Neoacadian–age orogenic deformation in what is traditionally considered the Alleghanian fold and thrust belt (Fig. 9A). Ages for early Valley and Ridge exhumation based on HeFTy thermal history models also correlate to a period of magmatism and deformation in the Alabama Piedmont. Age estimates of low Sr/Y, pre- to syn-kinematic plutons range from 390 to 365 Ma (Stowell et al., 2019), coeval with 385–360 Ma cooling in the southeastern Alabama Valley and Ridge. Age estimates for Appalachian metamorphism (ca. 350–320 Ma; Dallmeyer, 1988; McClellan et al., 2007; Steltenpohl et al., 2013; Stowell et al., 2019) suggest there is no temporal break between Neoacadian and Alleghanian orogenesis and deformation was an ongoing process.

The location of the southeastern Valley and Ridge thrust sheets dominated by Cambrian and Ordovician strata is notable, in that these strata are located southeast of a major detachment unit within the Coosa deformed belt (Bearce, 1978; Thomas and Drahovzal, 1988). Lower Cambrian strata are not observed northwest of the Coosa deformed belt. The Coosa deformed belt is interpreted to reflect sub-fold belt basement topography and faulting (Thomas and Bayona, 2005); therefore, we hypothesize that these basement structures may have served to partition Neoacadian stress in the southeastern Valley and Ridge. Lower Cambrian strata (Chilhowee Group) are stratigraphically below regional décollement units in the Cambrian Conasauga Formation (Thomas, 2001, 2007), explaining why lower Chilhowee Group rocks are not brought to the surface by Alleghanian structures. Our model suggesting initial deformational exhumation of the Cambrian–Devonian strata in rocks southeast of the Coosa deformed belt predicts structures containing exposures of Chilhowee Group experienced Neoacadian deformation (Fig. 9A) that may have been reactivated by later Alleghanian structures (Fig. 9C). Thrust faults within and southeast of the Coosa deformed belt are documented to display hinterland-breaking thrust faults (break-back sequences of Thomas, 2001; Thomas and Bayona, 2005; Cook, 2010). Several of the thrust sheets in Coosa deformed belt contain late Mississippian to early Pennsylvanian strata, and therefore, postdate 385–350 Ma cooling in some Chilhowee Group rocks. We interpret these age conflicts to reflect Alleghanian thrust fault overprinting of early structures, possibly reactivated Neoacadian thrust faults (Fig. 9C), like those bounding the Chilhowee Group rocks sampled in this study.

7. CONCLUSIONS

We demonstrate that the Mississippian Hartselle Sandstone in the Black Warrior foreland basin contains detrital zircon populations that can be accounted for by recycling of Paleozoic strata in the southern Appalachian fold and thrust belt. Our locally derived provenance model honors chemical-age zircon data, accounts for metamorphic grains recognized in thin-section petrography, provides an explanation for ca. 415 Ma zircons, and matches Mississippian–Pennsylvanian Black Warrior foreland lithostratigraphic relationships. Results from this study include:

(1) The detrital zircon U-Pb characterization of Paleozoic clastic strata in the southern Appalachians of Alabama and Georgia. Sandstone samples from the Cambrian Chilhowee Group exhibit age populations associated with Grenville, Mid-Continent, and Superior tectonism. The Ordovician Colvin Mountain samples exhibit age populations associated with Grenville and Mid-Continent tectonic

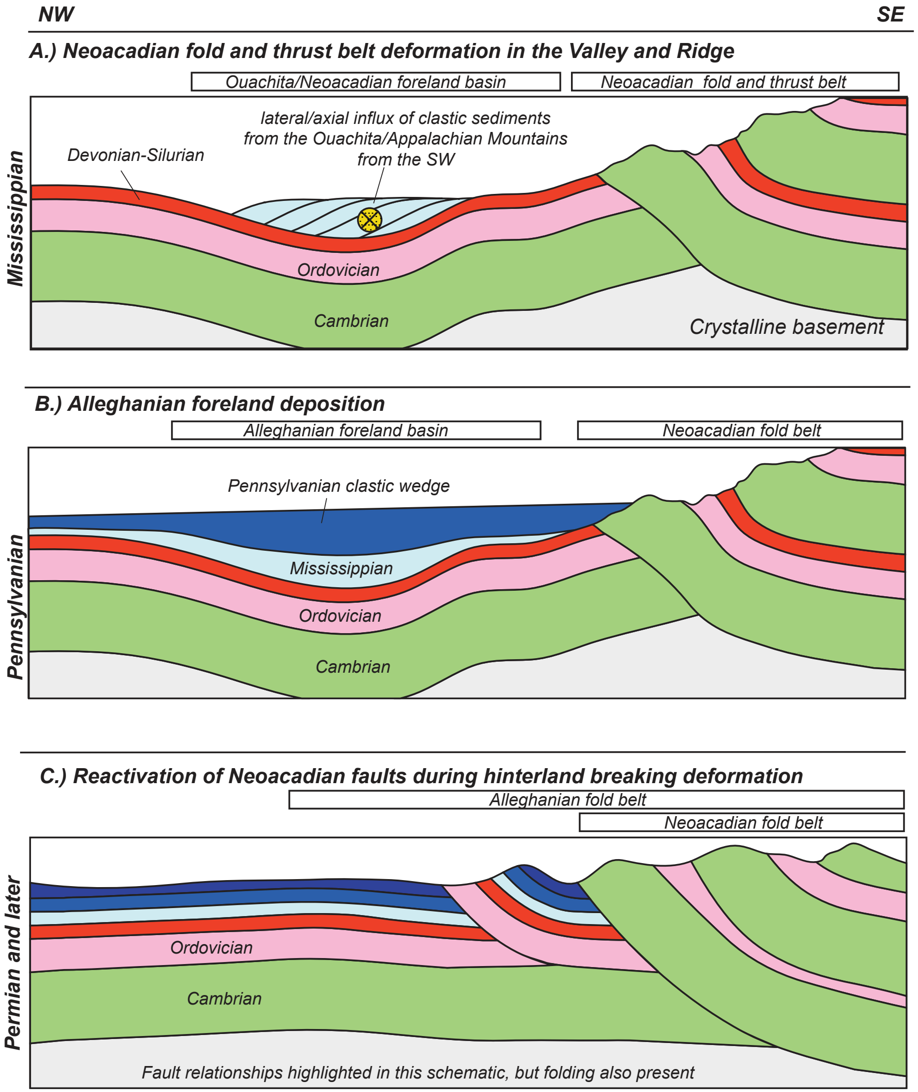

Figure 9. Schematic cross section during Mississippian and Pennsylvanian development of the southern Appalachian Valley and Ridge. (A) Mississippian fold and thrust belt development (Neoacadian?) is isolated to southeastern-most thrust sheets and coeval with metamorphism and deformation in the Alabama Blue Ridge within the Appalachian Piedmont. (B) During the Pennsylvanian, deformation transitions toward the foreland. (C) Neoacadian fold belt structures are reactivated late, creating a hinterland breaking sequence, as observed in map scale.

phases. The Devonian Frog Mountain sample exhibits age populations associated with Grenville, Mid-Continent, Granite-Rhyolite, Yavapai-Mazatzal, and Superior tectonic phases. Southern Appalachian Piedmont rocks coupled with a paleo-reconstructed Maya Block can account for all Phanerozoic and Late Proterozoic U-Pb ages. Mixing models show that the Mississippian Hartselle Sandstone detrital zircon age spectrum is reproducible with zircon mixing of 81.6%–87.7% Paleozoic strata, 0%–13.6% Piedmont and/or Alabama Blue Ridge, and 4.8%–12.3% Maya block material.

(2) A chemical-age comparison of source rocks and sedimentary deposits in the southern Appalachians using zircon U-Pb coupled with Th/U values (greater than or less than 0.75) shows that southern Appalachian thrust belt rocks, as well as Maya block rocks, are viable source rocks for provenance interpretations.

(3) (U-Th)/He dates and HeFTy thermal models for zircon from Cambrian and Pennsylvanian strata both show similar pre–350 Ma cooling paths. These data require exhumation of southern Appalachian Valley and Ridge Paleozoic strata coeval with estimates for Neoacadian tectonism.

An integrated source to sink model based on these results begins with initial Devonian–Mississippian exhumation of Cambrian–Devonian strata in southern Appalachian Valley and the Ridge. Subsequent sedimentary transport of recycled Valley and Ridge sediment would be directed parallel to developing structural fabrics toward the southern margin of the Alabama Promontory. Near the juncture between Ouachita-Appalachian thrust belts, Appalachian-sourced sediment is then rerouted toward the Black Warrior foreland and mixed with small amounts of material from the southern Appalachian Piedmont and Maya block or comparable terranes to the southeast and southwest, respectively.

Our results narrow the gap between Neoacadian and Alleghanian tectonism recorded in the Appalachian Valley and Ridge, a trend that has recently been observed in metamorphic rocks of the Appalachian Piedmont. These findings provide motivation for future studies to explore the temporal and spatial relationships between the foreland and hinterland deformation in the southern Appalachians. They also present opportunities for advancing our understanding of the transition from Andean to Alpine style orogenesis.

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