Detrital zircon U-Pb fingerprinting of the Appalachian signature: Early Pennsylvanian sediment routing from highlands to deep-sea fans and the persistence of recycled Appalachian-affiliated zircons

By

Isaac J. Allred

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Chair: Dr. Michael D. Blum

Dr. Greg A. Ludvigson

Dr. Noah M. McLean

Dr. Michael H. Taylor

Dr. William C. Johnson

Date Defended: 4 May 2022

The dissertation committee for Isaac J. Allred certifies that this is the approved version of the following dissertation:

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Abstract

Carboniferous sediment dispersal from the Appalachian orogenic system (eastern United States) has become a topic of widespread interest. However, the actual pathways for continental-scale, east-to-west sediment transfer have not been documented. This study presents detrital zircon (DZ) U-Pb ages and Hf isotopic values from the Lower Pennsylvanian Jackfork Group, Johns Valley Shale, and Pottsville Formation of the Ouachita and Black Warrior Basins and DZ U-Pb ages from the Caseyville Formation of the Illinois Basin to delineate the likely sediment-routing systems within the broader context of sediment dispersal across Laurentia.

We interpret results to suggest Alleghenian-sourced sediment and water were routed through at least two paleovalleys within the Appalachian foreland-basin foredeep and backbulge depozones to the Ouachita Basin terminal sink. Clearly circumscribed, southward- or southwestward-oriented paleodrainage areas provide a template of the Appalachian foreland-basin system, and as such the central and southern Appalachians were an unlikely source for the Appalachian signature observed in the western United States at this time. Collectively, the Ouachita Basin represents a terminal sink for sediments derived from much of the eastern and central United States.

After the closure of the Ouachita Basin and the culmination of the Alleghenian orogen, the DZ U-Pb signature of the Appalachian-Ouachita orogenic system, which includes the Grenville (1250–950 Ma) and Appalachian (500–275 Ma) age groups, dominates the Phanerozoic record of North America. An east-to-west, Pennsylvanian to modern, comparison of DZ samples across North America demonstrates a persistent Appalachian signature for samples, including a

recycled Appalachian signature in the West. The presence of this Appalachian signature in western Laurentia is clear, but the actual sediment-routing systems responsible for transferring this signal to the West during the Mississippian through early Triassic remain poorly defined. Lower Pennsylvanian deposits proximal to the Appalachian orogen, composed of 50–75% Appalachian- and Grenville-age DZ, represent the primary Appalachian signature, but it is unlikely this sediment was routed directly from the central and southern Appalachians to western Laurentia. Instead, this signal may have been derived from the northern Appalachians or perhaps the Ellesmerian orogen. By the Triassic, DZ samples in the West display a primary Appalachian signature and represent rivers sourced from the Ouachita-Marathon highlands.

DZ sampled from Mesozoic fluvial sandstones, such as along the Front Range, indicate drainage reversal due to the rise of the Western Cordillera; yet a persistent Appalachian signature exists in these western-sourced, eastward-flowing systems—a phenomenon that continues to the present. None of these systems are interpreted to be sourced by primary Appalachian or Grenville terranes, suggesting a recycled Appalachian signature. These western samples frequently are composed of >40% Appalachian- and Grenville-age DZ, accompanied by western age groups (e.g., Yavapai-Mazatzal and Western Cordillera). Although western drainage reorganization reversed the trajectory of Appalachian-sourced sediment routing, WC DZ are typically dwarfed by the recycled Appalachian signal and underrepresented across the continent. The persistent Appalachian signature, originally sourced by the concatenation of two supercontinent orogen terranes, continues to be the dominant contributor in the DZ record of North America.

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Chapter 1: Introduction

Detrital zircon (DZ) U-Pb ages fingerprint the source terranes of siliciclastics of North America and provide new perspectives of North American sediment routing. Over the last decade, Carboniferous sediment dispersal from the Appalachian orogenic system has become a topic of widespread interest, particularly regarding the arrival of Appalachian- and Grenville-age DZ along the western margin of Laurentia. Chapters 2 and 3 address Early Pennsylvanian barriers to transcontinental sediment transport from the central and southern Appalachians to western Laurentia: (A) the Ouachita Basin, a terminal sink filled with Appalachian- and midcontinent-sourced deep-sea fans; and (B) north-to-south oriented paleovalleys of eastern Laurentia and the midcontinent that likely sourced Ouachita deep-sea fans.

While Chapters 2 and 3 are focused on DZ analyses from Lower Pennsylvanian units, Chapter 4 addresses large-scale North American sediment routing from the late Paleozoic to the present, including the outsized role of recycled Appalachian- and Grenville-age DZ in the rock record. Chapter 4 tracks the late Paleozoic-early Mesozoic westward propagation of the Appalachian signature (defined as the sum of the percentages representing Appalachian- and Grenville-age DZ) to western Laurentia and then the subsequent recycling and return of the Appalachian signature back to the East. The early "Appalachian" signal observed in the West during the Carboniferous may have been derived from the northern Appalachians in the US and Canada, and perhaps from as far north as the Ellesmerian orogen. Chapter 4 emphasizes the outsized role of the Appalachian signature throughout the entire Phanerozoic and proposes that the longevity and magnitude of the Appalachian signature is due to crustal concatenation of the supercontinent-cycle provincial terranes.

Chapter 2: Early Pennsylvanian sediment routing to the Ouachita Basin (southeastern U.S.) and barriers to transcontinental sediment transport sourced from the Appalachian orogen based on detrital zircon U-Pb and Hf analysis

Isaac Allred[12] and Michael D. Blum[1]

[1]Department of Geology, University of Kansas, Earth, Energy & Environment Center, 1414 Naismith Drive, Lawrence, KS 66045, USA

[2]Indiana Geological and Water Survey, Indiana University, 1001 E 10th Street, Bloomington, IN 47405, USA

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Abstract

Carboniferous sediment dispersal from the Appalachian orogenic system (eastern United States) has become a topic of widespread interest. However, the actual pathways for continental-scale, east-to-west sediment transfer have not been documented. This study presents detrital zircon (DZ) U-Pb ages and Hf isotopic values from the Lower Pennsylvanian (Morrowan) Jackfork Group and Johns Valley Shale of the synorogenic Ouachita deepwater Basin of Arkansas to document provenance and delineate the likely sediment-routing systems within the broader context of sediment dispersal across Laurentia.

Twelve DZ U-Pb age distributions are interpreted to indicate that sediments were derived from the Appalachians to the east and northeast, as well as the midcontinent region to the north. All samples display prominent ca. 500–400 Ma, 1250–950 Ma, 1550–1300 Ma, and 1800–1600 Ma grains, consistent with ultimate derivation from Appalachian, Grenville, Midcontinent, and Yavapai-Mazatzal provinces. DZ Hf values obtained from the Ouachita Basin are similar to published Hf values from Pennsylvanian samples in the Appalachian and Illinois Basins. Age distributions are generally consistent for seven samples collected from the Jackfork Group and Johns Valley Shale in the southern Ouachita Mountains through ~2400 m of stratigraphic section, and are interpreted to indicate little change in provenance during the Morrowan in this part of the system. However, samples from the most northern and most source-proximal site in Little Rock, Arkansas, exhibit modest percentages of Appalachian ages and elevated contributions of Yavapai-Mazatzal ages when compared with samples collected farther to the south and west. We interpret differences between DZ signatures to indicate distinct sediment-

routing pathways to the Ouachita Basin. We infer the strong Appalachian-Grenville signals to represent an axial system flowing through the Appalachian foredeep, whereas the more diverse signals represent a confluence of rivers from the northeast through the backbulge of southern Illinois and western Kentucky, and from the north across the Arkoma shelf. Collectively, the Ouachita Basin represents a terminal sink for sediments derived from much of the eastern and central United States.

Introduction

Assembly of the Paleozoic Appalachian-Ouachita orogenic system had a profound effect on North American landscapes and sediment routing (Fig. 1). Early work by Patchett et al. (1999) presented Nd isotopic data from Phanerozoic fine-grained siliciclastic strata of North America (including the southern United States, western Canada, and the Arctic margin), and inferred that by ca. 450 Ma detritus from the Appalachian orogen had overwhelmed sediment from all older sources across North America. More recently, several authors (Dickinson and Gehrels, 2003; Gehrels et al., 2011; May et al., 2013; Link et al., 2014; Evans and Soreghan, 2015; Nair et al., 2018) observed Appalachian-Grenville (ca. 500–275 Ma and ca. 1250–950 Ma, respectively) and peri-Gondwanan (ca. 800-500 Ma) detrital zircons (DZ) in late Paleozoic deposits of the western Laurentian margin in the United States, from the present-day Grand Canyon of the Colorado Plateau to the Bighorn Basin in Wyoming. Although several authors interpret the central Appalachians to be the source region for large-scale east-to-west sediment transfer, as discussed by Thomas (2011), the actual fluvial systems that would have transported this Appalachian signal to the western United States have not been clearly identified and remain unclear.

Siliciclastic turbidites of the Lower Pennsylvanian Jackfork Group and Johns Valley Shale (Fig. 2) in the synorogenic Ouachita Basin of Arkansas and Oklahoma (Fig. 1) represent a known deepwater sediment sink for this time period. Moreover, several Early Pennsylvanian generally north-to-south trending paleovalleys have been recognized in theUnited States midcontinent from eastern Kentucky to western Kansas and southeastern Colorado (see Archer and Greb, 1995). Collectively, the Ouachita Basin and midcontinent paleovalleys should have limited sediment routing directly from the central and southern Appalachians to western North America. Sediment sources for the Jackfork Group and Johns Valley Shale have been debated over time, with several alternative models proposed from traditional paleocurrent, petrographic, and geochemical provenance data in the peer-reviewed (e.g., Bokman, 1953; Briggs and Cline, 1967; Morris, 1971, 1974b; Graham et al., 1976; Morris et al., 1979; Morris, 1989; Gleason et al., 1994; Slatt et al., 2000b; Zou et al., 2017) and non-peer-reviewed literature (e.g., Danielson et al., 1988; Jordan et al., 1991). Here we examine source terranes and sediment routing for the Jackfork Group and Johns Valley Shale using DZ U-Pb and hafnium (Hf) isotopic data, and place our results within the broader context of Early Pennsylvanian landscape evolution and sediment routing associated with the development of the Appalachian-Ouachita orogenic system.

Geological Background

The spatial distribution and age of sources for DZ in Laurentian North America are well known from decades of studies (Becker et al., 2005; Dickinson and Gehrels, 2009; Park et al., 2010; Laskowski et al., 2013), and reflect the episodic growth of the Laurentian landmass (Table 1). Important to our study, the Proterozoic suturing, growth, and evolution of terranes resulted in the assembly and subsequent rifting of the supercontinents Columbia (including the Nuna core, Rogers and Santosh, 2002; Meert, 2012; Meert and Santosh, 2017) and Rodinia, which resulted in the development of the Paleoproterozoic (ca. 1800-1600 Ma) Yavapai-Mazatzal orogenic system, the Midcontinent Anorogenic Granite-Rhyolite province (ca. 1550-1300 Ma), which intrudes Yavapai-Mazatzal rocks, and the Mesoproterozoic (ca. 1250-950 Ma) Grenville orogenic system in North America (see Whitmeyer and Karlstrom, 2007). The Neoproterozoic breakup of Rodinia first occurred along the western margin of Laurentia, then the eastern margin, and finally along the Ouachita embayment to the south (Thomas, 1991), which represents the precursor for the Ouachita Basin where the Pennsylvanian Jackfork Group and Johns Valley Shale would be deposited (Fig. 1).

Hatcher (2010) summarizes the three main stages of evolution for the Paleozoic Appalachian orogenic system on the eastern margin of Laurentia, as follows: (1) the ca. 490-430 Ma Taconic orogeny, which represents a succession of island arcs that accreted to Laurentia (Miller et al., 2000); (2) the ca. 430-345 Ma Acadian (northern) and Neoacadian (southern) orogenies, which represent a continental margin magmatic arc that formed in association with accretion of peri-Gondwanan superterrranes (Ganderia, Avalonia, and Carolina) to Laurentia; and (3) the ca. 330-275 Ma Alleghenian-Ouachita orogeny, which records a diachronous north-to-south continent-continent collision between Laurentia and Gondwana (Miller et al., 2006; Heatherington et al., 2010) and the assembly of Pangea. Hibbard and Karabinos (2013) distinguish the southern Appalachian segment (south of the New York promontory) from the northern segment based on observations that show Alleghenian plutonism was largely confined to south of the New York promontory (see also Speer et al., 1994). Collectively, then, the Appalachian orogenic system includes Mesoproterozoic Grenville, Neoproterozoic peri-Gondwanan, and Paleozoic Appalachian source terranes, which provide DZ U-Pb age groups that range from ca. 1250 to 275 Ma.

Ingersoll et al. (1995) and Coleman (2000) refer to the Carboniferous deepwater Basin where Jackfork sandstones and the Johns Valley Shale were deposited as the Ouachita Basin (Fig. 1), which was positioned near the future Laurentia-Gondwana suture, and has been interpreted to represent a remnant ocean basin (e.g., Ingersoll, 2012) that progressively narrowed with the northward advancement of the Ouachita magmatic arc. As the suturing of Pangea progressed, sediment flux eroded from the growing Appalachian orogen is interpreted to have increased at the same time that the deepwater basin was inverting (Ingersoll et al., 1995). Ouachita deepwater basin fill was then incorporated into the northward propagating fold-and-thrust belt, and flexural loading then formed the Arkoma peripheral foreland basin to the north. As basin architecture changed, Early Pennsylvanian synorogenic turbidite and deltaic sedimentation in the Ouachita Basin was succeeded by Middle to Late Pennsylvanian syn- to post-orogenic fluvial-deltaic deposition in the Arkoma Basin (Ingersoll et al., 2003).

General Stratigraphic Framework

Early workers described the general Carboniferous stratigraphic succession of the Ouachita Basin to consist of the Mississippian Stanley Group and the overlying Lower Pennsylvanian (Morrowan) turbidites of the Jackfork Group (see Fig. 2, Miser and Purdue, 1929; Harlton, 1938; Hass, 1950; Goldstein and Hendricks, 1962; Johnson, 1968; Niem, 1976). Belts of Jackfork Group deposits crop out for more than 300 km across Arkansas and Oklahoma (Fig. 3) striking east-to-west along the axis of the Ouachita trough (Morris, 1971, 1974b; Ingersoll et al., 1995). The deepwater Johns Valley Shale overlies the Jackfork Group and is in turn overlain by the ~6100-m-thick synorogenic Atoka Formation (Coleman, 2000). Atoka deposits generally represent a shallowing-up progradational and aggradational succession from initially deepwater deposits to deposits of deltaic origin based on observed facies successions, stacking patterns, and sedimentary structures (Coleman, 2000). The roughly coeval Hale, Bloyd, and Atoka

Formations farther to the north on the Arkoma shelf are generally interpreted to represent fluvial-deltaic deposits (Sutherland and Henry, 1977; Zachry, 1979; Sutherland, 1988; Xie et al., 2018).

Farther to the northeast and east, correlative Morrowan fluvial and marginal marine deposits of the Illinois, Black Warrior, and Appalachian Basins (Figs. 1 and 2) include the Caseyville Formation, Pottsville Formation, Sewanee Conglomerate, Lee Formation, and Corbin Sandstone (Archer and Greb, 1995; Thomas, 1997; Becker et al., 2005). Archer and Greb (1995) estimated a minimum contributing paleodrainage area of $>10^6$ km^2 for the Caseyville Formation and equivalent units of the Illinois Basin, based on paleogeographic constraints; similar estimates were applied to the Lee Formation and equivalent units of the Central Appalachian Basin. These prospective Early Pennsylvanian sediment-routing pathways from the eastern interior and the Appalachian orogen to the Ouachita Basin have also been recently sampled for DZ U-Pb analyses (Thomas et al., 2017; Thomas et al., 2020).

Previous Work on Early Pennsylvanian Sediment Routing

Within the above stratigraphic context, various authors have proposed that Ouachita Basin sediment sources were to the north (Laurentian craton), east (Appalachian orogen), and south (Gondwanan margin) (Bokman, 1953; Morris, 1971, 1974b; Mack et al., 1983; Thomas, 1988; Morris, 1989; Gleason et al., 1994), with additional workers considering the Himalayan-Bengal system to be a modern analog for sediment dispersal (Graham et al., 1975; Graham et al., 1976; Ingersoll et al., 1995; Ingersoll et al., 2003). Early provenance studies describe sandstone petrography (Morris, 1971, 1974b; Morris et al., 1979; Morris, 1989) and paleoflow directions (Briggs and Cline, 1967; Morris, 1971, 1974a) for Jackfork turbidites. Jackfork sandstones are predominantly arenites that become more feldspathic to the south, and feldspar content generally decreases eastward along the frontal (northern) Ouachita Mountains. Rock fragments comprise 3% of sandstones along the frontal Ouachitas to the north and 10% along the southern Ouachitas, and the Jackfork Group generally lacks volcanic detritus (Morris, 1971). Based on these data, Morris (1971) suggested the Black Warrior Basin may represent a shallower eastern extension of the Ouachita Basin and the Appalachians were the primary source for most of the Ouachita clastics, whereas craton-derived quartz sand and low-feldspar detritus were derived from the northern midcontinent, with a transport corridor to the Ouachita Basin located between the Ozark and Nashville domes, which implies there were two possible basin-floor fan sinks within the Ouachita Basin.

Subsequent petrographic studies revealed a lack of southern arc-related sediment in the Ouachita Basin and an affinity between deposits of the Ouachita and Black Warrior Basins. Graham et al. (1976) demonstrated low proportions of feldspathic and volcanic lithic fragments in Pennsylvanian rocks of the Ouachita and Black Warrior Basins, suggested a common Appalachian source where quartzose sediment was derived from the vigorously uplifted older interior of the Appalachian-Ouachita system, and implied that sedimentary and metasedimentary rocks were the dominant sources, not arc rocks in the orogens. Mack et al. (1983) subsequently observed an increase in volcanic rock fragments in the Lower Pennsylvanian Pottsville Formation in the Black Warrior Basin, relative to the underlying Parkwood Formation, but concluded that volcanic rock fragments in the Pottsville were too few in number to be solely derived from a southern arc. Owen and Carozzi (1986) paired cathodoluminescence frequency distributions of quartz with standard petrography of samples from the Ouachita and Black

Warrior Basins and interpreted the Ouachita Basin Jackfork Group and the Black Warrior Basin Parkwood Formation to have a common provenance.

Subsequent Nd studies interpreted Appalachian sources for Ouachita Basin deposits. Gleason et al. (1994) showed that Nd isotopic data from Pennsylvanian units of the Arkoma shelf, Illinois Basin, Black Warrior Basin, and the Ouachita Basin have coherent negative εNd values that follow the previously defined Grenville crustal evolution trajectory for Nd isotopes. Gleason et al. (1994) therefore suggested units from these areas were sourced from the Appalachian fold-and-thrust belt. Subsequent Nd data from the Johns Valley Shale and Atoka Formation in Oklahoma from Dickinson et al. (2003) continued to support the interpretation that the Appalachian orogen was the dominant regional source for sediment transferred across southern and eastern Laurentia after ~450 Ma (see Patchett et al., 1999). However, Nd data only reflect an average of contributing sources and are limited in determining unique provenance (Gleason et al., 1994) and dispersal pathways (Thomas et al., 1995).

The Mississippian Stanley Group, which lies below the Jackfork Group, contains interbedded silicic ash-flow tuffs that have an εNd isotopic composition of -2, and are interpreted to be sourced from a magmatic arc located to the south (Gleason et al., 1994). Shaulis et al. (2012) acquired a weighted average U-Pb age of ca. 320.7 ± 2.5 Ma (2σ) for the Chickasaw Creek tuff (n=38), which provides age constraints for the upper Stanley Group. However, in spite of historical interpretations of a proximal magmatic arc to the south, Shaulis et al. (2012) noted a lack of Pan-African DZ U-Pb age modes in tuffaceous material and suggested that most Mississippian sediment from the arc terrane was trapped within the forearc basin, with the exception of air-fall tuff (see Ingersoll et al., 1995). These tuffs are a significant component of interpreted Mississippian turbidites of the Stanley Group, but have not been recognized in the overlying Pennsylvanian succession (Gleason et al., 1994).

Earlier provenance studies of the Jackfork Group were followed by outcrop modeling of sand body architecture and a series of sequence-stratigraphic studies. Recently described locations in Arkansas include Baumgartner Quarry (Zou et al., 2012), Hollywood Quarry (Goyeneche et al., 2006), DeGray Lake Spillway (Al-Siyabi, 2000; Slatt et al., 2000a; Schlichtemeier, 2011) and Big Rock Quarry (Olariu et al., 2008; Olariu et al., 2011; Funk et al., 2012). Near the Baumgartner Quarry, roadcuts located to the south of Kirby, Arkansas (along State Highway 27) were partially described by Morris (1971) and later studied in detail by Zou et al. (2017). The Kirby, DeGray Lake Spillway, and Big Rock Quarry locations are discussed further below as part of the sampling strategy for this study (Fig. 3).

Methods

Detrital Zircon U-Pb Analysis

Use of DZ U-Pb ages as a provenance tool in a terminal depositional sink like the Ouachita Basin assumes the distribution of U-Pb ages in a sample provide a faithful fingerprint of the populations from specific source terranes (see Ross and Parrish, 1991), including distant sources that are not likely identified from conventional provenance studies alone (Dickinson and Gehrels, 2010). Faithful propagation of signals from specific source terranes with short lag times seem intuitive for small sediment-dispersal systems with short transport distances along active continental margins (see Romans et al., 2016). However, studies of the Late Pleistocene and

Holocene Mississippi (Fildani et al., 2016; Mason et al., 2017; Li et al., 2020), the Neogene to modern Bengal (Blum et al., 2018; Pickering et al., 2020), and the Late Pleistocene Amazon (Mason et al., 2019) fans demonstrate this to be the case for Earth's largest extant fluvial to deep-sea fan systems as well (see also Hessler and Fildani, 2019).

For this study we collected twelve samples of fine- to medium-grained sandstones of turbidite origin for DZ U-Pb analyses from three general locations in Arkansas that have been studied from a stratigraphic point-of-view by previous workers (Figs. 3 and 4; and Table 2): Big Rock Quarry (see Olariu et al., 2008; Olariu et al., 2011), DeGray Lake Spillway (see Al-Siyabi, 2000; Slatt et al., 2000b), and roadcuts on State Highway 27 south of Kirby (see Morris, 1971; Zou et al., 2017). The Jackfork Group is undifferentiated in the southern region of Arkansas, but we collected our samples throughout the entirety of the Jackfork Group and the lower part of the overlying Johns Valley Shale: two samples represent the lower Jackfork, two represent the middle Jackfork, six represent the upper Jackfork, and two represent the lower Johns Valley Shale (Table 2).

Ten of our samples (PennJ1 to PennJ10) were processed for mineral separation at the Arizona LaserChron Center (ALC; Tucson, Arizona), whereas two samples (PennJ11 and PennJ12) were processed at the Isotope Geochronology Lab at the University of Kansas. All twelve samples were then mounted and analyzed at the ALC employing methods outlined by Gehrels (2012). U-Pb analyses were conducted on the Element 2 single collector Laser Ablation-Inductively Coupled Plasma-Mass Spectrometer (LA-ICP-MS). The maximum uncertainty filter for $^{206}Pb/^{238}U$ ages was 10%. The maximum uncertainty filter for $^{206}Pb/^{207}Pb$ ages was also 10%, but only applied to analyses with $^{206}Pb/^{238}U$ ages >400 Ma. Maximum discordance and reverse discordance cutoffs were 20% and 5%, respectively, for analyses with $^{206}Pb/^{238}U$ ages >400 Ma. We chose a sample target of 300 grains for analysis, which reduces the probability of missing minor fractions of the total population, and better reflects the true abundance of age distributions in a sample compared to small-n (<100 analyses) samples (see Vermeesch, 2004; Andersen, 2005; Pullen et al., 2014; Saylor and Sundell, 2016). We also employed a "higher n" approach to determine the maximum depositional age (MDA) for the Jackfork Group by acquiring 600 additional U-Pb ages from DZ sample PennJ1 at a rate of 600 analyses per hour using the Nu Plasma multi-collector LA-ICP-MS (see Sundell et al., 2020). We distinguished the original PennJ1 ages from the n = 600 upgrade as PennJ1A and PennJ1B, respectively.

Detrital Zircon Hf Isotopic Analysis

DZ Hf isotopic analyses can strengthen interpretations of sediment routing by differentiating source areas that otherwise have the same or similar DZ U-Pb ages. Recent studies by Thomas et al. (2017) and Thomas et al. (2020) provide εHf values from zircons within fluvial systems of the Carboniferous Appalachian foredeep and eastern midcontinent basins, which serve as a comparative baseline for our study. To assist with fingerprinting source terranes and the reconstruction of sediment routing, we conducted Hf isotopic analyses on Ouachita deep-sea fan zircons at the ALC using the methods of Cecil et al. (2011) and Gehrels and Pecha (2014) on four samples: PennJ1A (DeGray Lake Spillway, upper Jackfork), PennJ4 (Kirby, lower Jackfork), PennJ8 (Kirby, upper Jackfork), and PennJ10 (Kirby, Johns Valley Shale). A mean of 26 Hf isotopic analyses were conducted for each sample, including a mean of 20 Hf analyses per sample from the Appalachian age group (ca. 500–275 Ma). We selected grains with U-Pb ages <800 Ma for Hf analyses due to the greater dispersion of εHf values compared with older age populations (e.g., see data from Thomas et al., 2017) and thus the greater possibility of source-terrane differentiation.

Kernel Density Estimate Visualization and Multi-Dimensional Scaling Analysis

Ages from twelve samples acquired from the Jackfork Group and Johns Valley Shale are plotted as normalized kernel density estimates (KDEs), which provide for visual inspection of the differences between samples in terms of age distributions and modes. KDEs are constructed without using uncertainty terms, which increase with older zircons, and thus KDEs are believed to be an unbiased estimator of the true age distribution (Vermeesch, 2012). We use the R-based package *provenance* (Vermeesch et al., 2016) to calculate and plot KDEs and visualize major and minor age modes.

Large-scale analysis of sediment routing requires large data sets, but visual inspection of large data sets likely introduces subjectivity (Saylor and Sundell, 2016). Therefore, dissimilarity between samples is commonly assessed by the Kolmogorov-Smirnov (KS) or Kuiper tests, which test the probability that samples are drawn from a single population. The KS-statistic is useful for multi-sample comparisons by multi-dimensional scaling (MDS) analysis (Vermeesch, 2013, 2018). MDS takes a table of pairwise dissimilarities as input, and produces a set of, in our case, two-dimensional coordinates as output; the scatterplot of samples in Cartesian space represents a 'map' in which similar samples plot closer together and dissimilar samples plot farther apart (Vermeesch, 2018). It is commonly interpreted that MDS sample clusters identify samples with the same or similar source terranes. We use the MATLAB graphical user interface by Vermeesch (2013) to identify DZ samples that cluster in Cartesian space to guide interpretations of sediment routing.

Results

DZ U-Pb Age Distributions

We obtained 3550 concordant DZ U-Pb ages from PennJ1A through PennJ12, which represents a mean of 295 concordant analyses per sample, plus an additional 503 concordant U-Pb ages from PennJ1B using the rapid acquisition "higher n" approach described above. DZ U-Pb ages for all samples from the Jackfork Group and Johns Valley Shale display prominent Appalachian-Grenville (ca. 1250–317 Ma), Midcontinent Granite-Rhyolite (ca. 1550–1300 Ma), and Yavapai-Mazatzal (ca. 1800–1600 Ma) age groups, as well as minor contributions from peri-Gondwanan (ca. 800–500 Ma), Penokean/Trans-Hudson (ca. 2000–1800 Ma) and Superior (ca. >2500 Ma) age sources (see listed age domains in Table 1). For the dataset as a whole, the 1250-950 Ma age group characteristic of Grenville terranes is the most prominent, contributing a mean representation of 36.7% of the U-Pb ages per sample, followed by Yavapai-Mazatzal (15.0%), Appalachian (14.2%), and Midcontinent (14.0%) age groups. Other ages are less significant in terms of their total contributions, with Archean Superior ages comprising 6.2% of the total, followed by the Penokean/Trans-Hudson ages (4.0%) and peri-Gondwanan ages (3.0%) (Fig. 5).

KDE plots in Figure 6 show that all samples display a great deal of visual similarity. Like most samples that are related to the Alleghenian orogenic system, the Appalachian and Grenville ages dwarf other age groups in our samples, and our samples generally have a high ratio of

Appalachian to Grenville grains. There are, however, minor differences in age distributions between samples. Most importantly, DZ U-Pb age distributions from PennJ11 and PennJ12, collected from the most northern and source-proximal site at Big Rock Quarry in Little Rock, exhibit a relatively modest percentage of Appalachian ages (7.4%), but an elevated percentage of Yavapai-Mazatzal ages (24.3%) when compared with samples collected farther south and west at DeGray Lake Spillway and Kirby (PennJ1A to PennJ10), which exhibit a relatively elevated percentage of Appalachian ages (15.5%) and a modest percentage of Yavapai-Mazatzal ages (13.1%) (see Figs. 3, 5, 6, and 7A).

Two-dimensional MDS plots are shown in Figure 7B and differentiate two sample clusters that are consistent with, and reinforce, the visual differences in the KDE plots described above. Cluster A is defined by larger percentages of Appalachian ages and generally modest Yavapai-Mazatzal modes that characterize samples PennJ1A to PennJ10. Within Cluster A, DZ U-Pb age distributions from the seven Kirby samples are indistinct (see Figs. 3 and 6), with the bottommost Jackfork sample (PennJ4) and the topmost Jackfork sample (PennJ8) defining the most distant points in this cluster. The three samples from the DeGray Lake Spillway (PennJ1A to PennJ3) reside in the center of Cluster A (Fig. 7B). Cluster B is defined by the relatively modest percentages of Appalachian ages but elevated Yavapai-Mazatzal age modes that characterize PennJ11 and PennJ12, as described above. Samples PennJ8 from Kirby and PennJ3 from the DeGray Lake Spillway from Cluster A plot closest to Cluster B in MDS space, whereas PennJ4 and PennJ5 plot farthest away.

Youngest DZ U-Pb Ages from Jackfork Group Samples

We anticipated that constraining the maximum depositional age (MDA) for the Jackfork Group would be difficult, unlike the underlying Mississippian Stanley Group, which contains ash beds (Niem, 1977; Shaulis et al., 2012). Indeed, from 3550 concordant U-Pb ages, only PennJ1 and PennJ11 produced single Early Pennsylvanian or Late Mississippian U-Pb ages (ca. 317.5 ± 4.0 Ma (at 2σ) and ca. 324.4 ± 3.6 Ma (at 2σ), respectively). As discussed more fully below, these two grains may represent the rare Alleghenian volcanogenic zircons that are syndepositional with respect to the Jackfork Group. We also obtained U-Pb ages that range from 208.9 to 339.8 Ma on seven grains from samples PennJ6, PennJ7, and PennJ10, but which have elevated U concentrations or U/Th ratios, and are not further considered in the context of maximum depositional ages.

Our attempt to identify more young volcanogenic grains by obtaining 503 additional concordant U-Pb ages from PennJ1 from DeGray Lake Spillway (PennJ1B) was unsuccessful. PennJ1B and PennJ1A represent separate analyses of the same sample, and have similar age distributions (Fig. 6), but the youngest U-Pb ages from PennJ1B were >365 Ma, more than 45 million years older than the U-Pb age from an ash bed from the uppermost Stanley Shale (Shaulis et al., 2012).

Detrital Zircon Hf Isotopic Data

New DZ Hf isotopic data from grains <800 Ma in age from the Jackfork Group and Johns Valley Shale are plotted in Figure 8 in epsilon Hf (εHf) units. The mean εHf value for all grains from the four samples and the standard error is -2.0 ± 1.0 (1σ); the mean εHf values for Appalachian-age and peri-Gondwanan-age grains are -1.8 ± 1.0 (1σ) and -2.8 ± 0.9 (1σ), respectively (see

Table 3). The three Kirby samples (PennJ4, PennJ8, and PennJ10), as well as the sample from the DeGray Lake Spillway (PennJ1A), consistently demonstrate intermediate εHf values of -5 to +5 (Fig. 8 and Table 3), and 65% of the 103 total analyses are within this intermediate range.

The mean εHf values from the three Kirby samples (PennJ10, -3.2 ± 1.0 [1σ]; PennJ8, -2.9 ± 1.0 [1σ]; and PennJ4, -1.7 ± 1.1 [1σ]) are slightly more evolved than that from the sample from the DeGray Lake Spillway (PennJ1A, -0.3 ± 0.9 [1σ], see Table 3). Sample PennJ1A has the distinction of having an Alleghenian-age εHf value (+0.3 ± 0.8 [1σ]) as well as the single most juvenile εHf value (+12.4 ± 1.0 [1σ]), whereas PennJ8 has the two most evolved values in the dataset (-19.3 ± 1.5 [1σ] and -17.0 ± 0.7 [1σ]). When comparing mean εHf values of Appalachian (n=78) versus peri-Gondwanan (n=25) age grains, both age groups show a slight trend toward more evolved values when comparing the stratigraphically oldest sample, PennJ4, to the stratigraphically youngest sample, PennJ10. Mean εHf values for grains with Appalachian and peri-Gondwanan U-Pb ages from the three Kirby samples are also more evolved than those from sample PennJ1A from the DeGray Lake Spillway. However, even with these subtle differences, most Hf analyses produced intermediate values, with 26% of all εHf values represented by values of -2.0 ± 2.0 (2σ).

Discussion

Provenance of Pennsylvanian Ouachita Basin Deepwater Deposits

Our data define characteristic DZ U-Pb ages for the Jackfork Group and Johns Valley Shale of the deepwater Ouachita Basin. From KDE and MDS plots we define two clusters of samples with distinct age distributions: Cluster A, which includes PennJ1A to PennJ10 from the DeGray Lake Spillway and Kirby, is dominated by Appalachian and Grenville ages, whereas Cluster B, which includes PennJ11 and PennJ12 from Big Rock Quarry, displays fewer Appalachian-Grenville and more Yavapai-Mazatzal ages. These differences are interpreted to represent at least two distinct source regions and sediment-routing pathways. Cluster A is most similar to select Lower Pennsylvanian DZ U-Pb age distributions from the Appalachian foredeep in Tennessee and Kentucky (Thomas et al., 2017), whereas cluster B is more similar to DZ U-Pb data that have been reported from a select few Pennsylvanian sandstones of the southern Illinois and Michigan Basins (Thomas et al., 2020) and the Arkoma shelf (Xie et al., 2018).

More subtle differences appear within these two clusters. The Kirby and DeGray Lake Spillway samples (Cluster A) are as a whole similar (Figs. 7A and 7B) and are interpreted to represent more distal portions of Jackfork and Johns Valley deep-sea fan systems (see Zou et al., 2017). The lowermost and uppermost Jackfork samples from Kirby (PennJ4 and PennJ8, respectively) define the most distant points in Cluster A, and are located ~140 km to the west of Big Rock Quarry, whereas samples from the DeGray Lake Spillway reside within the center of Cluster A, and are located ~100 km from Big Rock Quarry. Although there is some minor variability, age distributions are generally consistent for the seven Kirby samples collected from the Jackfork and Johns Valley Shale in the southern Ouachitas through ~2400 m of stratigraphic section (see Zou et al., 2017). We therefore interpret DZ U-Pb ages from the Kirby and DeGray Lake Spillway sections to indicate little to no change in provenance over Morrowan time for sediment delivered to this more distal part of the system, and that samples from the DeGray Lake Spillway and Kirby collectively represent the primary deep-sea fan of the Ouachita Basin, which is composed of sediment transported directly from the Appalachians.

Big Rock Quarry (Cluster B) represents a generally more proximal fan setting, and we interpret DZ U-Pb ages from that location to represent a fan that was sourced by a second distinct routing system with a mixed provenance. We interpret the source terranes to have included the United States midcontinent, based on the lower percentage of Appalachian ages and the increased contribution of Yavapai-Mazatzal ages. The Nemaha uplift of eastern Nebraska was subaerially exposed at that time and represents the most likely primary source (e.g., Steeples, 1982; Dolton and Finn, 1989; Burberry et al., 2015; Joeckel et al., 2019), whereas Yavapai-Mazatzal age crystalline rocks would have been buried by older Paleozoic sedimentary rocks of the northern midcontinent (Konstantinou et al., 2014), which could have provided a recycled source, although less likely. Both of these possibilities point to a northern source region, rather than directly from the Appalachians to the east. Sample PennJ8 in Cluster A is most similar to Cluster B samples, and Cluster A samples are composed of 13.1% Yavapai-Mazatzal grains (see Figs. 6, 7A, and 7B), which suggests this secondary fan system, derived from the north and northeast, may have sometimes contributed sediment to deposits at the Kirby and DeGray Lake Spillway locations as well. We therefore interpret these relatively distal samples to record a mixing of two distinct deep-sea fan systems, which collectively drained source regions to the east, northeast and north to northwest.

Epsilon Hf values obtained from Paleozoic Appalachian and Neoproterozoic peri-Gondwanan zircons of the Ouachita Basin are similar to εHf values from the Pennsylvanian Appalachian foredeep (Thomas et al., 2017) and the Pennsylvanian Illinois and Forest City Basins (Thomas et al., 2020). The mean εHf value for four Pennsylvanian samples from the Appalachian Basin for both Appalachian and peri-Gondwanan ages is -0.3 ± 1.2 (1σ) (Thomas et al., 2017, see Table 4), similar to the mean εHf value for PennJ1A grains from the DeGray Lake Spillway (-0.3 ± 0.9 (1σ)). However, the mean εHf value for the four samples from Ouachita Basin as a whole (-2.0 ± 1.0 (1σ)) is slightly more evolved than the mean εHf from samples from the Appalachian (-0.3 ± 1.2 (1σ)), Illinois (-1.2 ± 1.0 (1σ)), and Forest City (-0.1 ± 0.9 (1σ)) Basins for 307-833 Ma ages (Table 4). The intermediate εHf values from the Appalachian and peri-Gondwanan ages of the Ouachita Basin do not in themselves clearly distinguish different crustal sources, but support the interpretation that the provenance of siliciclastics in the Ouachita Basin include areas to the east, northeast, and north, and provide additional characterization of εHf signatures for Pennsylvanian sediment routing systems as a whole.

Only two DZ U-Pb ages of ca. 317 and 324 Ma from our data are consistent with the estimated Early Pennsylvanian age of the Jackfork sandstone and Johns Valley Shale (post-320 Ma, Shaulis et al., 2012). This low yield is similar to the earlier observation of Thomas et al. (2004), who noted that the youngest DZ U-Pb ages from Alleghenian foreland-basin deposits generally correspond to the previous Taconic and Acadian orogenic cycles, and consistent with the more recent detailed study of Appalachian DZ U-Pb ages by Thomas et al. (2017), who only observed one U-Pb age of approximately Early Pennsylvanian age (ca. 322 Ma) in Pennsylvanian-aged foreland basin deposits. Our results suggest that non-volcanogenic Alleghenian DZ sources were generally not exhumed by Pennsylvanian time, which hindered efforts to obtain reliable Jackfork and Johns Valley Shale MDAs.

Interestingly, our study and previous work in the Appalachian foredeep observed low yields for syndepositional zircons of Alleghenian age (Thomas et al., 2004; Thomas et al., 2017), but zircons of Pennsylvanian age are modestly more common in Middle to Upper Pennsylvanian samples from the Forest City and Illinois Basins, where ~17 grains produced DZ U-Pb ages that correspond in time to the Alleghenian orogeny (Kissock et al., 2018). We compiled 25 concordant DZ U-Pb ages that range from 301 to 333 Ma from Pennsylvanian units of eastern Laurentia (Fig. 9) from Sharrah (2006), Dodson (2008), Thomas et al. (2016), Kissock et al. (2018), and Chapman and Laskowski (2019), including 13 U-Pb ages that overlap within 2σ uncertainty with our youngest U-Pb ages from the Jackfork. The majority of these syndepositional zircons were collected in the Forest City Basin in Iowa, which is something of a conundrum because the nearest location for Alleghenian plutons is in the southern Appalachians of Georgia through Virginia, plutons of this age are rare in the northern Appalachians (Hibbard and Karabinos, 2013), and syndepositional zircons are rare in the Appalachian foredeep (Thomas et al., 2017) and Ouachita remnant ocean basin (this study). However, our youngest single grains from the Jackfork Group at ca. 317 Ma and 324 Ma, if robust, are not outliers within the broader context of Pennsylvanian units of eastern Laurentia.

Early Pennsylvanian Sediment Routing

High-amplitude and high-frequency glacio-eustasy was common in the Pennsylvanian (Heckel, 2008), hence shelves would have been submerged during interglacial periods, and exposed during glacial periods with low sea level. Based on DZ U-Pb ages and Hf isotopic data from the Jackfork Group and Johns Valley Shale, we conclude that at least two distinct fluvial systems to the east, northeast and north extended across the emergent Arkoma shelf during periods of low sea level to discharge sediments to two different slope canyons. Sediment routed through these canyons then fed two Ouachita Basin deep-sea fans: the Big Rock Quarry samples are interpreted to represent a proximal part of a more northerly-derived system, whereas the distal DeGray Lake Spillway and Kirby samples are interpreted to represent a mixing of these two fans. We interpret the distinct Yavapai-Mazatzal signature of Cluster B from Big Rock Quarry was derived from the north-northwest from the exposed Nemaha uplift of present-day Nebraska (Steeples, 1982; Dolton and Finn, 1989; Burberry et al., 2015; Joeckel et al., 2019). Alternative local sources consist of the Upper Mississippian Wedington Sandstone of northwestern Arkansas (Xie et al., 2016a) and the Aux Vases Sandstone in Missouri (Chapman and Laskowski, 2019), which contain ~15% and ~14% Yavapai-Mazatzal-age grains, respectively, which is insufficient to produce the proportion of Yavapai-Mazatzal-age grains in Cluster B (~24%). We therefore suggest that sediment was transported from the exposed Nemaha uplift to the south-southeast, across present-day Missouri, and the river system occasionally avulsed to the east to join a river system that was transporting sediment from the northeast through southern Illinois and Kentucky. During a subsequent sea-level lowstand, the two fluvial systems flowed together across the Arkoma shelf and discharged to a common submarine canyon located to the northeast of Big Rock Quarry (Fig. 10).

We see no clear evidence that the advancing Ouachita magmatic arc to the south of the remnant ocean basin contributed sediment to the Jackfork and Johns Valley Shale deep-sea fans. Instead, Ouachita arc-derived terrigenous sediment from the south was most likely transported by short and steep fluvial systems (see Helland-Hansen et al., 2016) that drained the arc, and sediment was trapped in the Gondwanan forearc basins, a situation perhaps analogous to the modern Sumatran forearc (e.g., Moore et al., 1982). Our data therefore generally support the view that multiple fluvial systems contributed to at least two deep-sea fans in the Ouachita Basin, but there was minimal contribution from the south (e.g., Morris, 1971; Graham et al., 1975; Gleason et al., 1994; Coleman, 2000). Thus prior to basin closure and uplift and propagation of the Ouachita fold and thrust belt in the Late Pennsylvanian (Coleman, 2000), the Jackfork and Johns Valley Shale deep-sea fans represented the primary terminal sink for interpreted fluvial systems that drained an area that stretched from the Appalachians in the eastern US to the midcontinent. Similar to the modern world (e.g., Sweet and Blum, 2016), the wide shelves of the Pennsylvanian would have been flooded during interglacial periods with high sea level, and the majority of sediment transfer to the Ouachita deepwater Basin would have occurred when these large regional-scale low-gradient river systems extended across emergent shelves to connect with slope canyons during glacial periods when sea level was low, and river mouths were proximal to shelf-margin canyon heads (Fig. 10).

Comparison with DZ U-Pb Data from Pennsylvanian Stratigraphic Units of Eastern Laurentia

We compared DZ U-Pb data from the Ouachita Basin with published data from Lower Pennsylvanian samples collected from the greater Appalachian foreland-basin system (Fig. 11A), including the Illinois Basin (Caseyville Formation and Caseyville-equivalents, Kissock et al., 2018; Thomas et al., 2020), the Appalachian Basin (Raleigh Sandstone, Sewanee Conglomerate, and Corbin Sandstone, e.g., Eriksson et al., 2004; Thomas et al., 2004; Thomas et al., 2017), and the Arkoma shelf (middle Bloyd sandstone member of the Bloyd Formation, Xie et al., 2018). The MDS plot in Figure 11B shows that many Lower Pennsylvanian DZ samples from eastern Laurentia surround and partially enclose Cluster A. While Cluster B is distinct in the broader context of other Pennsylvanian samples, a few samples plot relatively close to Cluster B as well: the two nearest neighbors to Cluster B, from the Lee Formation in Virginia (Becker et al., 2005) and from the Middle Bloyd Sandstone of northwest Arkansas (Xie et al., 2018), contain very few if any Appalachian ages and elevated Yavapai-Mazatzal contributions. The Corbin Sandstone sample from Kentucky (Thomas et al., 2017) and Caseyville Formation and Caseyville-equivalent sandstones in the Illinois Basin (Kissock et al., 2018; Thomas et al., 2020) also show an elevated Yavapai-Mazatzal signature, but the importance of the Appalachian-Grenville signature places these samples close to Cluster A.

Figures 11C and 11D show that DZ samples from Middle Pennsylvanian units of the Forest City and Illinois Basins (Kissock et al., 2018), and the Fort Worth Basin (south central United States) (Alsalem et al., 2018) closely encircle Cluster A and have similar Appalachian-Grenville signatures. This is also the case for the Atoka Formation samples from the Ouachita thrust belt (Sharrah, 2006), although some of these samples also contain the elevated Yavapai-Mazatzal signature, resulting in a prospective link between Clusters A and B (Fig. 11D). Moreover, a composite sample from locations in Missouri and Iowa (McFadden et al., 2012) and a sample from Michigan (Thomas et al., 2020) group with Cluster B due to characteristic elevated Yavapai-Mazatzal age modes. Most Upper Pennsylvanian units plot in the distal periphery relative to Clusters A and B (Fig. 11D).

This comparison between published Pennsylvanian data from eastern Laurentia and samples from the Ouachita Basin support the interpretation that the Ouachita Basin was the primary terminal sink for sediment derived from eastern Laurentia, from the Appalachians to the US midcontinent. To summarize, we interpret sediment routing to the Ouachita Basin to have included: (1) a west- to southwest-flowing longitudinal fluvial system within the Appalachian foredeep, through present-day Tennessee, northwestern Alabama, and northern Mississippi; (2) a southwest-flowing fluvial system that flowed through the Appalachian backbulge, including the Illinois Basin, then crossed the northern Arkoma shelf to deliver sediment to the Ouachita Basin; and (3) a smaller tributary system from the north-northwest, which delivered sediment from the midcontinent and joined the southwest-flowing system on the Arkoma shelf (Fig. 10).

Prospects for Large-Scale East-to-West Transcontinental Sediment Transfer

As noted above, previous authors interpreted the central Appalachians to be the source region for large-scale east-to-west sediment transfer to the western Laurentian margin during the Carboniferous. We agree with Thomas (2011) that the fluvial systems responsible for large-scale east-to-west sediment transfer are unclear, and add that the north-south oriented paleovalleys that routed water and sediment from the US midcontinent to the Ouachita Basin would have most likely obstructed westward sediment transport throughout the extent of the contributing drainage area for the Jackfork and Johns Valley Shale of the Ouachita Basin, especially during sea-level lowstands when river mouths were likely connected to submarine canyons. We therefore generally consider large-scale east-to-west sediment transfer by fluvial systems that drained the Appalachians during the Mississippian and Pennsylvanian to have been unlikely, and that sediment from the eastern and midcontinent US was instead routed directly to the Ouachita terminal sink.

Previous workers have proposed eolian transport as an alternative mechanism for transcontinental sediment transport across Laurentia during various times in the late Paleozoic, noting the Appalachian-Grenville-like DZ U-Pb signatures in late Paleozoic deposits of the Western US (Dickinson and Gehrels, 2003; Gehrels et al., 2011; Gehrels and Pecha, 2014; Nair et al., 2018; Chapman and Laskowski, 2019). However, we note that wind-transported particles greater than 1 μm generally fallout within 1000 km of the source area (e.g., Schutz et al., 1981), and eolian transport of sand-sized lower-density quartz grains (relative to zircon) is limited to distances of a couple hundred kilometers (see Boardman et al., 1995; Williams et al., 2016).

Chapman and Laskowski (2019), building on several of the provenance studies above, proposed an interesting alternative model that called on a coordinated multi-stage transport of Appalachian-derived DZ via delivery of sediment to the shoreline by fluvial processes, followed by longshore drift enhanced by trade winds and cyclones to transport this material to the western margin of Laurentia. However, while these processes certainly existed in Carboniferous equatorial Laurentia, transporting sands in a shallow marine environment at the scale necessary to contribute significantly to the Western Laurentian margin seems unlikely for the following reasons:

- Unlike the mud fraction, the sand fraction, including sand-sized zircons that are used for provenance studies, is transported in the longshore drift system within a kilometer or two of the shoreline, beyond which minimal large-scale sand transport takes place (see Sweet and Blum, 2016 for a recent discussion);
- Longshore transport of sand in the modern-day Gulf of Mexico (Stone and Stapor, 1996), on the Brazilian coast (e.g., Bittencourt et al., 2005), and elsewhere (see Inman, 2003), is typically organized into cells with length scales of kilometers to 100s of kilometers, beyond which there is little net exchange of sediment with adjacent longshore drift cells. The Holocene Gold Coast of eastern Australia is an exception in this context, because it shows evidence for ~1500 km of net longshore sand transport over a period of ~750,000 years (Pattearson and Patterson, 1983; Boyd et al., 2008), and was therefore cited by Chapman and

Laskowski (2019) as a potential analog. However, longshore drift would have encountered many obstacles to westward transport as well, including cross-shelf paleovalleys during sea-level lowstand, and muddy delta plains and drowned-valley estuaries during highstands.

- Longshore transport rates are typically of a scale comparable to the sediment discharge of individual regional-scale or smaller river systems. For example, sediment transport rates along the eastern Gulf of Mexico coast are typically in the ~1-3 x 10^5 m^3 yr^{-1} range (Stone and Stapor, 1996), whereas longshore sand transport along Australia's Gold Coast is ~5 x 10^5 m^3 yr^{-1} (Pattearson and Patterson, 1983; Boyd et al., 2008). By comparison, between 1950 and 2010 CE the Mississippi River delivered ~2 orders of magnitude more sand per year to the delta region (Blum and Roberts, 2014).

From the above, we find it difficult to justify longshore transport length scales, rates, and volumes that would have been capable of transporting sand across the continent at a scale required to produce the dominant DZ U-Pb signal for a continental margin, and do not see a viable pathway for large-scale sediment transfer between the U.S. part of the Appalachian-Ouachita orogenic system and southwestern Laurentia. However, we note that Leary et al. (2020) recently suggested long-distance transport from the Arctic Ellesmerian orogen and possibly the northern Appalachian orogen to the western United States. Our data and interpretations are compatible with this second model, but we note that, following the original objections raised by Thomas (2011), Carboniferous units with sand bodies that are of a scale that could represent a transcontinental-scale fluvial system have not been identified in the northern US or Canada. We also note that, on the other hand, Saylor and Sundell (2021) applied non-negative matrix factorization (NMF) to samples from the western Laurentian margin and suggested, tentatively, that Mississippian strata from Arizona which record an influx of ca. 1.0-1.2 Ga zircon ages

(Gehrels et al., 2011) were derived from the same sources that delivered sediment to the Appalachian foreland basin and midcontinental basins.

Conclusion

This study presents detrital zircon (DZ) U-Pb and εHf values from the Lower Pennsylvanian Jackfork Group and Johns Valley Shale of the synorogenic Ouachita deepwater Basin of Arkansas. All samples display abundant Appalachian-Grenville, Midcontinent and Yavapai-Mazatzal ages. Appalachian-Grenville ages dominate ten samples collected from the Jackfork Group and Johns Valley Shale in the present-day southern Ouachita Mountains. However, two additional samples from the most northern and most source-proximal site in Little Rock, Arkansas, exhibit only modest percentages of Appalachian ages and elevated contributions of Yavapai-Mazatzal ages when compared with samples collected farther to the south and west. Detrital Zircon U-Pb age distributions generally correspond to age distributions from the Appalachian foredeep, Illinois Basin, Forest City Basin, and the Arkoma shelf. Moreover, εHf values obtained from Appalachian- and peri-Gondwanan-age DZ of the Ouachita Basin are similar to εHf values from Pennsylvanian samples collected in the Appalachian, Illinois, and Forest City Basins (Thomas et al., 2017; Thomas et al., 2020); the intermediate εHf values characteristic of the Ouachita Basin do not in themselves clearly discriminate different crustal sources, but provide additional characterization of εHf signatures for Pennsylvanian units in the eastern United States as a whole.

Despite the proximity of the Ouachita arc south of the Ouachita Basin, most Mississippian- and Pennsylvanian-age sediment that was shed from this magmatic arc was likely trapped within Gondwanan forearc basins (Ingersoll et al., 1995; Shaulis et al., 2012). We therefore interpret that two distinct deep-sea fan systems in the Ouachita Basin were sourced by distinct feeder fluvial systems to the east, northeast and north (Fig. 10). Thus sediment-routing systems that fed the Ouachita Basin, including the generally east-to-west flowing fluvial systems of the Appalachian foredeep, the generally northeast-to-southwest flowing fluvial systems of the Appalachian backbulge, and the generally north-to-south flowing fluvial systems of the US midcontinent, would have drained much of eastern Laurentia in what is the present-day eastern and middle regions of the United States, and the Ouachita Basin represented a terminal sink for fluvial sediment transported from the US part of the Appalachian orogen.

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Figures

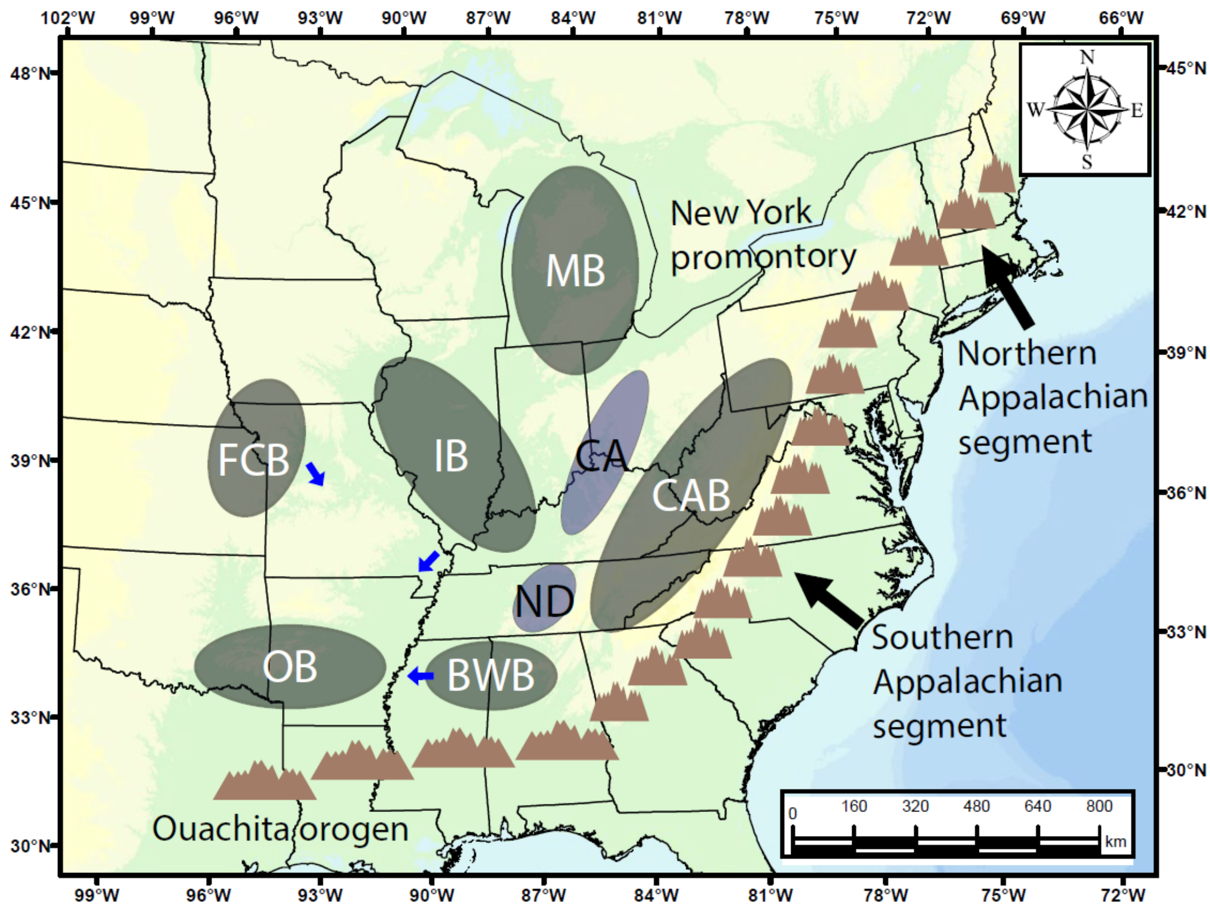

Figure 1. Major basins and structures of Early Pennsylvanian eastern Laurentia (after Nelson, 1989; Coleman and Cahan, 2012; Kissock et al., 2018). These structures reflect the assembly of the Paleozoic Appalachian-Ouachita orogenic system and the profound effect on Laurentian landscapes and sediment routing. Differentiation of northern and southern segments of the Appalachians is based on the strong asymmetry in the distribution of Alleghenian plutonic rocks, with the vast majority of magmatic systems south of the New York promontory (Hibbard and Karabinos, 2013). The three blue arrows indicate potential sediment routing pathways to the Ouachita Basin. BWB—Black Warrior Basin; CA—Cincinnati arch; CAB—Central

Appalachian Basin; FCB—Forest City Basin; IB—Illinois Basin; MB—Michigan Basin; ND—Nashville dome; OB— Ouachita Basin.

<table>
<tr><th>Period</th><th>Stage/ Series</th><th>Ouachita Basin</th><th colspan="2">Arkoma shelf</th><th>Illinois Basin</th><th>Black Warrior</th><th colspan="3">Appalachian basins</th></tr>
<tr><td rowspan="7">Lower Penn.</td><td rowspan="2">Atokan</td><td></td><td colspan="2" rowspan="2">Atoka Formation</td><td rowspan="2">Tradewater</td><td rowspan="6">Pottsville Formation</td><td rowspan="7">Breathitt Group</td><td rowspan="2">Breathitt</td><td rowspan="6">Pottsville Group</td></tr>
<tr><td>Atoka Formation</td></tr>
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<tr><td>Dye Shale</td><td>Bee Rock</td></tr>
<tr><td rowspan="3">Jackfork Group</td><td>Mid Bloyd Ss</td><td rowspan="2">Sewanee/ New River</td></tr>
<tr><td>Brentwood Ls</td></tr>
<tr><td>Hale</td><td rowspan="5">Parkwood/ Bangor Ls</td><td>Warren Point</td><td>Sharon</td></tr>
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<tr><td rowspan="3">Fayetteville Shale</td><td>U Fayetteville</td><td>Cypress</td><td>Princeton</td></tr>
<tr><td>Wedington</td><td>Aux Vases</td><td>Hinton</td></tr>
<tr><td>L Fayetteville</td><td rowspan="2">Ste. Genevieve</td><td>Stony Gap</td></tr>
<tr><td>Hindsville</td><td>Batesville</td><td>Pride Mtn</td><td>Bluefield</td></tr>
</table>

Figure 2. General Upper Mississippian and Lower Pennsylvanian lithological correlation between the Ouachita Basin, Arkoma shelf, Illinois Basin, Black Warrior Basin, and Appalachian basins (selected units from the Southern, Central, and Northern Appalachian Basins). The units from this study, the Jackfork Group and Johns Valley Shale of the Ouachita Basin, are shaded. After Sutherland (1988), Chesnut (1992), Archer and Greb (1995), Nelson et al. (2002), Becker et al. (2005), Xie et al. (2016a, 2016b, 2018), Thomas et al. (2017, 2020), Zou et al. (2017), and Wang and Bidgoli (2019). L—Lower; Ls—Limestone; Mid—Middle; Miss.—Mississippian; Mtn—Mountain; Penn.—Pennsylvanian; Ss—Sandstone; U—Upper.

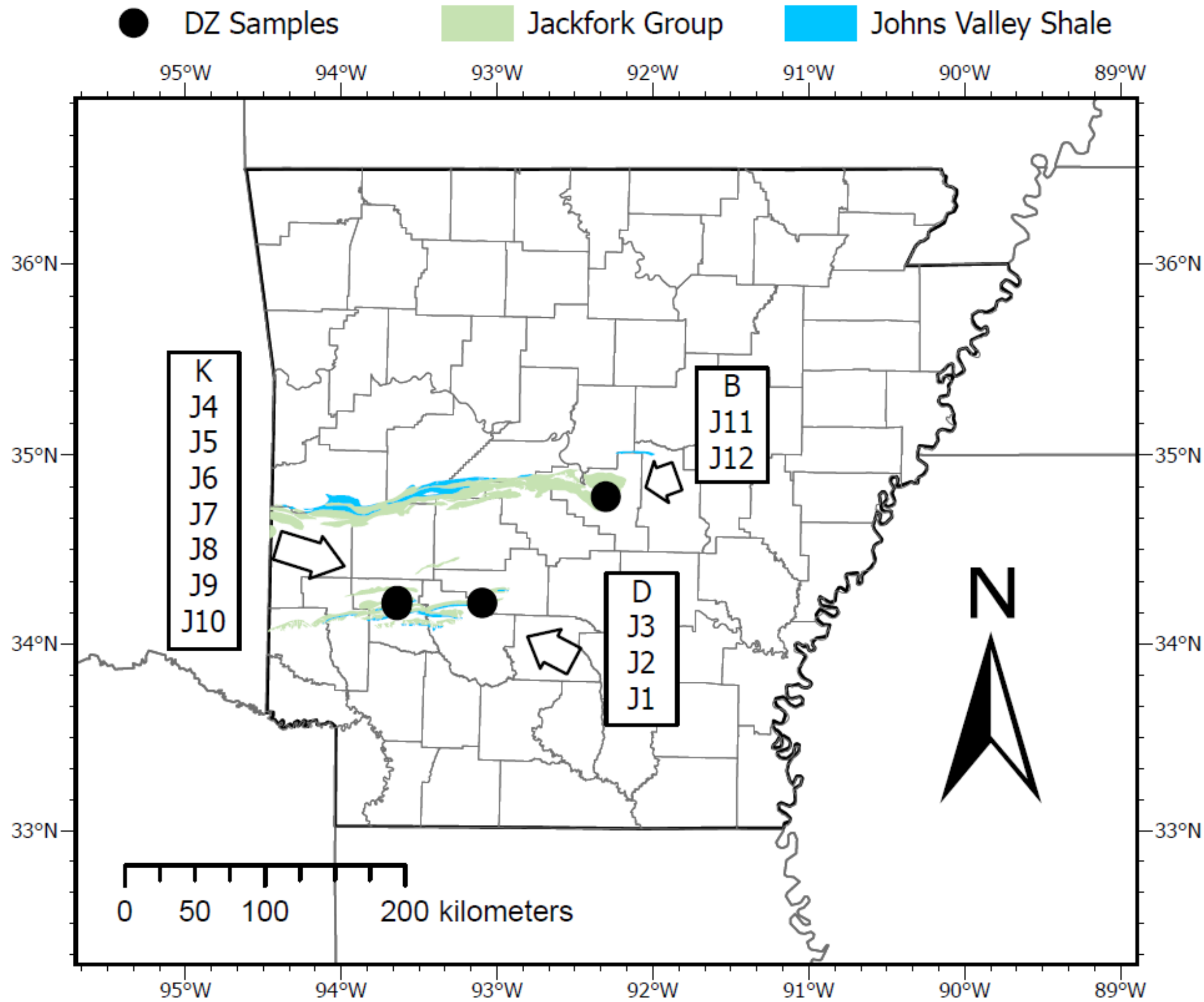


Figure 3. Map showing Jackfork Group (green) and Johns Valley Shale (blue) outcrops in Arkansas and detrital zircon sample locations and sample names from this study. From east to west, the sample locations are: Big Rock Quarry (B), DeGray Lake Spillway (D), and State Highway 27 roadcuts south of Kirby (K). Jackfork Group and Johns Valley Shale samples are shown as black dots (J1–J12, corresponding to PennJ1–PennJ12). The distribution of outcrops is based on mineral resources data from the U.S. Geological Survey (https://mrdata.usgs.gov/geology/state/state.php?state=AR).

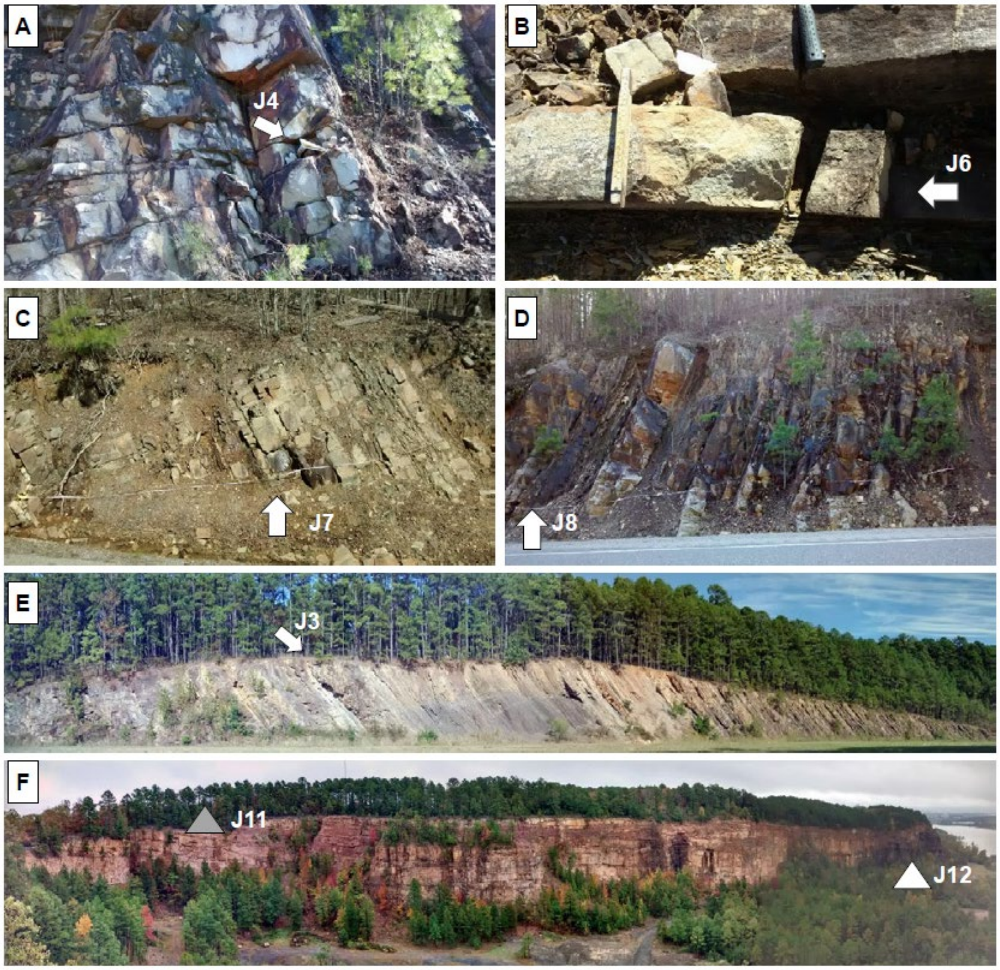


Figure 4. Examples of outcrop locations for detrital zircon sample collection from roadcuts along State Highway 27 south of Kirby (A–D; roadcuts after Zou et al., 2017), DeGray Lake Spillway (E), and Big Rock Quarry (F). See Table 2 for sample location coordinates. (A) Sample PennJ4, lower Jackfork Group, roadcut 1 (yellow notebook, near J4, is ~28 cm in length). (B) Sample PennJ6 from ~18-cm-thick bed, middle Jackfork Group, roadcut 5. (C) Sample PennJ7 from ~18-cm-thick bed, middle Jackfork Group, roadcut 7. (D) Sample PennJ8, from ~12-cm-thick bed, upper Jackfork Group, roadcut 9. (E) Sample PennJ3, upper Jackfork Group, northern section, looking northeastward. Width of photo ~100 m. (F) Samples PennJ11 (north, gray triangle) and PennJ12 (south, white triangle), upper Jackfork Group, looking eastward. Width of photo ~850 m.

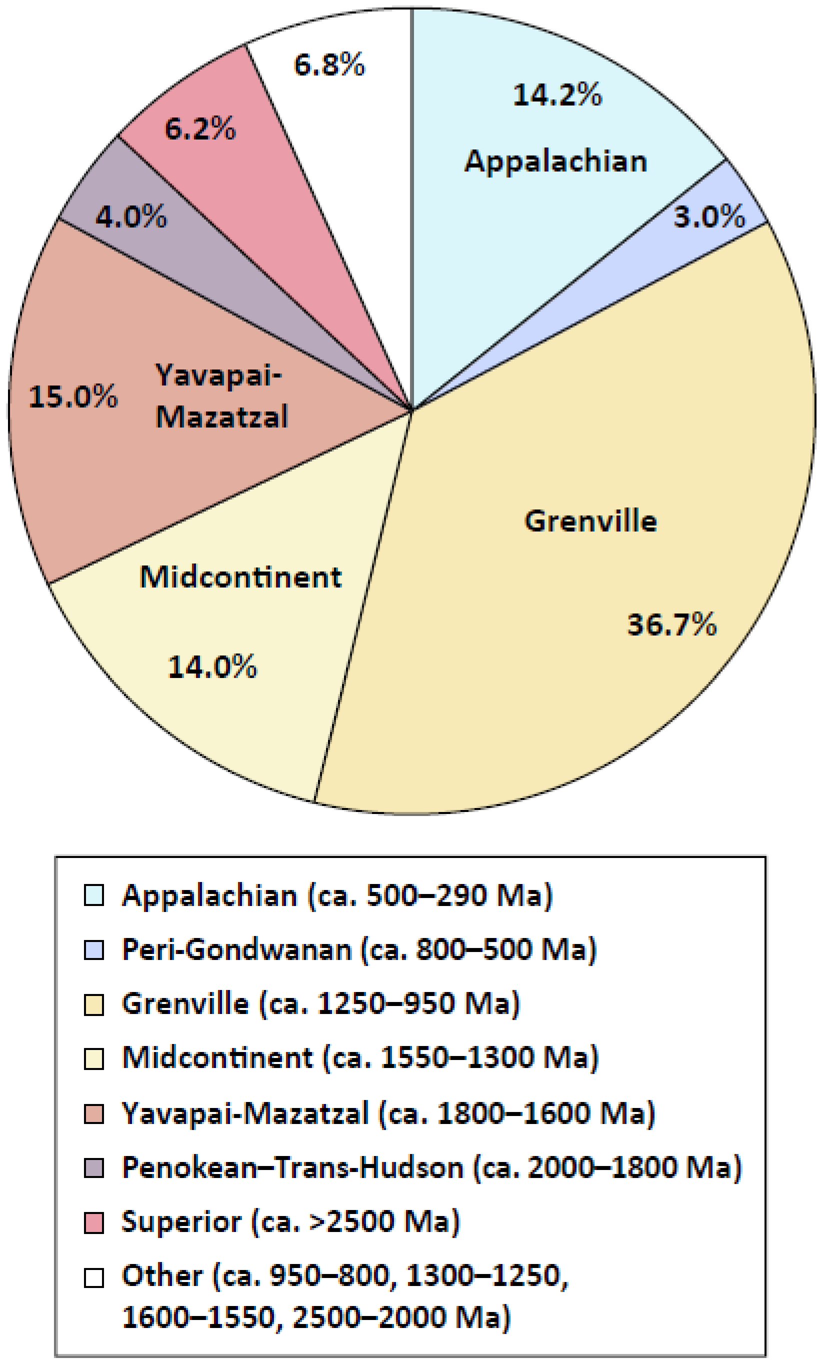


Figure 5. Contribution of different sources to the composite detrital zircon U-Pb record of Jackfork Group and Johns Valley Shale samples, including the "higher-n" analyses from sample PennJ1B (N = 12, n = 4053).

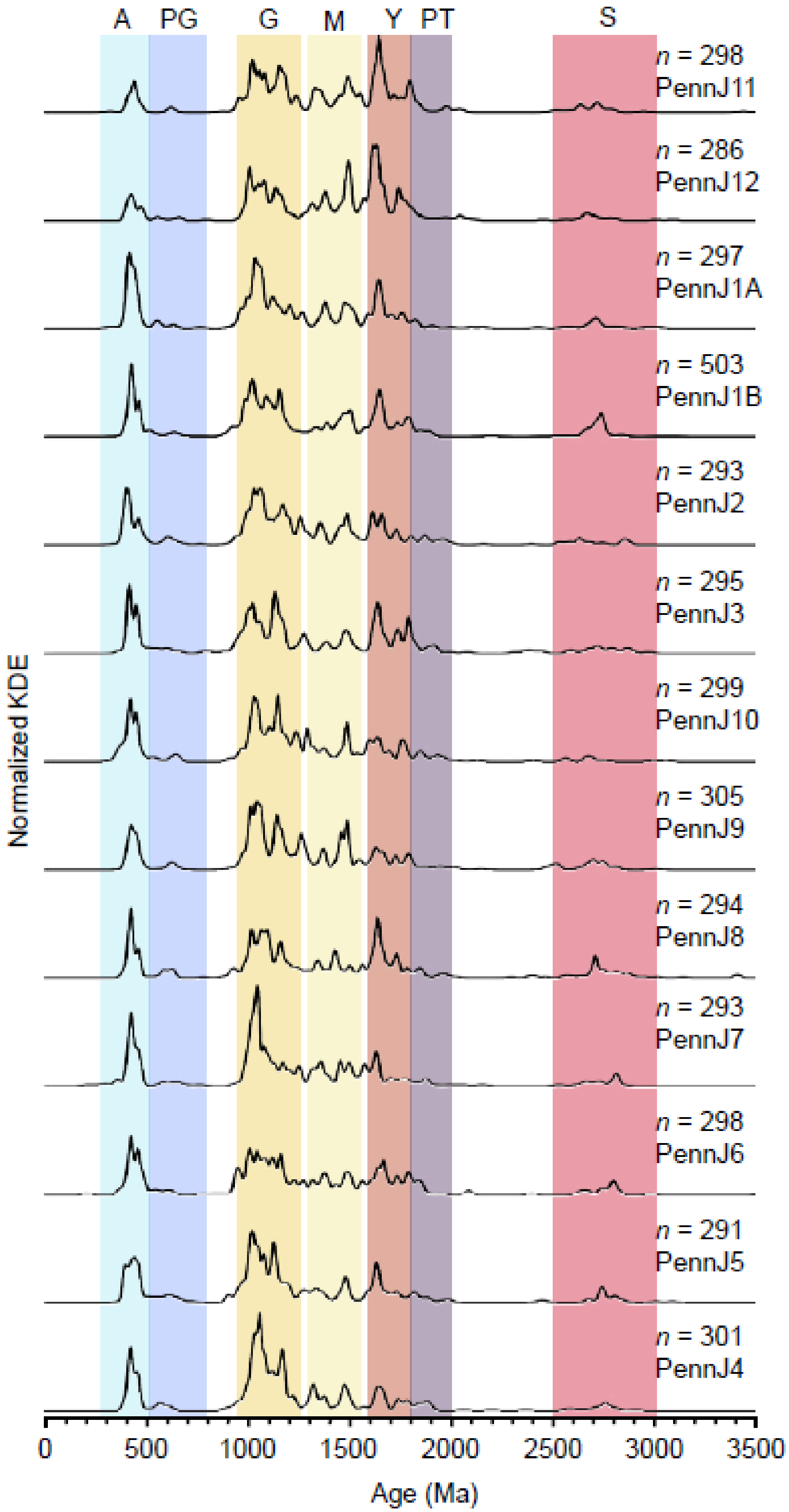

A
PG
G
M
Y
PT
S
n = 298
PennJ11
n = 286
PennJ12
n = 297
PennJ1A
n = 503
PennJ1B
n = 293
PennJ2
n = 295
PennJ3
n = 299
PennJ10
n = 305
PennJ9
n = 294
PennJ8
n = 293
PennJ7
n = 298
PennJ6
n = 291
PennJ5
n = 301
PennJ4
Normalized KDE
0
500
1000
1500
2000
2500
3000
3500
Age (Ma)

Figure 6. Normalized kernel density estimates (KDE) from 12 detrital zircon samples collected from three locations: Big Rock Quarry, Little Rock (samples PennJ11 and PennJ12); DeGray Lake Spillway (samples PennJ1 to PennJ3); and State Highway 27 roadcuts south of Kirby (samples PennJ4 to PennJ10). KDE are stacked by relative stratigraphic position for Kirby samples, while samples from Big Rock Quarry and DeGray Lake Spillway are from the upper portion of the Jackfork Group. The PennJ1B age distribution was acquired by a rapid acquisition approach applied to sample PennJ1A (see Sundell et al., 2020) and is distinguished from the original n = 297 analysis. To calculate KDE, bandwidth was set to 10. See Figure 5 for age distribution color key (A—Appalachian; PG—peri-Gondwanan; G—Grenville; M—Midcontinent; Y—Yavapai-Mazatzal; PT—Penokean–Trans-Hudson; S—Superior). Analytical data are provided in Supplemental Material Tables S1 and S2. n—number of grains.

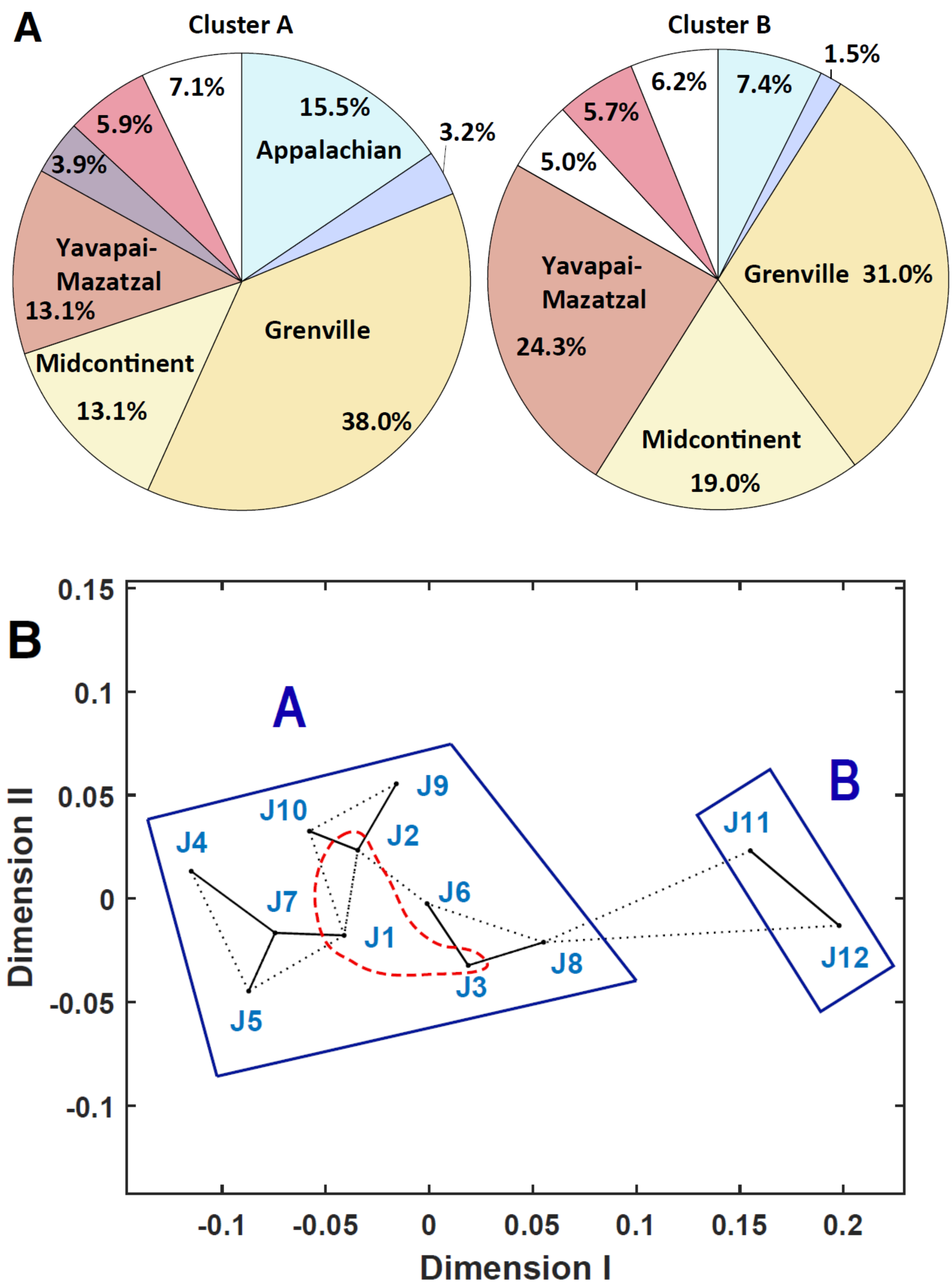

A
Cluster A
7.1%
15.5%
Appalachian
3.2%
5.9%
3.9%
Yavapai-
Mazatzal
13.1%
Grenville
Midcontinent
13.1%
38.0%
Cluster B
1.5%
6.2%
7.4%
5.7%
5.0%
Grenville 31.0%
Yavapai-
Mazatzal
24.3%
Midcontinent
19.0%
B
0.15
0.1
0.05
0
-0.05
-0.1
Dimension II
A
B
J9
J10
J2
J4
J7
J6
J1
J8
J3
J5
J11
J12
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Dimension I

Figure 7. (A) Contribution of different sources to sample clusters A and B in the multi-dimensional scaling (MDS) plot shown in panel B. See Figure 5 for age group color key. (B) Twodimensional MDS plot for detrital zircon U-Pb age distributions for Lower Pennsylvanian sandstones in the Ouachita Basin (Jackfork Group and Johns Valley Shale). Samples PennJ1A (J1) to PennJ3 (J3) (red long-dashed line) are from the Jackfork Group at DeGray Lake Spillway, and samples PennJ4 (J4, bottom of Jackfork Group) to PennJ10 (J10, uppermost sample from stratigraphic section, Johns Valley Shale) are from the Kirby roadcuts. Cluster A and cluster B, as discussed in the text, are as shown. Solid lines indicate nearest neighbors, and dashed lines indicate second-nearest neighbors. Transformation to Cartesian distance was calculated using metric stress (Shepard plot), which resulted in a stress value of 0.033, suggesting an excellent transformation (see Vermeesch, 2013).

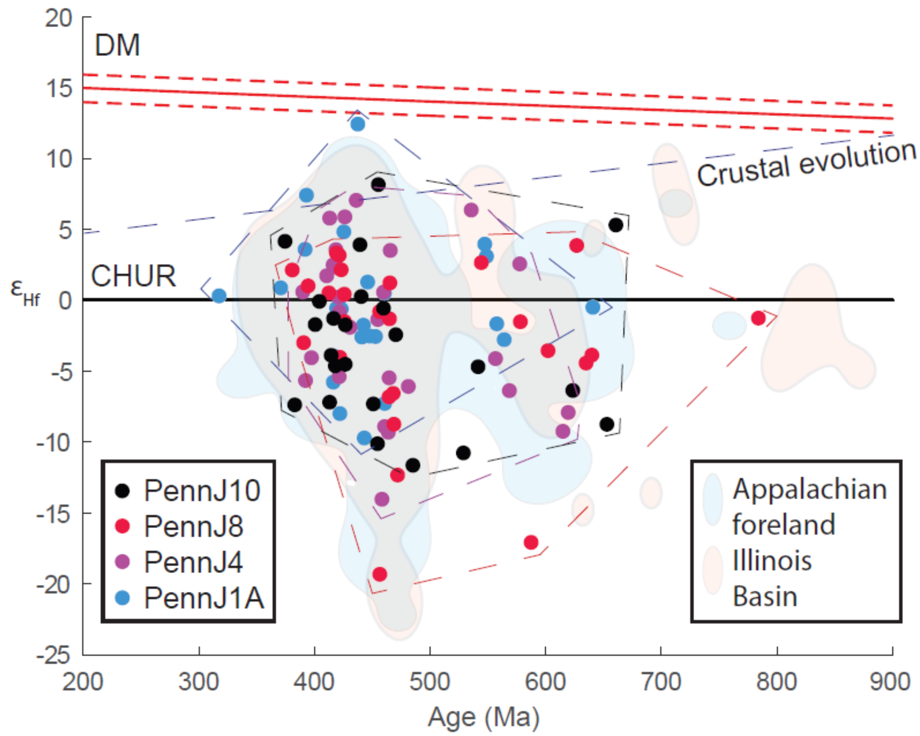


Figure 8. Hafnium evolution diagram showing results from the Pennsylvanian Jackfork Group (sample PennJ1A, DeGray Lake Spillway; samples PennJ4 and PennJ8, Kirby) and Johns Valley Shale (sample PennJ10, Kirby). Polygons delineated by dashed lines represent the parameter space for each sample and correspond to the sample colors in the key. Hf isotopic composition is shown in epsilon units (ε_{Hf}) relative to the chondritic uniform reservoir (CHUR; Bouvier et al., 2008; Vervoort, 2015) and the depleted mantle (DM, red line). There is a range of values for the DM array (red dashed lines; e.g., Vervoort and Blichert-Toft, 1999). Shown for reference is the evolution of typical continental crust (purple dashed line), which is based on a $^{176}Lu/^{177}Hf$ ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). The mean εHf value for all grains from the four samples and the standard error is −2.0 ± 1.0 (1σ). Shading represents the 95% density contour (2σ) for ε_{Hf} data from Pennsylvanian samples in the Appalachian foredeep (blue; Thomas et al., 2017) and Illinois Basin (orange; Thomas et al., 2020). Data plotted with Hafnium Plotter, version 1.7 (Sundell et al., 2019). Analytical data are in Supplemental Material Table S3.

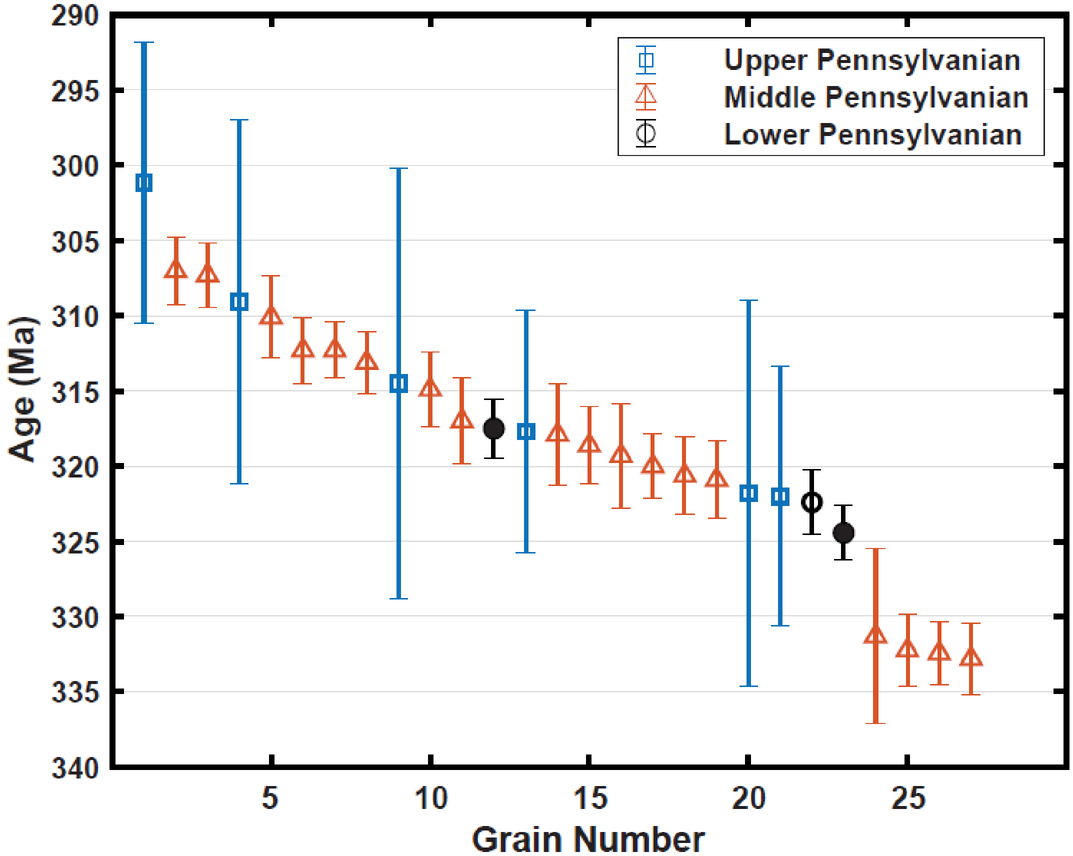


Figure 9. Aggregate concordant Late Mississippian and Pennsylvanian detrital zircon (DZ) U-Pb ages from Pennsylvanian-age stratigraphic units of eastern North America (2σ uncertainty). Squares represent U-Pb ages from Upper Pennsylvanian units, whereas triangles represent Middle Pennsylvanian units and circles represent Lower Pennsylvanian units. The two U-Pb ages from the Jackfork Group are shown by filled black circles (this study); the single open black circle is an age obtained from the Grundy-Norton stratigraphic interval (Thomas et al., 2017). U-Pb ages from other DZ studies of eastern Laurentia were taken from Sharrah (2006), Dodson (2008), Thomas et al. (2016), Kissock et al. (2018), and Chapman and Laskowski (2019), and include DZ collected from Iowa (n = 14), Missouri (n = 4), Illinois (n = 3), Ohio (n = 2), Oklahoma (n = 1), and Virginia (n = 1).

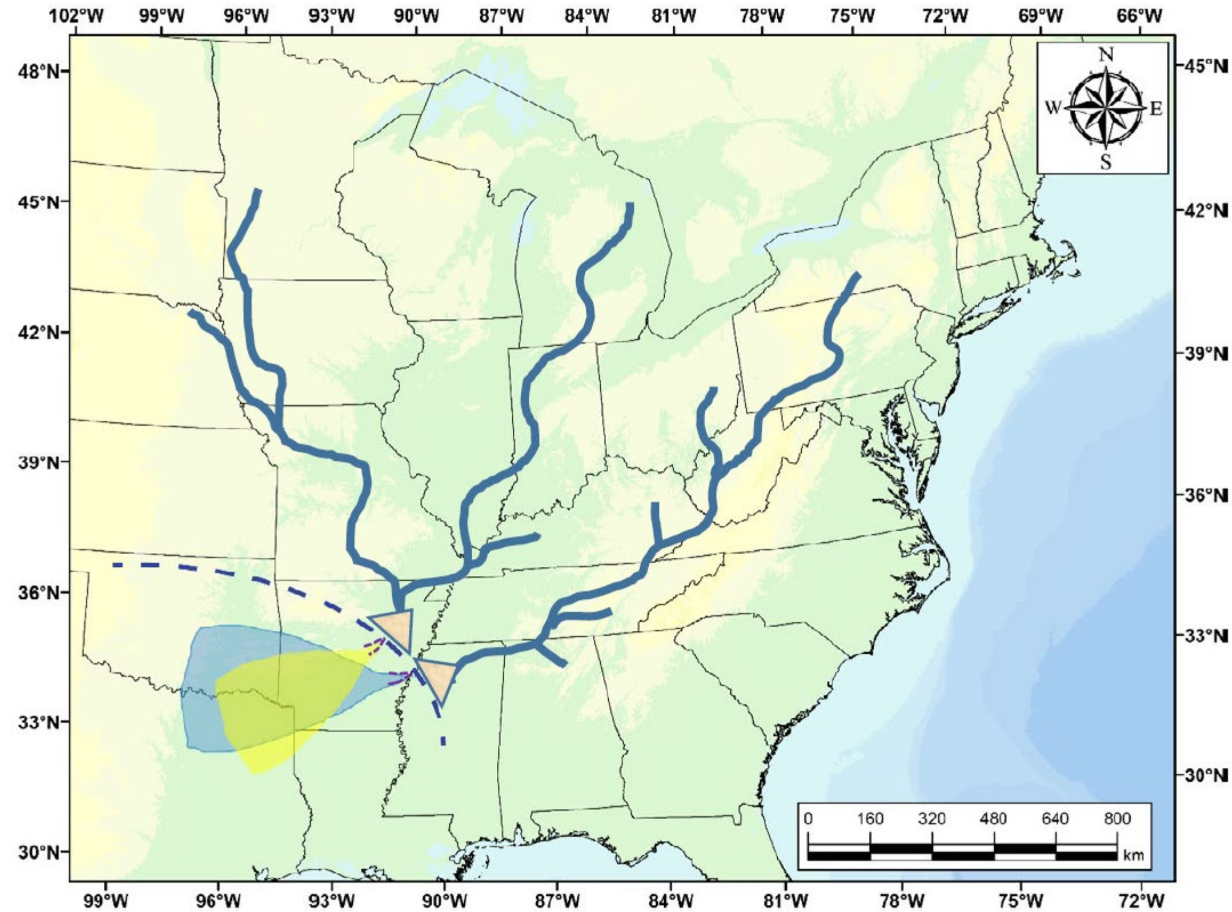
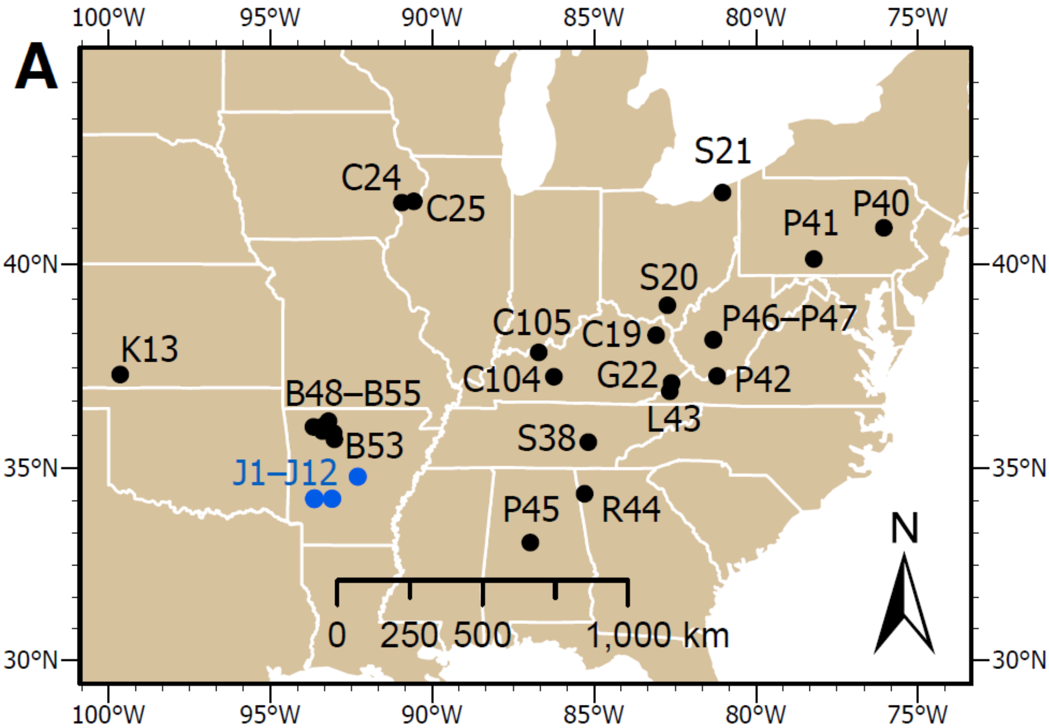
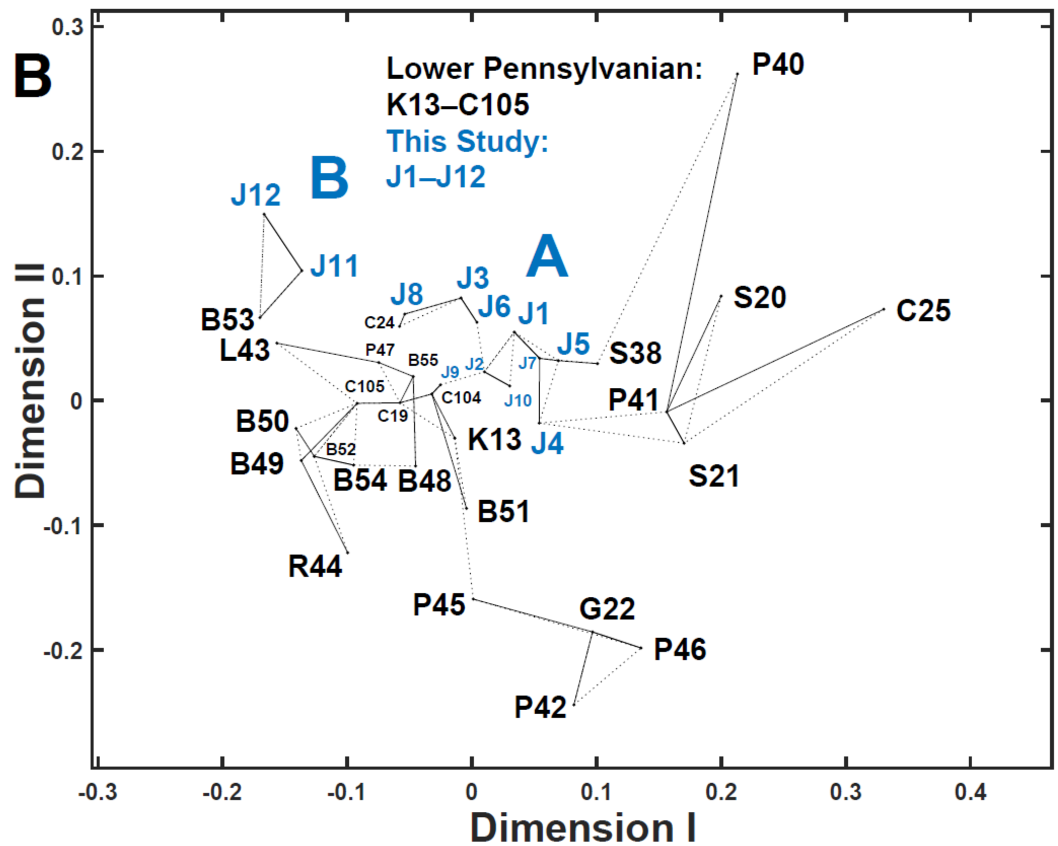
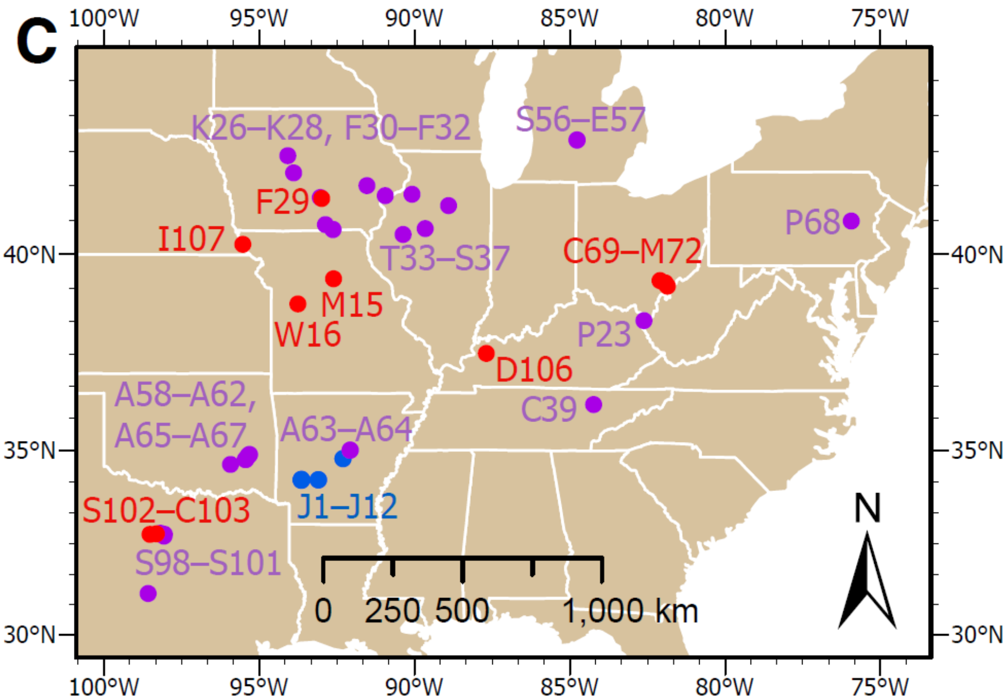


Figure 10. Schematic map of three interpreted fluvial routing systems for the two deep-sea fans of the Ouachita Basin (blue and yellow polygons). Map also shows the inferred lowstand shoreline (blue dashed line) and the likely positions of shelf-margin deltas (triangles).


A
100°W
95°W
90°W
85°W
80°W
75°W
40°N
35°N
30°N
S21
C24
C25
P41
P40
S20
C105
C19
P46–P47
K13
C104
G22
P42
B48–B55
L43
S38
B53
J1–J12
P45
R44
0
250
500
1,000 km
N


B
Lower Pennsylvanian:
K13–C105
This Study:
J1–J12
B
A
Dimension II
Dimension I
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.4
P40
J12
J11
B53
L43
J8
J3
J6
J1
J5
S38
S20
C25
P41
S21
K13
J4
B50
B49
B54
B48
B51
R44
P45
G22
P46
P42


C
100°W 95°W 90°W 85°W 80°W 75°W
40°N 35°N 30°N
K26–K28, F30–F32
S56–E57
F29
I107
T33–S37
P68
C69–M72
M15
W16
P23
D106
A58–A62,
A65–A67
A63–A64
C39
S102–C103
J1–J12
S98–S101
0 250 500 1,000 km
N

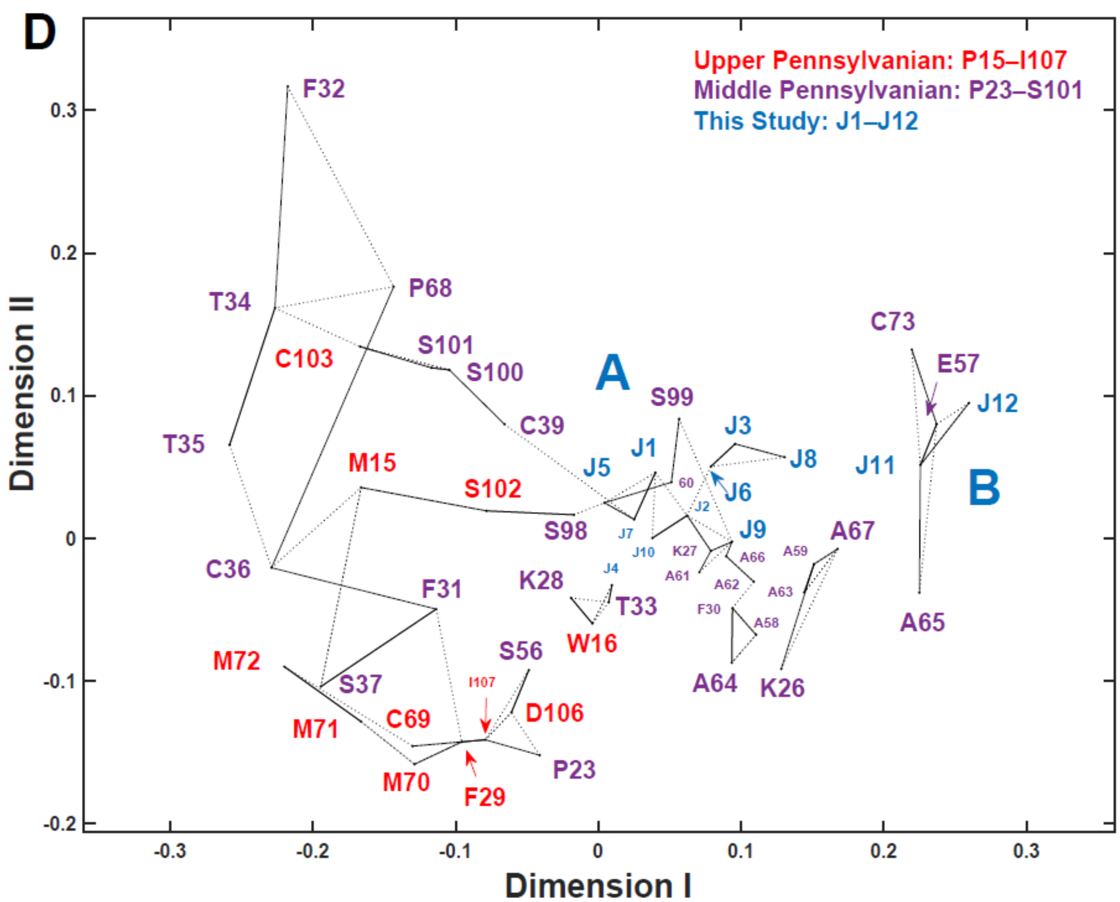

D
Upper Pennsylvanian: P15–I107
Middle Pennsylvanian: P23–S101
This Study: J1–J12
A
B
Dimension I
Dimension II
-0.3 -0.2 -0.1 0 0.1 0.2 0.3
0.3 0.2 0.1 0 -0.1 -0.2

Figure 11. (A) Locations of selected Lower Pennsylvanian DZ samples from the eastern and central United States. Jackfork Group and Johns Valley Shale samples are shown in blue (J1–J12 in Arkansas, corresponding to our samples PennJ1–PennJ12). (B) Multi-dimensional scaling (MDS) plot of 26 Lower Pennsylvanian detrital zircon samples of eastern and central Laurentia (black labels; Eriksson et al., 2004; Thomas et al., 2004, 2017, 2020; Becker et al., 2005; Kissock et al., 2018; Xie et al., 2018) as well as samples from the Ouachita Basin (blue, clusters A and B). The transformation stress was ~0.087, suggesting a good transformation (see Vermeesch, 2013). Solid lines indicate nearest neighbors, and dashed lines indicate second-nearest neighbors. (C) Locations of selected Middle Pennsylvanian (purple) and Upper Pennsylvanian (red) samples. Jackfork Group and Johns Valley Shale samples are also shown (blue). (D) MDS plot of 42 Middle (purple) and Upper Pennsylvanian (red) samples from eastern and central Laurentia and the data from this study (blue). Samples are from Gray and Zeitler (1997), Erikson et al. (2004), Thomas et al. (2004, 2016, 2017, 2020), Becker et al. (2005), Sharrah (2006), Dodson (2008), McFadden et al (2012), Alsalem et al. (2018), Kissock et al. (2018), and Chapman and Laskowski (2019). Note that the positions of clusters A and B are reflected relative to panel B, a relic of the plotting software that does not indicate a change in dissimilarity. The transformation stress was ~0.094, suggesting a fair transformation. See Table S4 for sample name key.

Tables

TABLE 1. SOURCES FOR DETRITAL ZIRCON AGE GROUPS IN LOWER PENNSYLVANIAN SANDSTONES

Age group name	Age range (Ma)	Primary source	Common geographic and stratigraphic sources for reworked ages
Paleozoic Appalachian province (Taconic, Acadian, and Alleghanian orogens)	500–300	Appalachian-Ouachita orogen	Paleozoic Appalachian-Ouachita foreland-basin strata
Neoproterozoic peri-Gondwanan terranes, Iapetus Rift, Wichita Mountains	800–500	Gondwanan margin of the Appalachian-Ouachita orogen, Wichita Mountains of Oklahoma	Paleozoic Appalachian-Ouachita foreland-basin strata
Mesoproterozic Grenville province	1250–950	Appalachian orogen, extending into central and western Texas and northwestern Mexico; Midcontinental Rift (1.1 Ga)	Paleozoic sandstones of the U.S. midcontinent, Appalachian-Ouachita foreland-basin strata
Mesoproterozoic Midcontinent Anorogenic Granite-Rhyolite Province	1550–1300	Northeast-southwest trend across the eastern U.S. midcontinent, plus numerous intrustions into Yavapai-Mazatzal basement in the Rocky Mountains	Paleozoic sandstones of the U.S. midcontinent, Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.
Paleoproterozoic Yavapai-Mazatzal orogens	1800–1600	Northeast-southwest trend across the central U.S. midcontinent to the wouthwestern U.S., including the central and southern Laramide Rockies and the Mogollon Rim of central Arizona	Paleozoic passive margin strata of the western U.S., Ouachita basin of Arkansas
Paleoproterozoic Penokean orogen	2000–1800	South-central Canada (Manitoba and Saskatchewan) and Great Lakes region of the U.S. (especially Wisconsin)	Common in low concentrations throughout the area, and in all stratigraphic units
Archean Superior and Wyoming provinces	>2500	Northern U.S. midcontinent to present-day northern Rocky Mountains province	Common in low concentrations throughout the area, and in all stratigraphic units

Note: Summarized from Becker et al. (2005), Whitmeyer and Karlstrom (2007), Dickinson and Gehrels (2009), Park et al. (2010), and Laskowski et al. (2013).

TABLE 2. DETRITAL ZIRCON SAMPLE LOCATION INFORMATION

Sample no.	Location	Outcrop details	Stratigraphic Position	Latitude (°N)	Longitude (°W)	n	Cluster
PennJ1	DeGray	South (W)	Jackfork, upper	34.216240	93.095775	800*	A
PennJ2	DeGray	Middle (E)	Jackfork, upper	34.218915	93.095732	293	A
PennJ3	DeGray	North (E)	Jackfork, upper	34.219597	93.096074	295	A
PennJ4	Kirby	K1†	Jackfork, lower	34.230034	93.641180	301	A
PennJ5	Kirby	K2†	Jackfork, lower	34.227850	93.640335	291	A
PennJ6	Kirby	K5†	Jackfork, middle	34.224705	93.642490	298	A
PennJ7	Kirby	K7†	Jackfork, middle	34.217020	93.647230	293	A
PennJ8	Kirby	K9†	Jackfork, upper	34.213860	93.645590	294	A
PennJ9	Kirby	JVS Section 1†	JVS, lower	34.210835	93.643860	305	A
PennJ10	Kirby	JVS Section 3† (W)	JVS, lower	34.204597	93.642370	299	A
PennJ11	Big Rock	Quarry top (N)	Jackfork, upper	34.783440	92.303071	298	B
PennJ12	Big Rock	Quarry bottom (S)	Jackfork, upper	34.777308	92.302858	286	B

Notes : n-number of grains; JVS-Johns Valley Shale; N-north; S-south; E-east; W-west.
*Total number of grains from PennJ1A and PennJ1B.
† See Zou et al. (2017) for Kirby roadcut details.

TABLE 3. SUMMARY OF ƐHF VALUES FOR SPECIFIC U-PB AGE GROUPS														
Location,	317.5 Ma*		485-370 Ma				800-500 Ma				All ages			
sample no.	Value	Error (1σ)	# Grains	Range	Mean	Error (1σ)	# Grains	Range	Mean	Error (1σ)	# Grains	Range	Mean	Error (1σ)
Kirby														
PennJ10, JVS			18	+8.1 to -11.7	-2.7	1.0	5	+5.3 to -10.8	-5.1	1.1	23	+8.1 to -11.7	-3.2	1.0
PennJ8, JU			18	+3.4 to -19.3	-2.7	1.1	8	+3.9 to -17.0	-3.1	0.9	26	+3.9 to -19.3	-2.9	1.0
PennJ4, JL			21	+7.0 to -14.0	-1.3	1.1	7	+6.4 to -9.2	-3.1	1.0	28	+7.0 to -14.0	-1.7	1.1
DeGray Lake														
PennJ1, JU	+0.3	0.8	20	+12.4 to -9.7	-0.6	0.9	5	+3.9 to -2.8	+0.4	0.9	26	+12.4 to -9.7	-0.3	0.9
Total			77	+12.4 to -19.3	-1.8	1.0	25	+6.4 to -17.0	-2.8	0.9	103	+12.4 to -19.3	-2.0	1.0†

Note : Comparison of range and mean of εHf values by age from this study. JVS—Johns Valley Shale; JU—Jackfork Group, upper; JL—Jackfork Group, lower.
*Only one εHf value of Alleghenian age (sample PennJ1).
†Standard Error.

TABLE 4. MEAN ƐHF VALUES FROM THE OUACHITA, APPALACHIAN, ILLINOIS, AND FOREST CITY BASINS												
Age groups	Ouachita (317-784 Ma)			Appalachian (330-711 Ma)			Illinois (307-833 Ma)			Forest City (320-624 Ma)		
(Ma)	# Grains	Mean	Error (1σ)	# Grains	Mean	Error (1σ)	# Grains	Mean	Error (1σ)	# Grains	Mean	Error (1σ)
Appalachian (307-500)	78	-1.8	1.0	48	-0.1	1.2	73	-1.0	1.0	84	+0.3	0.9
Peri-Gondwanan (501-833	25	-2.8	0.9	16	-0.9	1.3	17	-2.0	1.0	21	-1.6	0.9
Total	103	-2.0	1.0	64	-0.3	1.2	90	-1.2	1.0	105	-0.1	0.9

Notes : Mean Hf analyses per sample per basin: Ouachita, ~26; Appalachian, ~16; Illinois, ~23; and Forest City,~26.
Pennsylvanian samples from this study, Thomas et al. (2017), and Thomas et al. (2020).

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Supplemental Material

Table S1: Detrital zircon (DZ) U-Pb isotopic data.

Table S2: DZ U-Pb isotopic data from a higher-*n* approach.

Table S3: DZ Hf isotopic data.

Table S4: Multi-dimensional scaling (MDS) sample key.

Please visit **https://doi.org/10.1130/GEOS.S.16709722** to access the supplemental material from Chapter 2.

Chapter 3: Demarcation of Early Pennsylvanian paleovalleys within depozones of the Appalachian foreland-basin system based on detrital-zircon U-Pb and Hf analysis

Isaac Allred[1, 2] and Mike Blum[1]

[1]Department of Geology, University of Kansas, Earth, Energy & Environment Center, 1414 Naismith Drive, Lawrence, KS 66045, USA

[2]Indiana Geological and Water Survey, Indiana University, 1001 E. 10th Street, Bloomington, IN 47405, USA

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Abstract

Detrital zircon (DZ) U-Pb data show that Appalachian-affiliated sediment was transported to western Laurentia by the Carboniferous, yet additional DZ U-Pb data from the eastern United States suggest that sediment routing systems were oriented south toward the Ouachita deepwater sink. Within this context, this study presents DZ U-Pb ages from the Lower Pennsylvanian Caseyville Formation of Illinois, and U-Pb ages and εHf values from the coeval Pottsville Formation of Alabama as well as sandstone petrographic data from the Caseyville Formation, the Pottsville Formation, and Jackfork Group of the Ouachita Basin to document provenance, delineate drainage divides within the Appalachian foreland-basin system, and comment on the unlikelihood of transcontinental sediment routing from the eastern United States to western United States at this time.

Two DZ U-Pb age distributions from quartz arenite sandstones of the Caseyville Formation display prominent ca. 1250–950 Ma, 1550–1300 Ma, 1800–1600 Ma, and 3500–3000 Ma ages, consistent with ultimate derivation from Grenville, Midcontinent granite-rhyolite, Yavapai-Mazatzal, and Superior provinces, as well as minor contributions from ca. 500–400 Ma and 2000–1800 Ma grains. Two DZ U-Pb age distributions from sublitharenite sandstones of the Pottsville Formation display prominent ca. 500–400 Ma, 1250–950 Ma, 1550–1300 Ma, and 1800–1600 Ma ages, consistent with ultimate derivation from Appalachian, Grenville, Midcontinent granite-rhyolite, and Yavapai-Mazatzal provinces, as well as minor contributions from ca. 2000–1800 Ma and 3500–3000 Ma grains. The Pottsville Formation samples demonstrate a greater percentage of Appalachian and Grenville ages relative to the Caseyville Formation samples, whereas the Caseyville Formation samples have elevated Yavapai-Mazatzal

and Superior percentages relative to the Pottsville. We interpret these differences to suggest parallel fluvial systems in the foredeep and back-bulge depozones of the Appalachian foreland-basin system. Similarities in Hf isotopes from the Pottsville Formation and Ouachita turbidites, as well as sandstone petrographic data consistent with previous studies of Lower Pennsylvanian sandstones, also support this interpretation.

Like DZ studies of modern deep-sea fans that demonstrate an affinity to feeder fluvial systems, this study demonstrates fidelity between endmember segments of ancient fluvial-to-deepwater systems. Multidimensional scaling (MDS) analysis shows that DZ samples from the Pottsville and Caseyville Formations cluster with deepwater Jackfork Group samples, and we infer a source-to-sink relationship from these two distinct source areas to the Ouachita terminal sink. One example of large-scale inclined strata thickness from the Caseyville Formation also suggests a drainage basin area of $>10^5$ km^2. Contextualized with these observations, we suggest the foredeep and backbulge depozones of the Appalachian foreland-basin system steered distinct Early Pennsylvanian rivers across emergent continental shelves during periods of low sea-level, which discharged to distinct slope canyons and sourced >100-km-long deep-sea fans. Clearly circumscribed, southward- or southwestward-oriented paleodrainage areas provide a template of the Appalachian foreland-basin system, and as such the central and southern Appalachians were an unlikely source for the Appalachian signature observed in the western United States at this time.

Introduction

The Carboniferous Alleghenian continent-continent collisions (Fig. 1) and final assembly of the Appalachian-Ouachita orogenic system resulted in a rearrangement of Appalachian topography in eastern North America that would persist for the rest of the Phanerozoic. Emplacement of orogenic loads and crustal flexure formed depozones within the Early Pennsylvanian Appalachian foreland-basin system, such as the Black Warrior and Appalachian Basins. During the terminal suturing of Laurentia and Gondwana, however, there is uncertainty in the delineation of sediment routing corridors from eastern North America to marine sinks, such as the Ouachita remnant ocean basin of the south-central United States (sensu Ingersoll et al., 2003).

Studies of recent to modern deep-sea fans show that deepwater segments of sediment dispersal systems faithfully fingerprint the detrital zircon (DZ) signature of feeder systems (e.g., Fildani et al., 2016; Blum et al., 2018; Mason et al., 2019). From this perspective, Allred and Blum (2021) document DZ U-Pb and Hf isotopes from Early Pennsylvanian Jackfork Group and Johns Valley Shale turbidites of the Ouachita trough, interpret at least two distinct Ouachita deep-sea fans, and infer fluvial source areas that spanned from the Appalachians to the U.S. midcontinent. This study subsequently examines Lower Pennsylvanian terrestrial and marginal-marine units that represent potential sediment sources for Ouachita deep-sea fans and refines understanding of eastern Laurentian paleovalley fairways for deepwater sediment delivery. This is an investigation of proposed southward- and southwestward-oriented sediment routing within the Appalachian foreland-basin system, which would have prohibited sediment transfer from the southern and central Appalachians to western Laurentia during this time (see Allred and Blum, 2021).

Tectonic Template and Previous Work

Following Neoproterozoic rifting of the post-Grenville Iapetus Ocean and the development of the eastern Laurentian passive-margin (Simpson and Eriksson, 1989; Thomas, 1991; Bream et al., 2004), assembly of the Paleozoic Appalachian orogen occurred in three primary phases. The Taconic and Acadian collisional orogenies, ca. 490–430 Ma (Miller et al., 2000) and ca. 430–345 Ma, respectively (e.g., Thomas et al., 2004; Hatcher, 2010 and references therein), occurred prior to the Pennsylvanian Period. During these early phases, the Ouachita embayment along the Laurentian rift margin did not experience collisions (Thomas, 1991). The final phase, the collisional Alleghenian-Ouachita orogeny ca. 330–275 (Fig. 1), which stretched from eastern Canada to West Texas and northern Mexico (Hatcher, 2010), sutured together the supercontinent Pangea.

Although the Taconic and Acadian orogenies were important, the Alleghenian continent-continent collision drastically changed the trajectory of landscape evolution in Laurentia (see Lawton et al., 2021 for recent discussion). Emplacement of orogenic loads created an ensemble of foreland-basin foredeep depozones on the Laurentian side of the orogen (Hatcher et al., 1989), the most proximal being the Black Warrior and Appalachian Basins. Moreover, several Paleozoic intracratonic basins, including the Illinois (Eastern Interior) Basin west of the Cincinnati arch, served as fairways for sediment routing and depocenters for terrigenous clastics.

The Cincinnati and related arches have been recently considered a forebulge for the Appalachian foreland-basin system (Kissock et al., 2018).

Alleghenian clastics extend approximately 1300 km along the axial length of the foreland basin system and are composed almost entirely of terrestrial to marginal-marine deposits (Ettensohn et al., 2019). Siliciclastics within the foredeep Black Warrior Basin have been interpreted to represent fluvial and interfluvial deposits in the northeastern part of the basin and deltaic and marginal-marine sands in the northwestern part (Hobday, 1974; Greb et al., 2008); these deposits may have been remobilized by lowstand longitudinal fluvial systems that paralleled the Alleghenian and Ouachita clastic wedges (see Graham et al., 1976). North and west of the Alleghenian forebulge, the Lower Pennsylvanian of the Illinois Basin is represented by fluvial deposits of the Caseyville Formation in southern Illinois and western Kentucky and the Mansfield Formation in southwestern Indiana (Fig. 2A).

Previous Work on Early Pennsylvanian Sediment Routing

Previous authors primarily based interpretations of Early Pennsylvanian sediment routing within the greater Appalachian foreland-basin system on petrographic studies and the nature of the basal Pennsylvanian unconformity. In the Illinois Basin, petrographic and paleocurrent observations were used to infer sediment routing to the southwest (Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961), which was later confirmed by mapping of northeast-to-southwest-oriented paleovalleys incised into Mississippian-age strata (Bristol and Howard, 1971; Bristol and Howard, 1974; Droste and Keller, 1989). Early workers in the Ouachita deepwater basin in Arkansas and Oklahoma interpreted sediment to have been derived from the northern midcontinent and the southern Appalachians (Morris, 1971), the latter transported via the Black Warrior Basin (Graham et al., 1975; Graham et al., 1976). However, Thomas (1976) argued that inferred westward sediment routing from the southern Appalachians to the Ouachita deepwater sink is incompatible with mapped northeastward and northward prograding Ouachita clastic wedges in the Black Warrior Basin. Similarly Mack et al. (1983) presented petrographic data and suggested two distinct Carboniferous clastic wedges in the Black Warrior Basin, the Alleghenian wedge to the northeast and a second wedge composed of sediments derived from the Ouachita fold and thrust belt to the south and west.

Later studies applied varied geochemical techniques to understand large-scale sediment routing across eastern Laurentia. Owen and Carozzi (1986) interpreted quartz cathodoluminescence data from deepwater facies of the Lower Pennsylvanian Jackfork Group, as well as the coeval Parkwood, Pottsville, and Caseyville Formations (Fig. 2A), to indicate that Jackfork turbidites were derived from the same source area as Black Warrior Basin equivalent units. At an even larger spatial scale, Gleason et al. (1994) interpreted Nd isotopic data from Pennsylvanian units of the Appalachian, Illinois, Black Warrior, and Ouachita Basins to indicate that Appalachian-Ouachita sediments overwhelmed this region.

Archer and Greb (1995) leveraged paleogeographic constraints and observations of the relief along the Mississippian-Pennsylvanian unconformity to interpret several Early Pennsylvanian paleovalleys from eastern Kentucky to western Kansas during lowstand conditions. They estimated a minimum contributing paleodrainge area of ~10^6 km^2 each for the Caseyville Formation (and equivalent) conglomeratic sandstones of the Illinois Basin and the Lee Formation (and equivalent) conglomeratic sandstones of the Central Appalachian Basin. These estimates were independent of, yet similar to, the interpretation of two or more distinct sediment-routing corridors from the Appalachian orogen to the Ouachita Basin (e.g., Morris, 1971).

Recent studies focused on DZ U-Pb age distributions from late Paleozoic units of eastern Laurentia (Thomas et al., 2017; Kissock et al., 2018; Thomas et al., 2020; McKay et al., 2021; Thomas et al., 2021). These studies built on earlier work by Eriksson et al. (2004), Becker et al. (2005), and Park et al. (2010), and firmly established the DZ U-Pb signals from the Appalachians, signals which are also observed in the Ouachita deepwater basin (e.g., Allred and Blum, 2021). However, some potential sediment routing fairways within the Illinois and Black Warrior Basins were not sampled. Moreover, Early Pennsylvanian drainage divides within the Appalachian foreland-basin system framework remain uncertain. This study conducts DZ U-Pb analyses from the Illinois Basin and DZ U-Pb and Hf isotopic analyses from the Black Warrior Basin, as well as petrographic analysis of select samples from the Illinois, Black Warrior, and Ouachita Basins, to clearly delineate Early Pennsylvanian fluvial-to-deepwater sediment routing from the eastern U.S. and midcontinent to the Ouachita deepwater basin.

The Caseyville Formation of the Illinois Basin

The Illinois Basin is a northwest-southeast-trending, spoon-shaped structure (Collinson et al., 1988) that spans central and southern Illinois, southwestern Indiana, and western Kentucky (Fig. 1). During the Carboniferous, subsidence in the southern portion of the basin resulted in the accumulation of a significant depositional succession (Heidlauf et al., 1986; Collinson et al., 1988). During Mississippian time, the southern Illinois Basin was dominated by carbonate deposition, an indicator of the warm, equatorial climate that prevailed at this time (Cecil et al., 2003; Cecil et al., 2004). The Caseyville Formation is the basal Pennsylvanian sandstone that cuts into the underlying Kinkaid Limestone, a contact that is characteristic of the regional Mississippian-Pennsylvanian unconformity (Fig. 2A, Siever, 1951; Sloss, 1963; Collinson et al., 1988; Nelson et al., 2013). During the Carboniferous, the Illinois Basin was open to the south (Potter and Pryor, 1961), and subsurface mapping indicates a series of southwest-trending paleovalleys associated with the sub-Pennsylvanian surface (Bristol and Howard, 1971; Droste and Keller, 1989).

The Caseyville Formation is a quartz arenite that commonly contains numerous well-rounded granules and pebbles of white quartz (Siever and Potter, 1956; Nelson, 1989), a characteristic distinct from underlying siliciclastic units (Collinson et al., 1988). The Caseyville Formation is constrained to the Early Pennsylvanian (Bashkirian) by palynological studies (Peppers, 1996). In general, the Caseyville Formation is interpreted to be fluvial-deltaic in origin, although marine invertebrate fossils in shales that occur between the lower Battery Rock Member and the upper Pounds Member suggest estuarine conditions (Devera et al., 1987; Collinson et al., 1988; Denny et al., 2008). The Caseyville may exceed 150 m in thickness, but the thickness is highly variable because of the irregular nature of the sub-Pennsylvanian surface (Collinson et al., 1988). In southern Illinois intervals of Caseyville sandstone form a relatively continuous escarpment (Nelson et al., 2013), such as 15–30 m cliffs near Ferne Clyffe State Park, which is capped by the overlying Tradewater Formation. The southernmost extent of the Caseyville Formation in Illinois is in the Dixon Springs graben (Devera, 1991; Nelson et al., 2016). The Ferne Clyffe and Dixon Springs locations are discussed further below as part of the sampling strategy for this study (Fig. 2B).

Hf Isotopes from the Eastern Interior

Recent work by Thomas et al. (2020) reported two Caseyville DZ samples from western Kentucky and presented a range of εHf values (+9.1 ± 1.2 to -20.9 ± 0.8, at 1σ) for DZ grains with Appalachian ages (ca. 500–320 Ma). In general, the greatest densities of εHf values from these samples and other Carboniferous sandstones in the Midwest are nearly identical to those in the Appalachian Basin. Thomas et al. (2021) also reported similar DZ U-Pb and Hf values from the Lower Pennsylvanian Hale Formation on the Arkoma shelf to the southwest of the Illinois Basin.

The Pottsville Formation of the Black Warrior Basin

The Black Warrior Basin is situated in the Appalachian-Ouachita syntaxis, between the southern Appalachian fold and thrust belt to the east and deep-sea fans of the Ouachita remnant ocean basin to the west (Fig. 1). The Black Warrior Basin is a foreland basin bound by clastic wedges prograding from the Alleghenian and Ouachita orogens, respectively (Mack et al., 1983; Thomas, 1988). The Black Warrior Basin is separated from the Illinois Basin by the Nashville dome to the north, and is separated from the Appalachian Basin foredeep by a low arch that plunges southeastward from the Nashville dome (Thomas, 1988).

Similar to the Illinois and Appalachian Basins, the Black Warrior Basin records the early stages of the Alleghenian collision, the end of carbonate deposition, and the transition to quartz-rich Lower Pennsylvanian sandstones (Ferm, 1974; Becker et al., 2005). In contrast to the Illinois Basin, no significant regional Mississippian-Pennsylvanian unconformity is present throughout much of the Black Warrior and Appalachian Basins (Siever and Potter, 1956; Thomas, 1972; Horne et al., 1974; Ettensohn and Chesnut, 1989). Instead, the contact between Upper Mississippian carbonates and Lower Pennsylvanian siliciclastics is gradational: siltstones and thin-bedded sandstones rest on Mississippian carbonates, which are then overlain by the quartz arenites and quartz-pebble conglomerates of the Pottsville Formation (Wahl et al., 1971). The basal sandstones of the Pottsville Formation crop out in northern Alabama along stream valleys, such as the Sipsey River and Brushy Creek locations (Wahl et al., 1971), which are discussed further below as part of the sampling strategy for this study (Fig. 2B).

In contrast to the Caseyville Formation outlined above, basal Pennsylvanian siliciclastics in the Black Warrior Basin have been interpreted to represent northeastward-prograding deltas with associated barrier island systems (Ferm et al., 1967; Thomas, 1972; Hobday, 1974; Thomas, 1974; Horsey, 1981; Thomas and Mack, 1982; Thomas, 1988; Mars and Thomas, 1999). Coeval quartz arenites of the Appalachian Basin, represented by the Lee Formation, were previously interpreted as barrier-island complexes as well (Englund and DeLaney, 1966), but are now considered to be fluvial in origin (Rice, 1984; Rice and Schwietering, 1988; Wizevich, 1992; Archer and Greb, 1995; Churnet, 1996; Greb and Chesnut, 1996; Hurd and Stapor, 1997): basal Pennsylvanian sandstones in the Black Warrior Basin may require additional scrutiny as well. Regardless, abundant palynological and megafloral assemblages constrain the Pottsville Formation to be Early Pennsylvanian in age (Eble et al., 1985; Gillespie and Rheams, 1985; Eble et al., 1991).

Early DZ U-Pb provenance studies in the vicinity suggested a strong Appalachian component among DZ sources. Becker et al. (2005) collected several DZ U-Pb samples near the Alleghenian hinterland, including in the Black Warrior Basin from the upper Pottsville Formation (Montevallo coal zone, n = 62), and most DZ along the Alleghenian clastic wedge are of Laurentian affinity, suggesting recycling of synrift and passive-margin sources (Thomas et al., 2004). Weislogel et al. (2015) also collected a DZ sample from the upper Pottsville Formation (n = 75) and observed only a minor Appalachian-age mode and a prominent Grenville-age mode.

Recent provenance studies have suggested various interpretations for sediment routing to the Carboniferous Black Warrior Basin, which differ from the view of a primary Ouachita source (e.g., Mack et al., 1983). Xie et al. (2016b) and Gifford et al. (2020) sampled Chesterian sandstones, reported DZ U-Pb ages, including ages ca. 415, 1500–1300, and >2500 Ma, and interpreted a sediment source to the northwest. In contrast, Uddin et al. (2016) reported detrital muscovite $^{40}Ar/^{39}Ar$ ages and identified ages as young as Early Pennsylvanian in the lower and middle Pottsville Formation, and interpreted sediment to have been delivered from both transverse and longitudinal systems that drained the southern Appalachian hinterland. Alternatively, recent work identified evidence for local transport of metamorphic clasts during the Pennsylvanian, supporting a proximal source to the southeast (Haque and Uddin, 2017). Furthermore, DZ U-Pb data and zircon (U-Th)/He thermochronology from the Mississippian Hartselle (N = 2; n =285) and Pennsylvanian Pottsville (N = 2; n = 166) Formations suggest a southeastern source from pre-Alleghenian exhumation in the Appalachian Valley and Ridge, particularly during the Mississippian (McKay et al., 2021).

Methods

DZ U-Pb and Hf Analysis

DZ U-Pb ages from fluvial and related sandstones have become a common method to define provenance and large-scale sediment routing. The use of DZ U-Pb ages as a provenance tool assumes that the distribution of ages in a sample provides a fingerprint of the populations from specific source terranes (Ross and Parrish, 1991). The spatial distribution and ages of sources for DZ in Laurentian North America are well known (Becker et al., 2005; Dickinson and Gehrels, 2009; Park et al., 2010; Laskowski et al., 2013), with summaries of the pre-Phanerozoic evolution of North America and the stages of the Paleozoic Appalachian orogen provided in Whitmeyer and Karlstrom (2007) and Hatcher (2010), respectively.

For this study, we collected four samples of medium-grained sandstone for DZ U-Pb analyses from quartz arenites of the Caseyville Formation in the southern Illinois Basin and sublitharenites of the Pottsville Formation in the Black Warrior Basin (Table 1). Sample C1 was collected south of Ferne Clyffe State Park (Fig. 2B and 3D) and represents the top of the Caseyville Formation (Pounds Member) near the Tradewater Formation contact (Fig. 2A, Jacobson, 1991). Sample C5 was collected from the lower Caseyville Formation (Battery Rock Member) in Dixon Springs State Park, near the base of large-scale inclined strata (Fig. 3E). Two samples from the basal Pottsville Formation, P1 and P2, were collected in Bankhead National Forest near the Sipsey River Bridge and Brushy Creek Lake, respectively (Fig. 3A and 3B).

These four DZ samples were processed for mineral separation, mounted, and analyzed at the Arizona LaserChron Center (Tucson, Arizona) employing methods outlined by Gehrels (2012). U-Pb analyses were conducted on the Element 2 single-collector Laser Ablation-Inductively Coupled Plasma-Mass Spectrometer (LA-ICP-MS), using a target population of n = 300 randomly selected grains. Maximum discordance and reverse discordance cutoffs were 20% and -5%, respectively. The best age division was 900 Ma (<900 Ma, the $^{206}Pb/^{238}U$ age was applied; >900 Ma, the $^{206}Pb/^{207}Pb$ age was applied). We also conducted Hf isotopic analysis on Pottsville sample (P2), targeting grains with U-Pb ages of <850 Ma, by applying the methods of Cecil et al. (2011) and Gehrels and Pecha (2014).

U-Pb age distributions from the four DZ samples are plotted as normalized kernel density estimates (KDEs) using the R-based package "provenance" (Vermeesch et al., 2016) for visual inspection of sample age distributions. We use multidimensional scaling (MDS) to identify clusters of DZ U-Pb samples that likely had the same or similar source terranes via the MATLAB GUI created by Vermeesch (2013). Hf isotopic values are plotted using Hafnium Plotter (Sundell et al., 2019).

Petrographic Analysis

We complement DZ U-Pb and Hf analysis with petrographic analysis of one Caseyville Formation sample (C5) and one Pottsville sample (P2), as well as three samples from the Jackfork Group in Arkansas (see samples J4, J11, and J12, Allred and Blum, 2021). Core Laboratories prepared thin sections and point counting was conducted by Richard Larese. A mean of 342 points was counted for each of the five samples to provide representative compositional analyses.

Results

Caseyville Formation DZ U-Pb Age Distributions

We obtained 599 U-Pb ages from C1 and C5 with 286 and 294 concordant analyses, respectively. DZ U-Pb age distributions from both Caseyville Formation samples display prominent ca. 1250–950 Ma, 1550–1300 Ma, 1800–1600 Ma, and 3500–3000 Ma age groups, consistent with ultimate derivation from Grenville, Midcontinent granite-rhyolite, Yavapai-Mazatzal, and Superior provinces. Minor age modes are represented by ca. 500–400 Ma and 2000–1800 Ma grains, consistent with minor contributions from Appalachian and Penokean–Trans-Hudson provinces. For the two Caseyville samples, the Appalachian ages represent 8% of the total, Grenville ages represent 40%, Midcontinent ages represent 13%, Yavapai-Mazatzal ages represent 17%, and Superior ages represent 10% (Fig. 4A). No Alleghenian-age grains are observed in either sample, but the youngest Acadian ages for C1 and C5 are 393.5 ± 4.2 Ma and 401.5 ± 3.4 Ma (at 2σ), respectively. For Paleoproterozoic ages, C1 has two medium-amplitude modes (ca. 1639 Ma and 1757 Ma) and C5 has one large-amplitude mode (ca. 1648 Ma, Fig. 4A). DZ U-Pb data, as well as a table of potential sources of DZ age groups, are reported as supplemental files.

Pottsville Formation DZ U-Pb Age Distributions and Hf Isotopic Data

We obtained 604 U-Pb ages from P1 and P2 with 296 and 298 concordant analyses, respectively. DZ U-Pb age distributions from the Pottsville Formation display prominent ca. 500–400 Ma, 1250–950 Ma, 1550–1300 Ma, and 1800–1600 Ma age groups, consistent with ultimate derivation from Appalachian, Grenville, Midcontinent granite-rhyolite, and Yavapai-Mazatzal terranes. Minor age modes are represented by ca. 2000–1800 Ma and 3500–3000 Ma grains, consistent with minor contributions from Penokean–Trans-Hudson and Superior terranes. For the two Pottsville samples, the Appalachian ages represent 10% of the total, Grenville ages represent 49%, Midcontinent ages represent 12%, and Yavapai-Mazatzal ages represent 10%, whereas the peri-Gondwanan ages represent 2%, Penokean–Trans-Hudson ages represent 5%, and Superior ages represent 6% (Fig. 4B). The youngest U-Pb ages from P1 are 371.3 ± 3.6 Ma, 372.1 ± 6.0 Ma, and 375.9 ± 3.2 Ma; the youngest ages from P2 are 350.4 ± 3.3 Ma and 385.2 ± 2.9 Ma (all ages at 2σ). For Appalachian ages, percentages of the total for P1 and P2 are 12.1% and 8.0%, respectively. DZ U-Pb data are reported in Supplemental File S1.

Pottsville Formation sample P2 Hf isotopic data from grains <850 Ma are plotted in Figure 5 in epsilon Hf (εHf) units. The mean εHf value and error for all 28 grains (830–350 Ma) are -3.1 ± 0.8 (1σ); the mean εHf values and errors for Appalachian- and peri-Gondwanan-age grains are -2.6 ± 0.8 and -4.6 ± 0.8, respectively (see Table 2). The majority of the εHf values are within the +2 to -5 εHf range, inclusively; only considering the 21 Appalachian-age grains, the 25th percentile to 75th percentile εHf values are represented by -4.4 ± 0.8 and +1.9 ± 0.8. DZ Hf data are reported in Supplemental File S2.

Petrographic Analyses

We report petrographic modal analysis data from the Lower Pennsylvanian Caseyville Formation sample C5 and Pottsville Formation sample P2, as well as from three Jackfork Group DZ samples in Arkansas (see samples J4, J11, and J12, Allred and Blum, 2021). Upper Jackfork Group samples J11 and J12 are from the top and bottom, respectively, of Big Rock Quarry near

Little Rock (Fig. 2A and 2B) and represent relatively source-proximal deep-sea fan deposits. Sample J4 was collected from the basal Jackfork Group south of Kirby, ~140 km southwest of Big Rock Quarry (see Allred and Blum, 2021). Sample J4 represents a more distal portion of the deep-sea fan, although the deep-sea fan continues westward of the Kirby location. Compositional data are summarized in Table 3 and raw data are reported in Supplemental File S3.

Collected from the Illinois Basin, Caseyville Formation sample C5 is a medium lower-grained, well sorted, quartz arenite sandstone collected from a sand body that is at least 8 m thick (Fig. 3E), and which gently slopes to the northeast over an estimated 130 m (Fig. 3F). The normalized framework composition (as deposited before burial) is 97.03% quartz, no observed feldspar, and 2.97% lithic fragments (Table 3). Based on total framework composition (volume %), C5 has the highest percentage of authigenic quartz cement (10.92%) compared to the other four samples. Collected from the Black Warrior Basin, Pottsville Formation sample P2 is a medium lower-grained, well sorted, sublitharenite sandstone. The normalized framework composition is 88.00% quartz, 5.60% feldspar (the highest percentage of the five samples), and 6.40% lithic fragments.

In the Ouachita Basin, the three Jackfork Group samples are generally fine-grained, poorly- to moderately well-sorted, sublitharenite sandstones. Based on normalized framework composition, the three Jackfork Group samples have the highest percentages of lithic fragments (mean of 12.46%). These three samples also have the highest percentages of total detrital quartz among the five thin sections (mean of 68.90%), in part due to the highest percentages of polycrystalline quartz (mean of 3.96%), especially from samples J11 and J12 from Big Rock Quarry (4.99% and 4.11%, respectively).

Discussion

DZ U-Pb Provenance Analysis of Pottsville and Caseyville Formations

The data obtained in this study define characteristic DZ U-Pb ages for the Lower Pennsylvanian Pottsville Formation of northern Alabama and the Caseyville Formation of southern Illinois within the context of the Appalachian foreland-basin system. Collectively, Pottsville samples have larger contributions from the Appalachian and Grenville age groups (P1 and P2, mean of 58.6%) relative to Caseyville samples (C1 and C5, mean of 47.7%). Such high percentages of Appalachian and Grenville contributions to the Pottsville Formation are diagnostic of the southern Appalachian source area, referred to in Thomas et al. (2017) as the “Appalachian signature”, with similarly high percentages observed in Pennsylvanian sandstones of the southern Appalachian Basin (e.g., Sewanee Conglomerate, 65.9%, Thomas et al., 2004), as well as in most samples from the Jackfork Group and Johns Valley Shale in the Ouachita Basin (45.5–62.5%, Allred and Blum, 2021).

Although more distal from the Appalachians, previous workers presented DZ U-Pb and Hf data and recognized Appalachian-derived detritus in the Early-Middle Pennsylvanian Illinois Basin (Kissock et al., 2018; Thomas et al., 2020). These interpretations suggest that the Appalachian forebulge (the Cincinnati arch) was ultimately overtopped by sediments from the unroofing of the Appalachians. Models by Quinlan and Beaumont (1984) and Beaumont et al. (1988) suggest this possibility by at least Late Pennsylvanian time, if not earlier.

Two Caseyville Formation samples from southern Illinois (C1 and C5), like two Caseyville samples collected in Kentucky (Fig. 4A, Thomas et al., 2020), correspond closely to the signature of Lower Pennsylvanian sandstones in the Appalachian Basin. These two samples have combined Appalachian-Grenville contributions (C1 and C5, 45.1% and 50.3%, respectively) that are comparable with samples from coeval sandstones in Iowa (Kissock et al., 2018), Kentucky (Thomas et al., 2017; Thomas et al., 2020), and Arkansas (Xie et al., 2018; Thomas et al., 2021; Wang et al., 2021). Although most Jackfork Group samples have Appalachian-Grenville percentages of >50%, three Jackfork samples from DeGray Lake Spillway and Kirby (J3, J6, and J8, Fig. 2B and 4B) demonstrate lower percentages (45.2–50.3%). Curiously, the two Jackfork samples from Big Rock Quarry (J11 and J12, Fig. 2B and 4A) are distinct from other Jackfork Group samples to the southwest due to significantly lower percentages of Appalachian and Grenville ages (41.6% and 35.0%, respectively). The mean percentage of only Appalachian DZ ages for Big Rock Quarry samples (7.4%) also resembles the mean percentage of Caseyville Formation samples C1 and C5 (8.0%). While J11 and J12 are distinct from other samples in the MDS plot (Fig. 6A), the relative proximity of Caseyville Formation (C1, C5, C24, and C105) and Saginaw Formation (S56) samples, as well as a select Bloyd Formation sample (B53), suggest that a Caseyville fluvial system, as well as a fluvial system on the Arkoma shelf, may have together sourced the proximal deep-sea fan at Big Rock Quarry (see Allred and Blum, 2021).

It is notable that two Caseyville Formation samples (C1 and C5) also show a high proportion of Paleoproterozoic (e.g., 1800–1600 Ma, mean of 17.0%) and Archean (mean of 9.8%) age groups relative to Pottsville Formation samples (Fig. 4A and 4B). A high proportion of Paleoproterozoic ages is also observed in select samples from the Kentucky Caseyville Formation (C105, Thomas et al., 2020), Bloyd Formation (B53 and B55, Xie et al., 2018), Hale Formation (C109, Wang et al., 2021), Lee Formation (L43, Becker et al., 2005), Corbin Sandstone (C19, Thomas et al., 2017), and especially Jackfork Group samples from Big Rock Quarry (J11 and J12, mean of 24.4%, Allred and Blum, 2021). The nearest direct source for Paleoproterozoic DZ would have been from the Nemaha uplift of present-day Nebraska (Steeples, 1982; Burberry et al., 2015). Alternatively, these DZ could have been originally sourced from the Makkovik orogen of eastern Canada (e.g., Ketchum et al., 2002) or the Central Plains orogens farther south, which were then transported to the Early Paleozoic passive-margin of eastern Laurentia (e.g., Cawood and Nemchin, 2001), and subsequently incorporated into the Alleghenian orogen (Thomas et al., 2004). This second interpretation is less likely due to the variability in Neoproterozoic-Early Paleozoic drainage systems to the eastern Laurentian passive-margin (Cawood and Nemchin, 2001) and the added distance recycled DZ would have traveled.

In contrast to samples from the eastern interior, Pottsville Formation samples (P1 and P2), a Sewanee Conglomerate sample (S38), and distal deep-sea fan samples of the Jackfork Group and Johns Valley Shale (J1-J10) occupy the opposite side of the MDS plot of Lower Pennsylvanian DZ samples (Fig. 6A). We interpret this difference to suggest a distinct source area from that of the eastern interior. Jackfork Group samples at Big Rock Quarry (J11 and J12) would represent proximal deep-sea fan deposits predominantly sourced by eastern interior fluvial systems with headwaters that may include: (1) the northern and central Appalachians, including possible recycled Early Paleozoic passive-margin strata that contained Paleoproterozoic-age DZ; (2) the eastern interior as farther north as Michigan, when the Cincinnati and Kankakee arches were not major barriers to sediment transport (see Siever and Potter, 1956; Quinlan and Beaumont, 1984); and (3) the Arkoma shelf to the northwest. Concurrently, a syn-orogenic drainage in the

Appalachian-Ouachita syntaxis directly sourced a second deep-sea fan in the Ouachita Basin, analogous to the modern Brahmaputra River feeding the Bengal fan. It is unclear if sediment was routed from the Appalachian foredeep to the Black Warrior foredeep, but it is probable that, like during the Mississippian, the exhumed Appalachian Valley and Ridge to the southeast was a sediment source during the Early Pennsylvanian (McKay et al., 2021). Thus, we suggest a southeastern sediment source, facilitated by high sediment flux accompanying the climate of Early Pennsylvanian humid glacial intervals (Cecil et al., 2003), for a deep-sea fan in the Ouachita Basin.

The objective of this study was to examine Lower Pennsylvanian terrestrial and marginal-marine units that represent potential sources for Ouachita deep-sea fans. However, this study is limited in its scope with the presentation of four large-*n* (*n* ~ 300) DZ samples: two from the basal Pennsylvanian sands of the Illinois Basin and two from the basal Pennsylvanian sands of the Black Warrior Basin. There is a possibility that our samples do not completely characterize the full depositional succession of each formation. Nevertheless, these large-*n* data are internally consistent without major aberrations and likely detect true population abundance (see Andersen, 2005). This, together when viewed within the context of an ensemble of coeval DZ samples from other studies (Fig. 4A and 4B, Thomas et al., 2020; McKay et al., 2021), supports a source-to-sink relationship from Caseyville and Pottsville rivers to the Ouachita deepwater sink.

Hf Isotopic Values from the Pottsville Formation

Epsilon Hf values obtained from Paleozoic Appalachian and Neoproterozoic peri-Gondwanan DZ from the Pottsville Formation of the Black Warrior Basin are similar to εHf values from the

Lower Pennsylvanian Appalachian foredeep (Thomas et al., 2017), Illinois Basin (Thomas et al., 2020), Arkoma shelf (Thomas et al., 2021), and Ouachita Basin (Allred and Blum, 2021). The mean εHf values from select Ouachita Basin samples (e.g., J8 and J10) are within error of the Pottsville Formation sample (P2), especially for Paleozoic grains (Table 2), suggesting that Black Warrior Basin siliciclastics were a possible source for Jackfork Group, and subsequent Johns Valley Shale, deep-sea fans. Select samples from the Caseyville and Hale Formations (from the Illinois Basin and Arkoma shelf, respectively; Thomas et al., 2020; Thomas et al., 2021) also demonstrate mean values like Lower Pennsylvanian units in the Ouachita and Black Warrior Basins. Although DZ samples were collected in relative proximity, there appears to be a distinction between the mean εHf values from Lower Pennsylvanian samples collected in the Appalachian Basin (more juvenile, Table 2) and Pottsville Formation sample P2 (more evolved, Fig. 5). This distinction may indicate limited sediment routing from the Appalachian Basin into the Black Warrior Basin. In general, the predominately intermediate εHf values from the Pottsville DZ sample do not in themselves clearly distinguish different crustal sources, but at least support the interpretation that there may have been a connection between a Black Warrior lowstand fluvial system and an Ouachita deep-sea fan.

Petrography of the Caseyville Formation, Pottsville Formation, and Jackfork Group

We complement DZ analysis of the Caseyville Formation, Pottsville Formation, and the Jackfork Group with conventional petrographic analyses. Generally, these Lower Pennsylvanian sandstones are quartz arenite with only minor contributions from other detrital fractions. Three Jackfork Group samples are the most lithic-rich samples in this study, although not quite as lithic-rich as other Ouachita samples (Graham et al., 1976). Nevertheless, our three Jackfork Group petrographic samples are similar to Ouachita Basin data reported by Morris (1974) and Graham et al. (1976). In the Illinois Basin, the quartz arenite Caseyville Formation sample (C5) also is similar to Lower Pennsylvanian (Siever and Potter, 1956; Kissock et al., 2018) and Upper Mississippian (Potter and Glass, 1958) sandstones.

The petrographic signature in the source-proximal Black Warrior Basin is different from the quartz arenites of the eastern interior. Based on modal composition from the eastern Black Warrior Basin, Graham et al. (1976) suggested that a clastic wedge was sourced from a collisional orogen to the northeast (see Metzger, 1965 for sample locations). Modal composition data from Uddin et al. (2016) also support this interpretation. In contrast, samples from Mack et al. (1983) were more geographically distributed, including in the southwestern portion of the Basin, and showed more diverse composition. Nevertheless, Mack et al. (1983) observed that the lack of igneous grains and the presence of metamorphic grains in Upper Mississippian-basal Pennsylvanian sandstones and suggested a proximal, mixed source that included a fold and thrust belt dominated by sedimentary and low-grade metamorphic rocks, although volcanic rocks became progressively more important as a source by the Upper Pottsville.

The basal Pottsville Formation petrographic sample (P2) in this study was collected from the north-central part of the Black Warrior Basin. The percentage of feldspar for P2 is 5.6%, like Pottsville samples of Mack et al. (1983); however, P2 did not have any volcanic lithics, while other Pottsville samples, especially from the Upper Pottsville, record the progressive increase in volcanic lithics. This difference may be due to spatial and stratigraphic variability of volcanic lithics, as Pottsville samples more proximal to the Ouachita arc and higher up section demonstrate an increase in volcanic lithics. Nevertheless, we suggest that the Ouachita magmatic arc had a minimal contribution of sediment at the time of deposition of the basal Pottsville, especially in the central portion of the Black Warrior Basin, and that most sediment was supplied from the Appalachians to the southeast.

Xie et al. (2016a) also reported DZ U-Pb and petrographic data from Chesterian sandstones in the western part of the Black Warrior Basin and observed quartz arenites that largely lacked feldspars and lithic fragments. Based on these petrographic results, together with high percentages of Paleoproterozoic DZ U-Pb ages (1800–1600 Ma, mean of 20.5% for all samples), Xie et al. (2016a) interpreted a source area that spanned much of the eastern United States and Superior craton. However, this continental-scale interpretation seems disproportionately large relative to the scale of Chesterian sand bodies in the Black Warrior Basin. Furthermore, as noted in McKay et al. (2021), such a paleogeographic reconstruction requires sediment transport around or through multiple active depositional basins. Instead, Paleoproterozoic DZ ages in Chesterian sands may have been derived from local Cambrian-Devonian units deposited on the southeastern passive-margin of Laurentia (McKay et al., 2021).

The Appalachian Foreland-Basin System and a Template for Sediment Routing

Jackfork Group sediments were deposited as turbidites in a complex array of deep-sea fans within the Ouachita Basin. For decades, previous workers postulated sources for Ouachita Basin deep-sea fans from traditional petrographic data (e.g., Morris, 1971; Graham et al., 1976) and more recently from geochemical analyses (e.g., Gleason et al., 1994, 1995). DZ U-Pb and Hf data from terrestrial units in this study, complemented by deepwater DZ data from Allred and

Blum (2021), indicate that Jackfork Group turbidites in the Ouachita Basin had at least two distinct sources, one of which had a characteristic Appalachian signature. Sediment was delivered to the Ouachita deepwater basin during glacial period sea-level fall and lowstand, when fluvial systems extended across a newly emergent continental shelf to the shelf margin.

During high sea-level conditions in the Early Pennsylvanian Black Warrior Basin, sand likely was deposited in proximal marginal-marine environments; during humid glacial periods and low sea-level, sand was routed across the exposed continental shelf. Coincidently, the Early Pennsylvanian Illinois Basin was open to the south-southwest (Potter and Pryor, 1961) toward the Ouachita Basin, through which feeder fluvial systems transited the continental shelf to a slope canyon during low sea-level conditions.

We interpret our ensemble of DZ U-Pb data, as well as the clustering of Lower Pennsylvanian samples in MDS space (Fig. 6A), to suggest Ouachita Basin deep-sea fans were primarily sourced via distinct feeder fluvial systems that flowed from the eastern interior of Laurentia and the Appalachian-Ouachita syntaxis (Fig. 6B). We see no evidence to support sediment transport from the Central Appalachian Basin to the Black Warrior Basin; instead during humid glacial period lowstands, recycled sediment from the Appalachians southeast of the Black Warrior Basin (see McKay et al., 2021) was routed to the Ouachita trough. Moreover, sediment was dispersed through the Appalachian Basin to the eastern midcontinent, crossing the Cincinnati arch to the Illinois Basin (see Thomas et al., 2020), and then onward to the Ouachita Basin (Fig. 6B). This dispersal pathway is plausible considering that samples from the Corbin Sandstone, Caseyville Formation, and Hale Formation in Kentucky, Illinois, and Arkansas, respectively, plot together in MDS space (Fig. 6A) and have similar Hf signatures (Table 2), and thus suggest a possible sediment routing fairway to the Ouachita remnant ocean basin.

We suggest a template consisting of the Appalachian foreland-basin system with accompanying Ouachita orogenic loading (see Whiting and Thomas, 1994) that steered Early Pennsylvanian rivers toward the Ouachita trough. Much of the foredeep depozones of the Black Warrior and Appalachian Basins lacks a significant Mississippian-Pennsylvanian unconformity (Thomas, 1972; Horne et al., 1974; Ettensohn and Chesnut, 1989), suggesting accommodation was continuous. In contrast, the eastern interior backbulge depozone preserved a distinct Mississippian-Pennsylvanian unconformity, potential evidence of forebulge propagation. Separate rivers in the foredeep and backbulge depozones, orthogonal to the foreland basin system flexural profile, both supplied sediment to Ouachita deep-sea fans.

Scaling Relationships in Early Pennsylvanian Fluvial Systems and Source-to-Sink Sedimentology

Sømme et al. (2009) documented empirical scaling relationships between drainage area and the different segments of modern sediment-dispersal systems. Subsequently, Blum et al. (2013) applied these relationships to fluvial systems, particularly the relationships between drainage basin size, bankfull discharge, and point-bar thickness. Thus, based on an example of large-scale, inclined strata near sample C5 (Fig. 3F), an interpreted fluvial point-bar, the Caseyville fluvial system in southern Illinois potentially had a bankfull channel depth of 10 m. This bankfull depth estimate scales to a drainage basin area of ~10^5 km^2 and a trunk stream length of ~750–1000 km^2 (see Sømme et al., 2009). These constraints cast a Caseyville paleodrainage area that may have included portions of Michigan and the areas to the northeast, similar to minimum estimates of Archer and Greb (1995).

Sømme et al. (2009) also documented morphometric relationships between fluvial and shelf to deepwater systems, such that there are strong positive correlations between the drainage area of rivers and the dimensions of downstream basin-floor fans and vice versa (Blum et al., 2013). For example, a 100–200 km long (medium-sized) deep-sea fan scales, to the first order, to a drainage area >10^5 km^2. If there were two fans >100 km in length within the Ouachita trough, one sourced from the eastern interior and one sourced from the Appalachian-Ouachita syntaxis, then these fans would have crossed and coalesced on the abyssal plain. Furthermore, during low sea-level glacial periods, as was frequently the case during the Pennsylvanian, small rivers would have become incorporated into expanding large rivers transiting the continental shelf (Blum and Hattier-Womack, 2009). Thus, during icehouse high-amplitude lowstands, it would have been large rivers that connected with submarine canyons. Based on Jackfork Group deep-sea fan lengths of >100 km, as well as Caseyville sand body (point-bar) thickness of ~10 m, we suggest two distinct river systems, one with a drainage area >10^5 km^2 in the case of the eastern interior, fed Ouachita deep-sea fans, and we propose that contributions from small lowstand rivers to deep-sea fans would have been minimal at this time.

Studies of the Bengal Fan (Blum et al., 2018) and the Jackfork Group deep-sea fans (Allred and Blum, 2021) demonstrate that the full extent of fans consistently record the DZ signal of feeder systems, even for the largest extant deep-sea fans. Even with transport distances that connect >2500 km of river flow with ~1400–2400 km turbidity currents, the Bengal Fan DZ U-Pb record faithfully records Himalayan source terranes (Blum et al., 2018). Furthermore, this DZ signal propagation occurred within a ~2–3 Myr time frame through the Ganges-Brahmaputra-Bengal Fan system. It is inferred that during an episode of river-sourced sediment flux, the large-scale DZ signal transfer was consistent through a proximal-to-distal transect of a fan, without a sifting of grains that could distort DZ age distributions. In like manner, sediment transfer may have been rapid for Lower Pennsylvanian Jackfork Group deep-sea fans, and as observed by Allred and Blum (2021), the consistency of the age distributions between the Kirby and the DeGray Lake Spillway samples suggests that there is not a change in the DZ U-Pb signature along a proximal-to-distal transect of an ancient deep-sea fan. Thus, the distinct DZ U-Pb signature of Big Rock Quarry samples compared to DeGray Lake Spillway and Kirby samples (Allred and Blum, 2021) instead suggests that separate rivers within the Appalachian foreland-basin system sourced distinct deep-sea fans in the Ouachita Basin.

Conclusion

The DZ signature of ancient deep-sea fans, like recent to modern deep-sea fans (e.g., Fildani et al., 2016; Blum et al., 2018; Mason et al., 2019), faithfully fingerprints feeder fluvial systems. This DZ U-Pb and Hf study, as well as petrographic study, complements a recent DZ U-Pb and Hf isotopic characterization of the Early Pennsylvanian Jackfork Group deep-sea fan system (Allred and Blum, 2021) by delineating probable Early Pennsylvanian feeder fluvial systems, and thereby links a source-to-sink relationship. Our proposed Early Pennsylvanian sediment routing template reflects the topography of the Appalachian foreland-basin system with two distinct paleovalley systems in the eastern interior of Laurentia and the Appalachian-Ouachita syntaxis (Fig. 6B). Medium-sized drainage areas (>10^5 km^2) fed at least medium-sized deep-sea fan systems (100–200 km long) in the Ouachita Basin (see Sømme et al., 2009). Thus sizeable sediment routing systems were oriented southward or southwestward to the Ouachita deepwater sink, which would have curbed fluvial transport from the eastern United States to western United States at this time (Allred and Blum, 2021).

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Figures

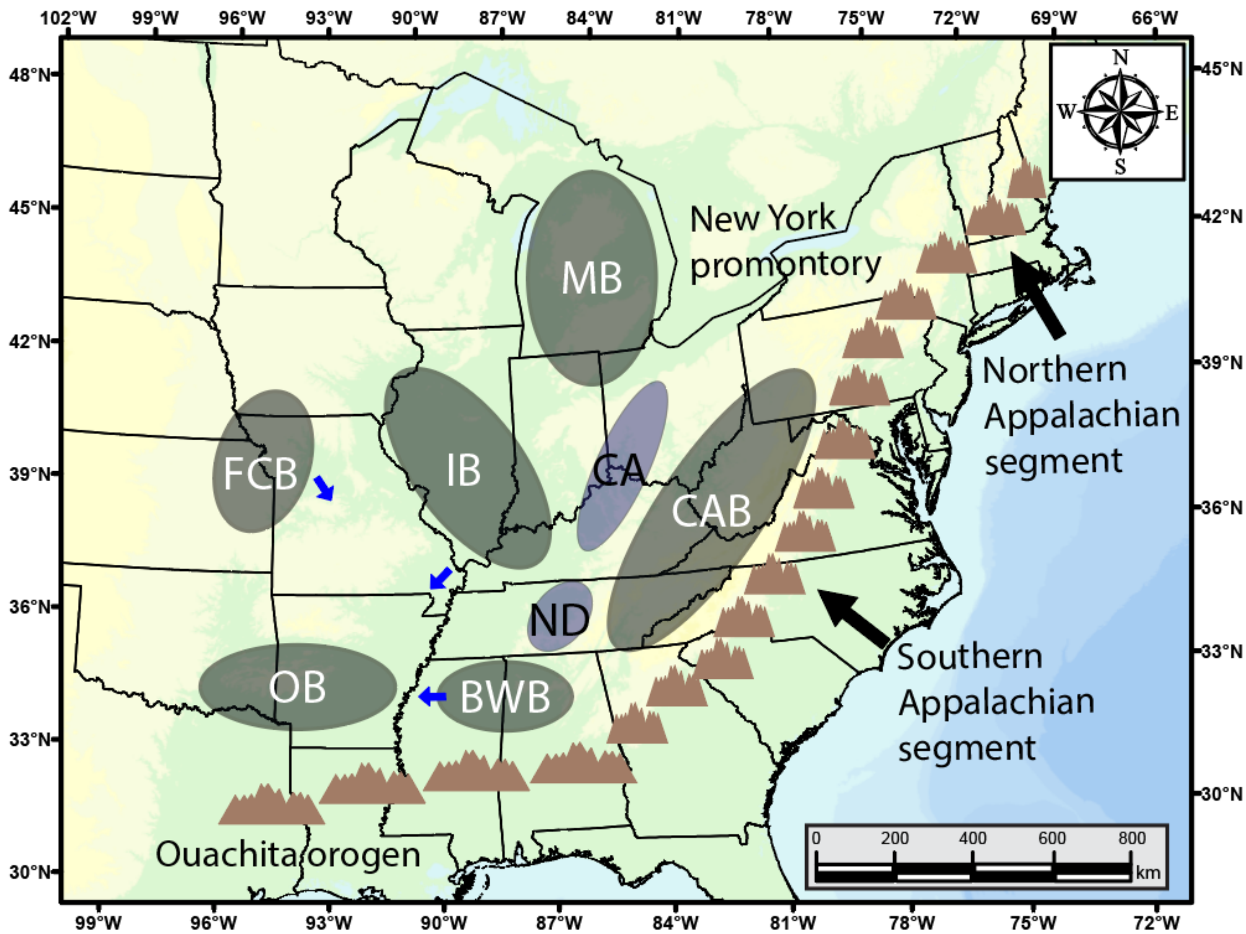


Figure 1. Map of major basins and structures of Early Pennsylvanian eastern Laurentia (modified from Allred and Blum, 2021). Differentiation of northern and southern segments of the Appalachians based on the strong asymmetry in the distribution of Alleghenian plutonic rocks, with the vast majority of magmatic systems south of the New York promontory (Hibbard and Karabinos, 2013). The three blue arrows indicate potential sediment routing pathways to the Ouachita Basin. BWB—Black Warrior Basin, CA—Cincinnati Arch, CAB—Central Appalachian Basin, FCB—Forest City Basin, IB—Illinois Basin, MB—Michigan Basin, ND—Nashville Dome, OB—Ouachita Basin.

A

Period	Stage/ Series	Ouachita Basin	Arkoma shelf		Illinois Basin	Black Warrior	Appalachian Basin		
Lower Penn.	Atokan	Atoka Formation	Atoka Formation		Tradewater	Pottsville Formation P1 P2	Breathitt Group	Breathitt	Pottsville Group
	Morrowan	Johns Valley Shale	Bloyd Formation	Kessler Ls	C1 Caseyville/ Mansfield C5			Corbin	
				Dye Shale				Bee Rock/Lee	
		Jackfork Group J11 J12 J4		Mid Bloyd Ss				Sewanee/ New River	
				Brentwood Ls					
				Hale		Parkwood/ Bangor Ls/ Pennington		Warren Point	Sharon
Upper Miss.	Chesterian	Stanley Group	Pitkins Limestone		Kinkaid Ls		Pennington Group	Bluestone	Mauch Chunk Group
			Fayetteville Shale	U Fayetteville	Tar Springs			Princeton	
				Wedington	Hardinsburg	Pride Mtn/ Monte Eagle Ls		Hinton	
				L Fayetteville	Cypress			Stony Gap	
			Hindsville	Batesville	Aux Vases			Bluefield	

B

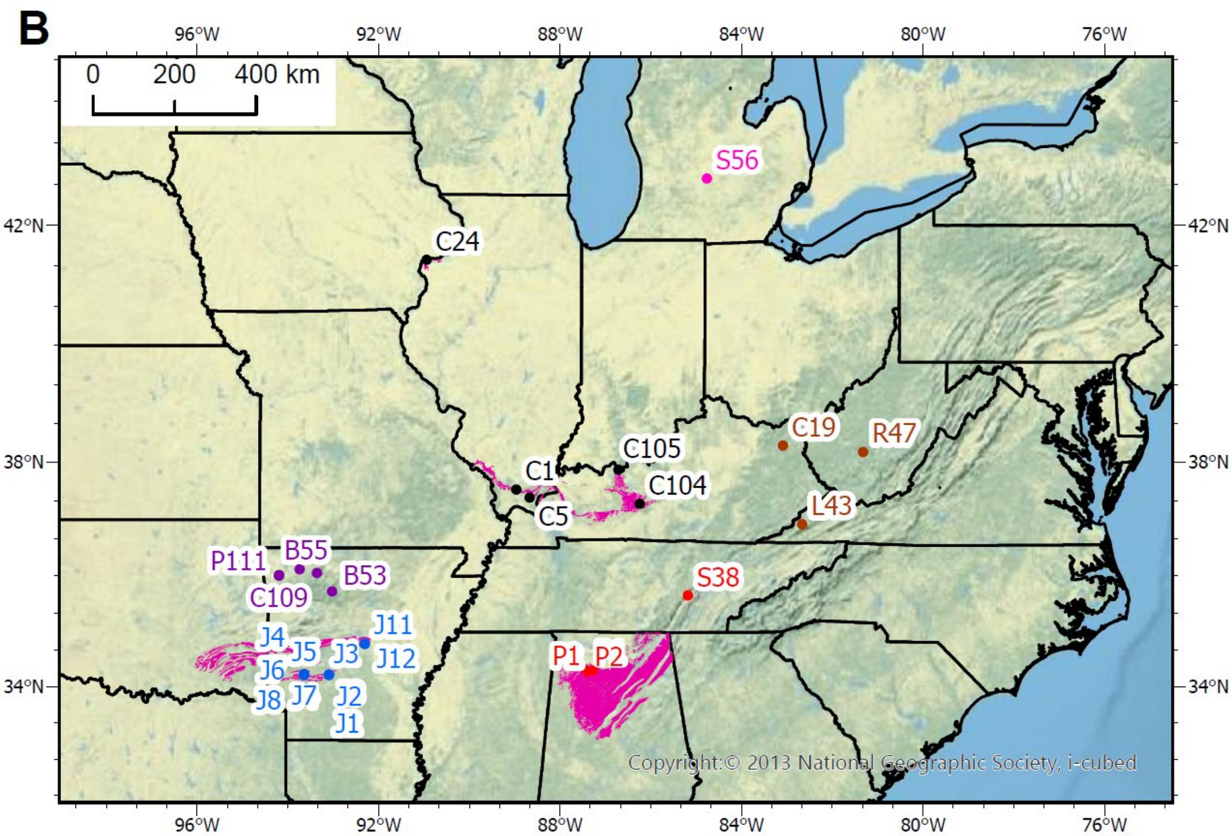


Figure 2. **A**. Stratigraphic correlation chart showing general Upper Mississippian and Lower Pennsylvanian lithological correlations between the Ouachita Basin, Arkoma shelf, Illinois Basin, Black Warrior Basin, and Appalachian Basin (selected units from south to north). The units from this study, the Caseyville Formation, Pottsville Formation, and Jackfork Group, are shaded and detrital zircon (DZ) samples are labeled. After Bristol and Howard (1971), Sutherland (1988), Chesnut (1992), Archer and Greb (1995), Nelson et al. (2002), Becker et al. (2005), Ruppert et al. (2014), Xie et al. (2016a), Xie et al. (2016b), Thomas et al. (2017), Zou et al. (2017), Xie et al. (2018), Wang and Bidgoli (2019), and Thomas et al. (2020). L—Lower, Ls—Limestone, Miss.—Mississippian, Mtn—Mountain, Penn.—Pennsylvanian, Ss—Sandstone, U—Upper. **B**. Map of DZ and petrographic sample locations from this study and outcrops of the Caseyville Formation (C1 and C5), Pottsville Formation (P1 and P2), and Jackfork Group (J4, J11, and J12). Outcrop data for the three Lower Pennsylvanian units of interest (pink) obtained from https://mrdata.usgs.gov/geology/state/. See Allred and Blum (2021) for Jackfork Group DZ data collected from Arkansas. The key for select Lower Pennsylvanian DZ samples found in Supplemental File 4 (Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas et al., 2017; Xie et al., 2018; Thomas et al., 2020; Allred and Blum, 2021; Thomas et al., 2021; Wang et al., 2021). Sample color key: black—Illinois Basin; red—Black Warrior and Southern Appalachian Basins; blue—Ouachita Basin; pink—Michigan Basin; brown—Central Appalachian Basin; purple—Arkoma shelf.

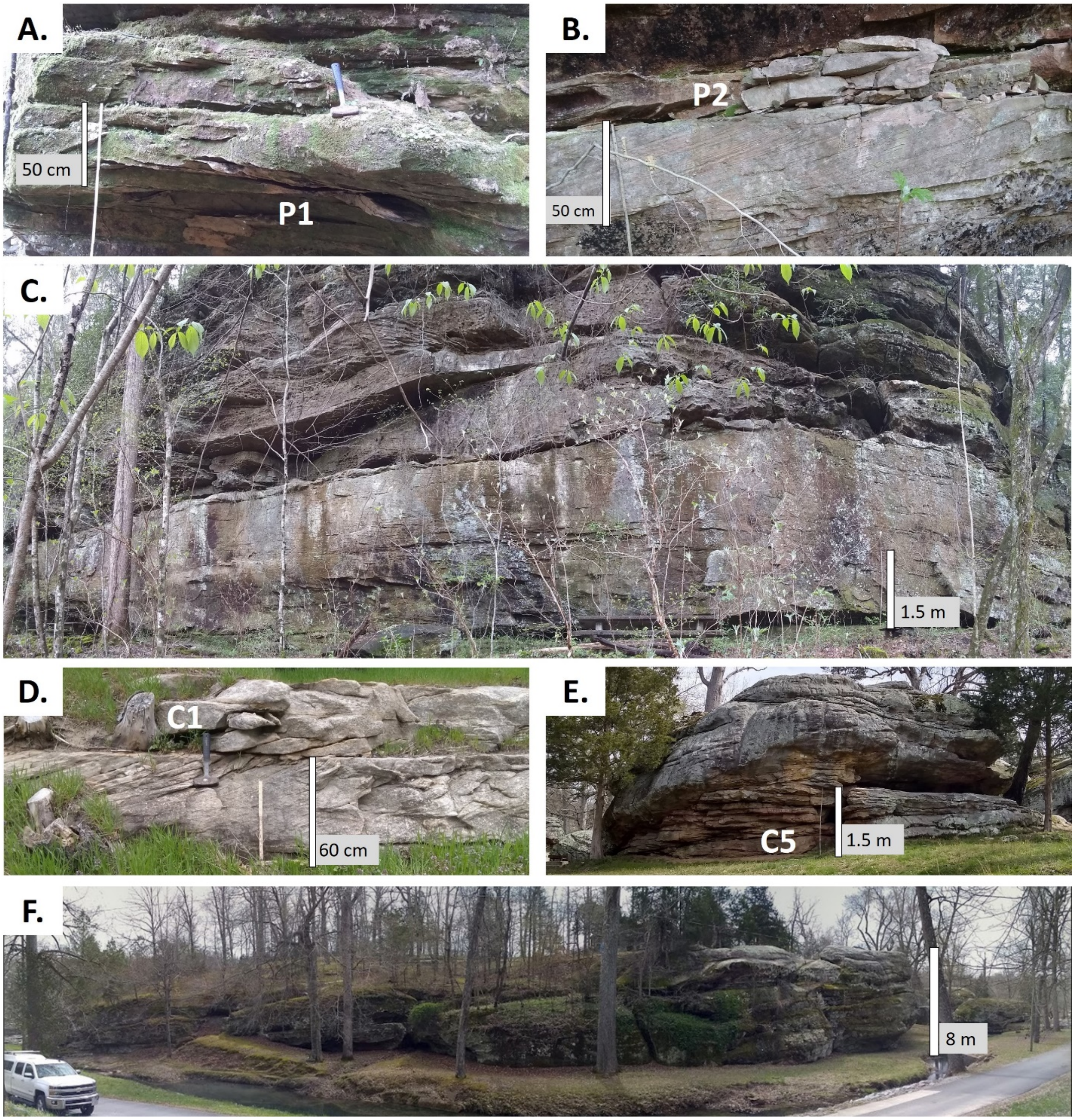


Figure 3. Photographs of outcrops for detrital zircon samples. **A**. Sample P1, lower Pottsville Formation, near Sipsey River Bridge, Bankhead National Forest. **B**. Sample P2, lower Pottsville Formation near Brushy Creek Lake, Bankhead National Forest. **C**. Thick sand body (~8 m) directly south of sample P1. **D**. Sample C1, upper Caseyville Formation, roadcut on the west side of Illinois Route 37, south of Ferne Clyffe State Park. **E**. Sample C5, lower Caseyville

Formation, Dixon Springs State Park. **F**. Large-scale inclined strata directly north of sample C5. Outcrop length is ~130 m. See Table 1 for additional sample details.

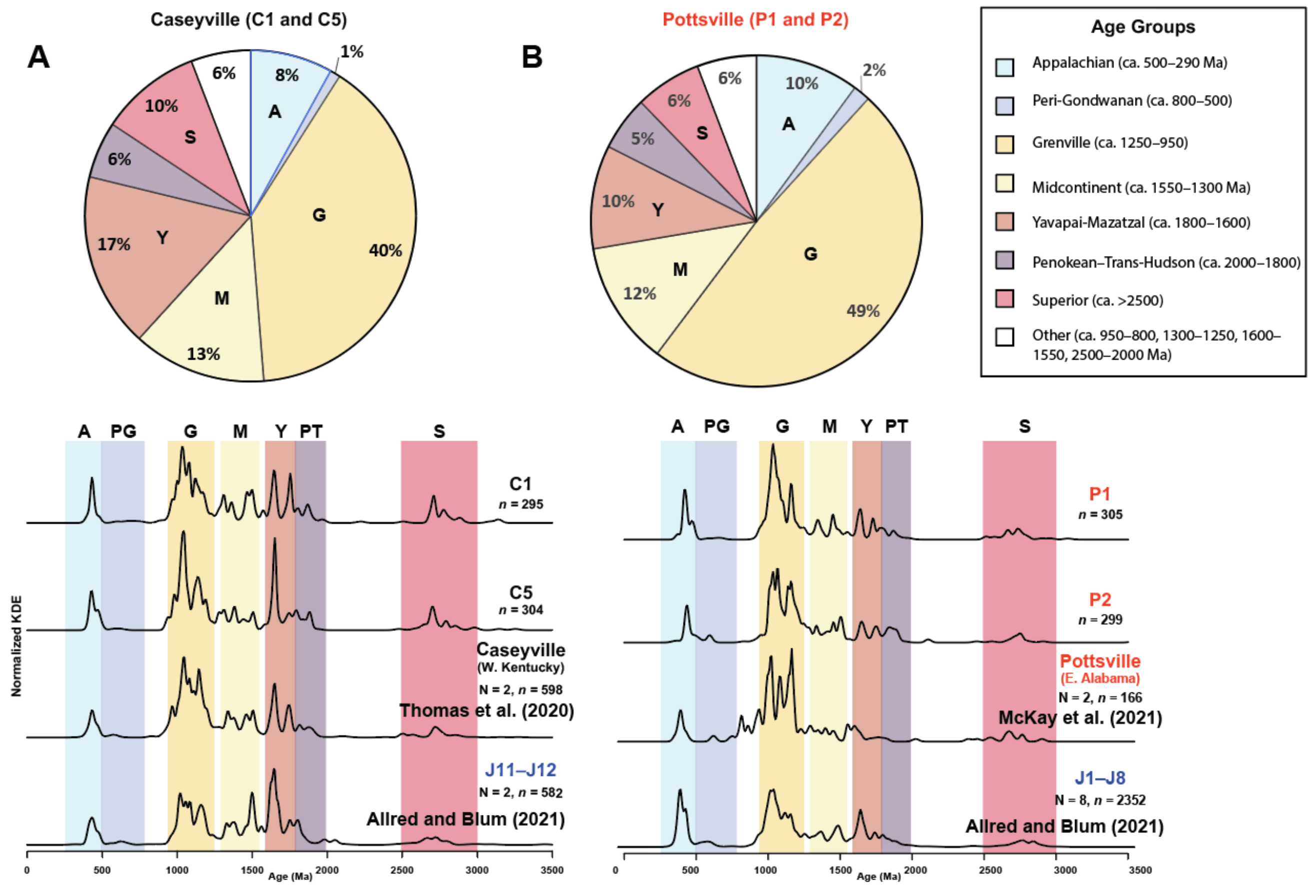


Figure 4. Pie diagrams and Normalized kernel density estimates (KDE) showing the contribution of different source terranes. **A**. Contribution of sources to the composite DZ U-Pb record of Caseyville Formation samples (N = 2, *n* = 599). C1 represents the uppermost Caseyville Formation, while C5 represents the lower Caseyville Formation. DZ samples from the Jackfork Group at the Big Rock Quarry (J11 to J12, AR) are shown for reference (Allred and Blum, 2021). KDE are calculated with a bandwidth of 10. **B**. Contribution of sources to the composite DZ U-Pb record of Pottsville Formation samples (N = 2, *n* = 604). Both P1 and P2 are from the basal Pottsville Formation. DZ samples from the Jackfork Group at DeGray Lake Spillway and Kirby (J1 to J8, AR) locations are shown for reference (Allred and Blum, 2021). Analytical data are provided in Supplemental File S1. *n*—number of grains. A—Appalachian; PG—peri-

Gondwanan; G—Grenville; M—Midcontinent; Y—Yavapai-Mazatzal; PT—Penokean–Trans-Hudson; S—Superior.

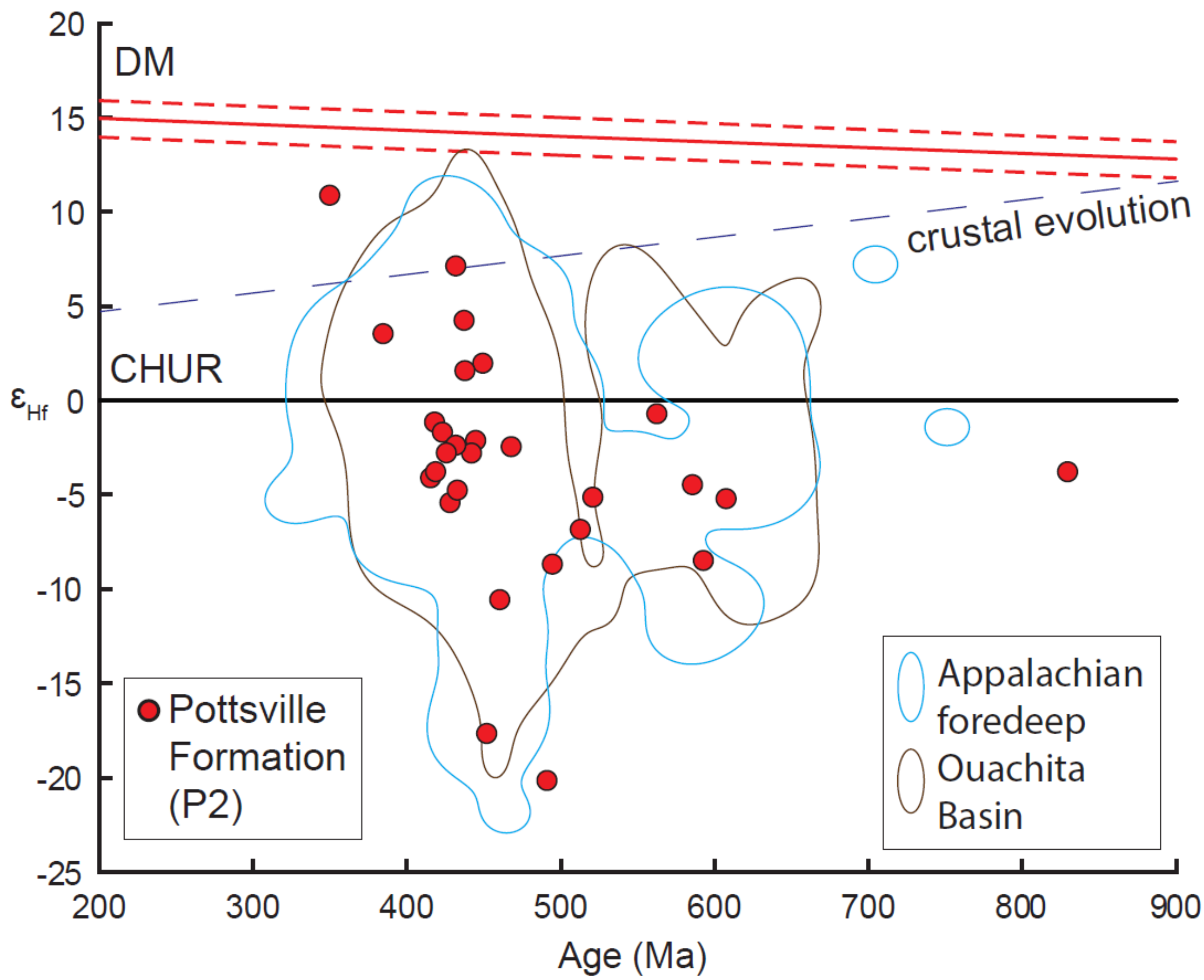


Figure 5. Hf evolution diagram showing results from the lower Pennsylvanian Pottsville Formation (sample P2, red circles). Hf isotopic composition is shown in epsilon units (ε_{Hf}), relative to the chondritic uniform reservoir or CHUR (Bouvier et al., 2008; Vervoort, 2015) and the depleted mantle or DM (Vervoort et al., 1999). Strictly considering the 21 Appalachian-age grains, the 25th to 75th percentile values range from -4.4 ± 0.8 to +1.9 ± 0.8. Shown for reference is the evolution of typical continental crust (purple dashed line labeled crustal evolution), which is based on a $^{176}Lu/^{177}Hf$ ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999).

The mean ε_{Hf} value for all 28 grains (830–350 Ma) and the standard error is -3.1 ± 0.8 (1σ). Amorphous blue and brown colored outlines represent the 95% density contour (2σ) for ε_{Hf} data from Pennsylvanian samples in the Appalachian foredeep (blue, Thomas et al., 2017) and Ouachita Basin (brown, Allred and Blum, 2021). Data plotted with Hafnium Plotter, v. 1.7 (Sundell et al., 2019). Analytical data are in Supplemental File S2.

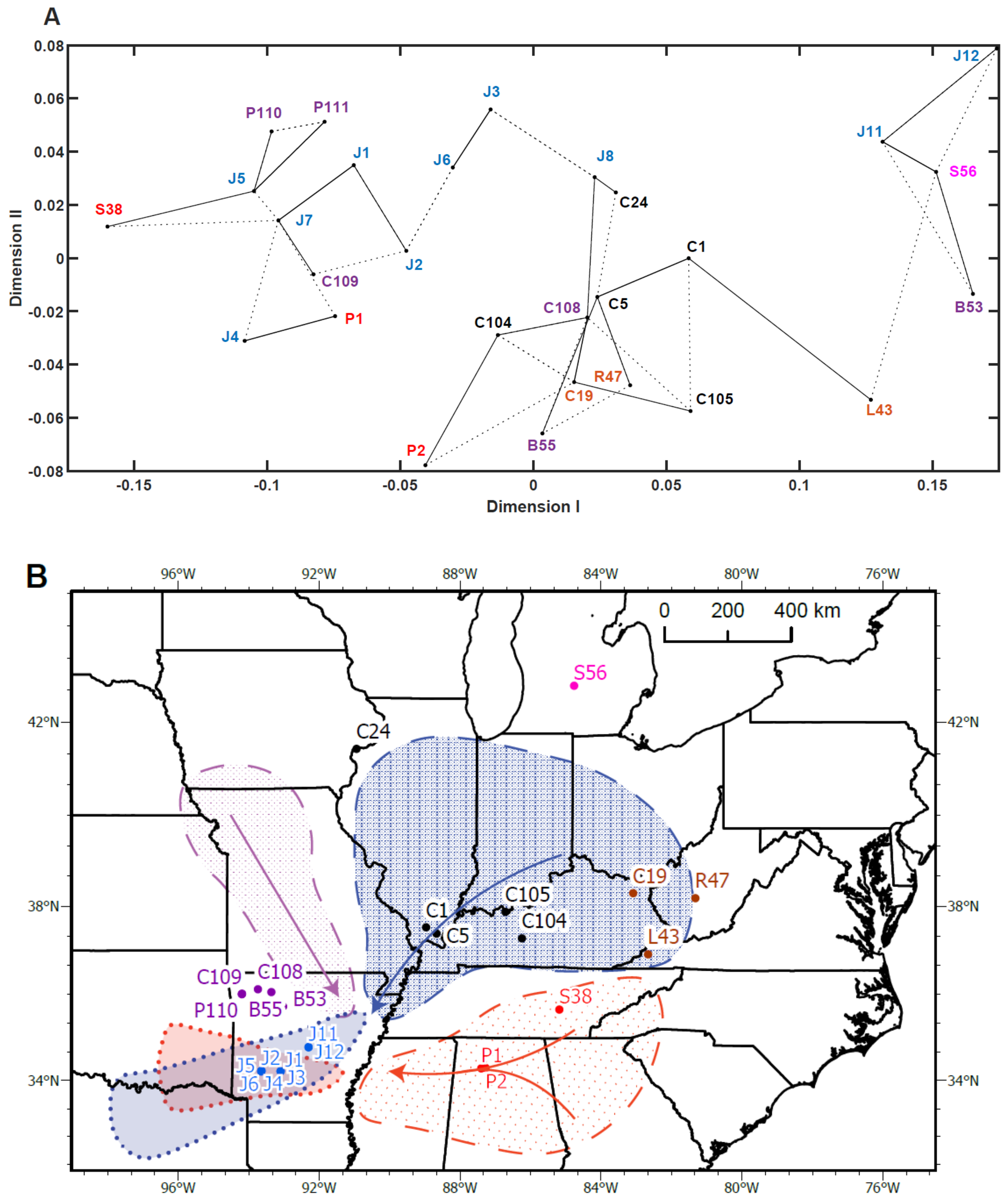


Figure 6. **A**. Multidimensional scaling (MDS) plot of detrital zircon (DZ) samples mapped in Figure 2B (see Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas et al., 2017; Xie et al., 2018; Thomas et al., 2020; Allred and Blum, 2021; Thomas et al., 2021; Wang

et al., 2021). Solid lines indicate nearest neighbors and dashed lines indicate second-nearest neighbors. The transformation stress was 0.098484, suggesting a fair transformation (Vermeesch, 2013). **B**. Interpreted Early Pennsylvanian paleodrainage areas that sourced Jackfork Group deep-sea fans in the Ouachita Basin (DZ samples J1–J6 and J11–J12). At least two deep-sea fans were sourced by major paleovalleys centered within the Illinois Basin (blue arrow) and Black Warrior Basin (red arrow). Yavapai-Mazatzal source terranes near the midcontinent may have contributed to major midcontinent fluvial systems (purple arrow) and ultimately to Ouachita deep-sea fans, particularly the proximal deep-sea fan deposits at Big Rock Quarry. J7 and J8 are not shown but are near J6.

Tables

TABLE 1.—*Detrital zircon (DZ) and petrography sample locations. DZ sample numbers followed by * indicate samples presented with petrographic data. The three Ouachita Basin DZ samples (J4, J11, and J12) are from Allred and Blum (2021). n-number of grains.*

Sample Number	General Location	Stratigraphic Position	Latitude (°N)	Longitude (°W)	n	Concordant Grains
Illinois Basin						
C1	Ferne Clyffe	Caseyville, upper	37.526440	88.965570	295	286
C5*	Dixon Springs	Caseyville, lower	37.384953	88.670100	304	294
Black Warrior Basin						
P1	Sipsey River	Pottsville, lower	34.284367	87.400510	305	296
P2*	Brushy Creek Lake	Pottsville, lower	34.294746	87.274550	299	298
Ouachita Basin						
J4*	Kirby	Jackfork, lower	34.230034	93.641180	301	286
J11*	Big Rock Quarry	Jackfork, upper	34.783440	92.303071	298	293
J12*	Big Rock Quarry	Jackfork, upper	34.777308	92.302858	286	279

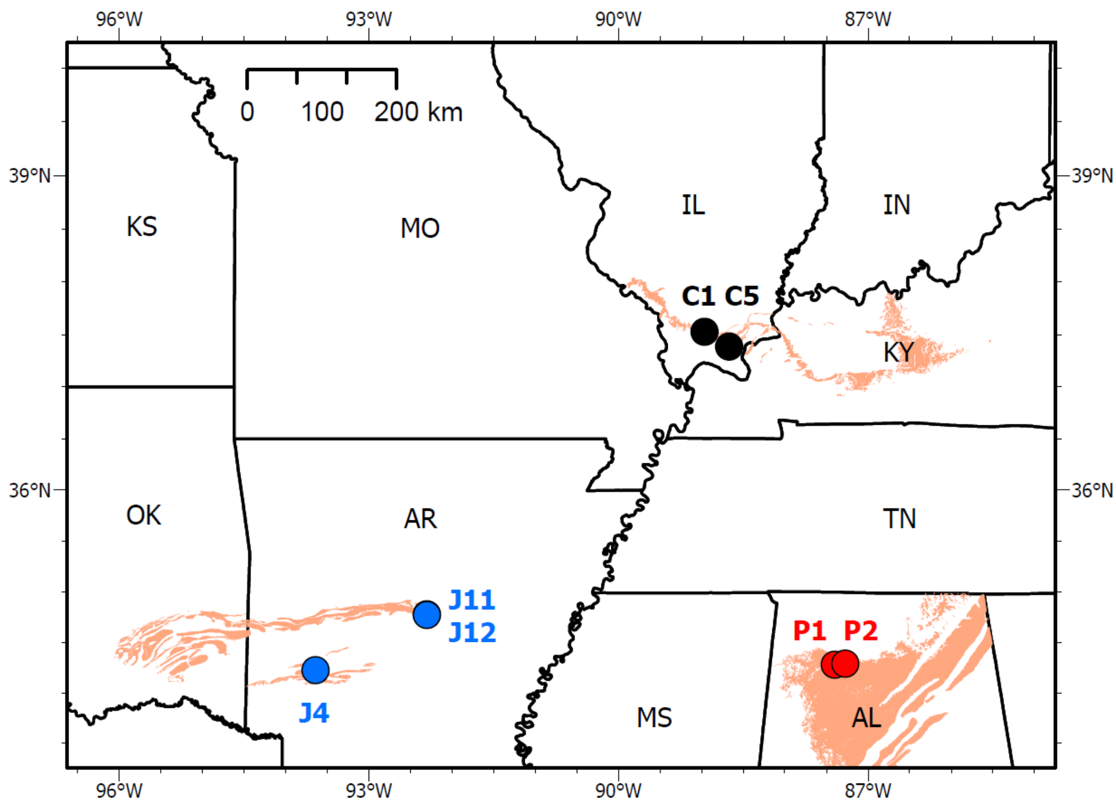
TABLE 2.—*Comparison of εHf values for 833–317 Ma grains from Lower Pennsylvanian samples. εHf values are from this study, Thomas et al. (2017), Thomas et al. (2020), Thomas et al. (2021), and Allred and Blum (2021). Only one εHf value of Alleghenian age is observed in samples Oh-1-SS and J1. CB—Corbin; CK—Caseyville, Kyrock; CV—Caseyville; GN—Norton/Grundy; HC—Hale, Cane Hill; L—Lower; OB—Ouachita Basin; no.—number; SS—Sharon; U—Upper.*

Basin and	330-317 Ma		499-350 Ma				833-500 Ma				All Ages (833-317 Ma)			
sample no.	Value	Error (1σ)	# Grains	Range	Mean	Error (1σ)	# Grains	Range	Mean	Error (1σ)	# Grains	Range	Mean	Error (1σ)
Black Warrior														
P2, Pottsville			21	+11.2 to -19.8	-2.6	0.8	7	-0.4 to -8.2	-4.6	0.8	28	+11.2 to -19.8	-3.1	0.8
Appalachian														
KY-18-CB			10	+10.4 to -12.3	-1.1	1.4	1	+3.6	+3.6	1.2	11	+10.4 to -12.3	-0.7	1.4
OH-1-SS	-5.5	1.0	21	+5.1 to -7.7	-0.3	1.1	9	+7.1 to -11.5	-1.0	1.2	31	+7.1 to -11.5	-0.7	1.1
VA-1-GN			7	+5.2 to -1.6	0.8	1.1	4	+2.8 to -8.7	-2.5	1.6	11	+5.2 to -8.7	-0.4	1.3
Illinois														
KY-4-CV			15	+5.8 to -20.9	-2.8	1.0	2	0.7	0.7	1.4	17	+5.8 to -20.9	-2.4	1.0
KY-15-CK			18	+9.1 to -18.7	-1.3	1.0	4	+1.6 to -3.3	-1.2	0.9	22	+9.1 to -18.7	-1.3	1.0
Arkoma														
AR-2-HC			33	+10.0 to -19.2	-3.4	1.0	5	+6.4 to -10.1	-0.1	1.0	38	+10.0 to -19.2	-2.9	1.0
DeGray (OB)														
J1, U Jackfork	+0.3	0.8	20	+12.4 to -9.7	-0.6	0.9	5	+3.9 to -2.8	+0.4	0.9	26	+12.4 to -9.7	-0.3	0.9
Kirby (OB)														
J10, Johns Valley			18	+8.1 to -11.7	-2.7	1.0	5	+5.3 to -10.8	-5.1	1.1	23	+8.1 to -11.7	-3.2	1.0
J8, U Jackfork			18	+3.4 to -19.3	-2.7	1.1	8	+3.9 to -17.0	-3.1	0.9	26	+3.9 to -19.3	-2.9	1.0
J4, L Jackfork			21	+7.0 to -14.0	-1.3	1.1	7	+6.4 to -9.2	-3.1	1.0	28	+7.0 to -14.0	-1.7	1.1

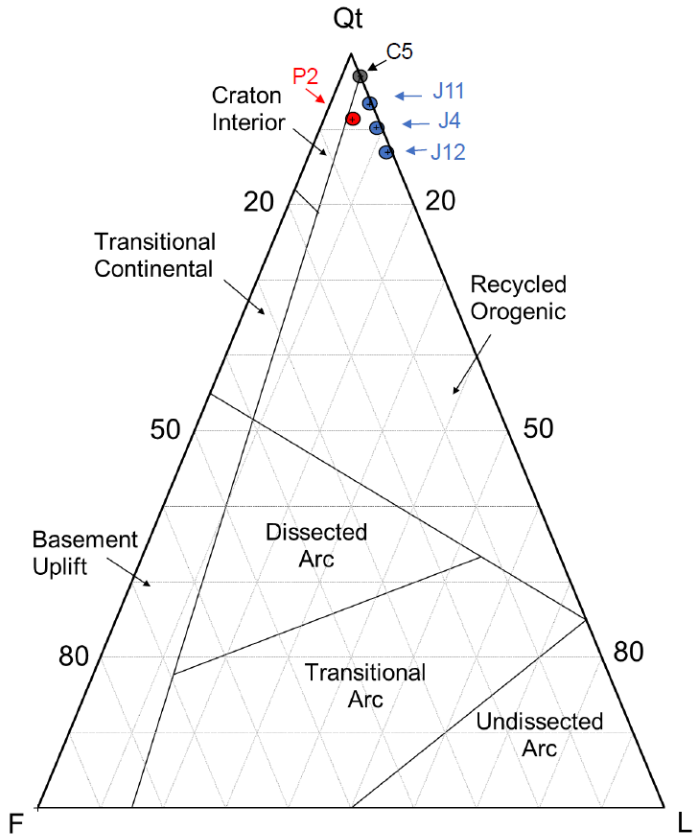
TABLE 3.—*Summary of petrographic modal analysis. Samples J4, J11, and J12 were originally studied for detrital zircon U-Pb analysis in Allred and Blum (2021). * indicates sandstone (rock) type, Folks Classification, 1974. b—basal; u—upper.*

Sample	C5	P2	J4	J11	J12
Basin	Illinois	Black Warrior	Ouachita	Ouachita	Ouachita
Location	Dixon Springs	Brushy Creek	Kirby	Big Rock Quarry	Big Rock Quarry
Formation or Group	Caseyville (b)	Pottsville (b)	Jackfork (b)	Jackfork (u)	Jackfork (u)
Sandstone Type (original deposition)*	Quartz Arenite	Sublitharenite	Sublitharenite	Sublitharenite	Sublitharenite
Grain Size Designation (framework grains only)	medium	medium	medium lower/ fine upper	fine	fine
Average Size (mm)	0.300	0.251	0.280/0.110	0.240	0.150
Sorting (Framework, no matrix)	well	well	poor (bimodal)	moderate	moderately well
Contains Fe-Stained Clays (yes/no)	yes	yes	yes	yes	no
Normalized Framework Composition (%)†					
Quartz	97.03	88.00	84.23	91.21	84.67
Feldspar	0	5.60	0.77	0.73	1.00
Lithic Fragments	2.97	6.40	15.00	8.06	14.33
Total Framework Composition (Vol. %)					
Total Detrital Quartz	64.66	62.64	66.67	71.55	68.49
Monocrystalline	62.93	62.36	63.89	66.57	64.38
Polycrystalline	1.72	0.29	2.78	4.99	4.11
Total Detrital Feldspar	0	2.87	0.62	0.29	0.55
K-Feldspar	0	2.01	0	0	0
Plagioclase	0	0.86	0.62	0.29	0.55
Total Detrital Lithics	2.59	4.89	10.8	9.38	12.60
Shale	0	0.29	1.54	1.17	4.38
Sandstone/Siltstone	0	1.44	0.93	0.29	0.82
Chert	0.29	0.29	1.85	2.05	0.82
Unidentified Silicied Argillaceous	0.29	0.29	1.23	0.29	1.10
Micaceous	0.29	1.44	2.16	2.35	1.92
Metamorphic/Quartzite	1.15	0.57	0.93	1.47	1.10
Metamorphic/Other	0.29	0.57	1.85	1.76	1.64
Volcanic	0.29	0	0.31	0	0.27
Argillaceous Matrix (organics common)	2.59	4.02	5.86	4.69	6.03
Total Authigenic Minerals	13.51	7.18	5.56	6.74	7.95
Total Mineral/Organic Cement	12.64	6.32	5.56	6.45	6.03
Quartz cement	10.92	6.03	5.56	6.45	4.66
Carbonate cement	0	0	0	0	1.37
Clay pore fill	1.72	0.29	0	0	0
Total Mineral Fracture Fill (e.g., quartz)	0.29	0	0	0.29	0.55
Total Mineral Replacement	0.57	0.86	0	0	1.37
Carbonate	0	0	0	0	1.10
Clay	0.57	0.86	0	0	0
Pyrite	0	0	0	0	0.27
Total Thin Section Porosity	16.09	18.39	8.95	2.93	3.01
Intergranular	12.64	11.49	2.47	0.88	0.27
Intragranular	2.01	4.6	6.17	1.76	2.74

Supplemental Materials



Supplemental Material Figure A. Map of detrital zircon (DZ) and petrographic sample locations and outcrops (coral) of the Caseyville Formation (C1 and C5, IL), Pottsville Formation (P1 and P2, AL), and Jackfork Group (J4, J11, and J12, AR). Outcrop data for the three units obtained from https://mrdata.usgs.gov/geology/state/.



Supplemental Material Figure B. Ternary Qt-F-L diagram for samples from the Lower Penn. Caseyville Fm. (C5, IL), Pottsville Fm. (P2, AL), and Jackfork Group (J4, J11, and J12, AR).

Table S1: DZ U-Pb Isotopic Data

Table S2: DZ Hf Isotopic Data

Table S3: Petrographic Data

Table S4: MDS Sample Key

Table S5: Sources for DZ Age Groups

Table S6: DZ Percentage per Age Group

See Appendix for supplemental files S1-S6

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Chapter 4: There and Back Again: Recycling of the Appalachian Signature in DZ U-Pb Records of Phanerozoic North America

Isaac Allred[1, 2], Mike Blum[1], Bruce Frederick[1]

[1]Earth, Energy & Environment Center, University of Kansas, Lawrence, KS 66045
[2]Indiana Geological and Water Survey, Indiana University, Bloomington, IN 47405

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Abstract

The detrital zircon (DZ) U-Pb signature of the Appalachian-Ouachita orogenic system, which includes the Grenville (1250–950 Ma) and Appalachian (500–275 Ma) age groups, dominates the Phanerozoic record of North America. This study presents a comparison of Pennsylvanian to modern DZ samples across North America and demonstrates a persistent Appalachian signature in samples, including a recycled Appalachian signature in the West. Lower Pennsylvanian deposits proximal to the Appalachian orogen are composed of 50–75% Appalachian- and Grenville-age DZ, representing the key component in the primary Appalachian signature. It remains unclear how the Appalachian signal was propagated to the West, but Appalachian-age DZ observed in Carboniferous western Laurentian strata may have been derived from the northern Appalachians in the US and Canada or the Ellesmerian orogen.

Triassic DZ samples document transcontinental fluvial systems that reached the western Laurentian margin, but subsequent Jurassic-Cretaceous samples indicate drainage reversal due to the rise of the Mesozoic Western Cordillera. A persistent Appalachian signature exists in these western-sourced, eastward-flowing systems—a phenomenon that continues to the present: samples are frequently composed of >40% Appalachian- and Grenville-age DZ. However, none of these systems are interpreted to be sourced by primary Appalachian or Grenville terranes, suggesting a recycled Appalachian signature. The persistent Appalachian signature, originally sourced by the concatenation of two supercontinent-forming orogenic terranes, continues to be the dominant contributor in the DZ record of North America.

Introduction

Appalachian-derived detrital zircons with U-Pb ages from ca. 1300–275 Ma accumulated along the western Laurentian margin in the US during the Late Paleozoic and Early Mesozoic (Gehrels et al., 2011; May et al., 2013; Leary et al., 2020; Lawton et al., 2021). Then, following development of the Mesozoic Western Cordillera (hereafter MWC), this "Appalachian signature" (sensu Thomas et al., 2017) was recycled and transported back to the east, where it became an important component in the DZ U-Pb provenance and geochronological record of the US Western Interior foreland basin (Laskowski et al., 2013; Dickinson, 2018). Here we examine DZ U-Pb age distributions from Pennsylvanian to modern stratigraphic units across North America to illustrate the broader transcontinental scale and trajectory of the recycled Appalachian signature. We argue this broader trajectory reflects major continental- to regional-scale tectonic and geodynamic events, and has dominated the record of sediment dispersal to Mesozoic and Cenozoic basins across North America.

Routing of the Appalachian Signal to the Western Laurentian Margin

The western Laurentian passive margin of southern North America was an active depocenter from the Neoproterozoic through the Early Jurassic (Stewart and Suczek, 1977). DZ U-Pb data from the Grand Canyon in Arizona, the Big Horn Basin in Wyoming and elsewhere show that pre-Mississippian strata were generally derived from the Paleoproterozoic Great Plains orogens (Yavapai-Mazatzal and Midcontinent granite-rhyolite provinces, ca. 1800–1600 Ma and 1550–1300 Ma, respectively) of the midcontinental and southwestern US (Fig. 1), and

Mesoproterozoic Grenville sources that represent assembly of the supercontinent Rodinia (Gehrels and Pecha, 2014). DZ U-Pb ages from the Grenville orogen (Moecher and Samson, 2006) record several stages of orogenesis in eastern and southern Laurentia, and span the period ca. 1300–950 Ma. Grenville zircons first reached the western Laurentian margin of the US during the Neoproterozoic, and had been dispersed across Laurentia from the present-day Arctic to the SW US by the Early Paleozoic (e.g., Rainbird et al., 1997; Dehler et al., 2010; Spencer et al., 2012; 2015; Mulder et al., 2017; Rainbird et al., 2017).

The Appalachian cordillera extends >5000 km from eastern Canada to West Texas and northern Mexico (Thomas, 2006; Hatcher, 2010), and formed after Neoproterozoic rifting of the post-Grenville Iapetus Ocean. Arc magmatism was common in the Ordovician Taconic (ca. 480–440 Ma) and Devonian to Mississippian Acadian phases (ca. 400–350 Ma), whereas the Mississippian through early Permian (ca. 320–275 Ma) witnessed the formation of the Alleghenian and Ouachita-Marathon collisional belts on Laurentia and magmatic arcs on Gondwana during the assembly of Pangea. The provincial "Appalachian" DZ U-Pb signature initially accumulated in clastic wedges of the Appalachian foredeep, and represents the integrated record of sediment sources within the Appalachian cordillera (sensu Lawton et al., 2021). This signature is dominated by what we refer to as the APG age group, composed of Paleozoic DZ U-Pb age groups that reflect the different phases of Appalachian orogenesis (10–15% of the total sample DZ), small (<5%) contributions from Neoproterozoic and Cambrian peri-Gondwanan terranes (ca. 850–510 Ma) that accreted to, or formed in, eastern and southern Laurentia prior to and during the assembly of Pangea, and Mesoproterozoic age groups that reflect erosion of Grenville inliers within the Appalachians (40–60% of the total) (e.g., Hibbard and Karabinos, 2013; Thomas et al., 2017).

Isotopic and DZ U-Pb data show that Appalachian-derived detritus reached western Laurentia by ca. 450 Ma (Patchett et al., 1999; Gehrels et al., 2011; May et al., 2013; Gehrels and Pecha, 2014; Gehrels et al., 2020; Leary et al., 2020; Lawton et al., 2021; Saylor and Sundell, 2021). On the initial stages of the journey west the provincial Appalachian signature, dominated by the APG age group, became increasingly cosmopolitan. For example, during the Carboniferous, the provincial Appalachian signature was initially diluted by contributions from the Paleoproterozoic Great Plains orogens that most likely represent recycling of sediments from Paleozoic rocks of the northern US (see Kissock et al., 2018; Allred and Blum, 2021). This diluted signal accumulated in backbulge and peripheral parts of the foreland-basin system, as well as the synorogenic Ouachita deepwater trough. The latter is especially important because collision during the Latest Pennsylvanian and Permian assembly of Pangea also resulted in transformation of the Ouachita deepwater sink into the Ouachita fold-and-thrust-belt source.

Although it is clear the Appalachian signature was transported to western Laurentia during the Carboniferous, the sediment-routing systems that transferred this signal remain poorly defined through the Permian (see Thomas, 2011). Chapman and Laskowski (2019) suggest that longshore drift along the southern Laurentian margin played a significant role. However, Allred and Blum (2021) consider it unlikely that sediment was routed directly to the West from the central and southern Appalachians since much of the eastern US drained to the Ouachita deep-water trough during sea-level lowstands, much of the midcontinent was flooded and dominated by carbonates during sea-level highstands, and the Ancestral Rocky Mountains represented a significant barrier to westward transport. An alternative view by Leary et al. (2020) suggests that part of the APG age group that populates the western Laurentian margin may have been derived from the northern Appalachians in the US and Canada, and perhaps as far north as the Pangean Ellesmerian and Caledonian orogenies of present-day Arctic Canada and parts of Greenland (Trettin et al., 1991; Beranek et al., 2010) (Fig. 1). Leary et al. (2020) further argue this long-distance transfer may have occurred via transcontinental fluvial systems that have not yet been identified, and/or via north-to-south longshore drift along the western margin.

Breakup of Pangea during the Late Paleozoic to Early Mesozoic resulted in opening of a new rift basin that would later evolve to become the passive margin Gulf of Mexico (GoM) (Filina et al., 2022). Frederick et al. (2020) show the Late Triassic synrift Eagle Mills Formation represented deposition within an internally drained basin, with the provincial Appalachian signature dominating the northern and western extent of the rift system (Fig. 2 and 3). Farther west, however, DZ U-Pb data from the contemporaneous Late Triassic Chinle Formation in the US western interior fingerprints a transcontinental fluvial system that routed the Appalachian signature to the western Laurentian margin (Dickinson and Gehrels, 2008, 2010; Gehrels and Pecha, 2014; Umbarger, 2018; Gehrels et al., 2020). Along the way, the primary Appalachian signature was further diluted by the Paleoproterozoic Great Plains orogens age groups, first from recycling sedimentary rocks of the Ouachita-Marathon collision belts, and then directly from the Mogollon highlands of central Arizona. The Chinle also has a significant ca. 275–200 Ma age group derived from the early Western Cordillera magmatic arc (Gehrels et al., 2020).

Eastward Return and Recycling of the Appalachian Signature

The provincial Appalachian signature still characterizes DZ U-Pb records for river systems discharging to the eastern Gulf of Mexico from the Jurassic to the present day. However, in the western US, development of the MWC resulted in uplift and incorporation of western Laurentian passive-margin strata into the eastward-propagating Sevier fold and thrust belt (Fuentes et al., 2009; LaMaskin, 2012; May et al., 2013), and formation of the retroarc Sevier foreland-basin system (DeCelles, 2004). By the middle Jurassic, river systems in the west were flowing generally eastward: this large-scale reversal of flow for river systems in the western US was the first stage in development of the modern template for North America sediment routing, and in the transport of a recycled and more cosmopolitan Appalachian signature back to the east. This recycled signature included additional contributions from the Paleoproterozoic Great Plains orogens exposed in the SW US, and volcanogenic zircon grains of Jurassic age from the MWC magmatic arc, which collectively represent the fingerprints that define this change in source and transport direction.

Through the Early Cretaceous, this cosmopolitan recycled Appalachian signature was sequestered within Sevier foreland-basin strata in the US (Laskowski et al., 2013; Dickinson, 2018), and/or merged with east-derived sediment characterized by the primary Appalachian signature within the US midcontinent, and was then routed north to the Alberta part of the foreland-basin system and the Boreal Sea (Blum and Pecha, 2014; Wahbi et al., in review). The zenith of this sediment-routing system is represented by the continental-scale river system that deposited the Aptian McMurray Fm and other members of the Early Cretaceous Mannville clastic wedge, which host the Alberta Oil Sands. In the Albian, the Western Interior Seaway then expanded in the north-south direction, connecting the Boreal Sea to the Gulf of Mexico, which disrupted the convergence of west- and east-derived tributary systems. During this time, Cenomanian fluvial systems of the Dakota group delivered a cosmopolitan recycled APG age group to the western shoreline of the seaway in Wyoming, Colorado, and New Mexico, and a provincial primary APG age group to the eastern shoreline, which extended from South Dakota to Texas (Nazworth, 2019). However, prior to the latest Cretaceous, the GoM drainage area was restricted to the southeastern US, south of the Appalachian and Ouachita collision belts. To the east of the Mississippi embayment, the DZ U-Pb record is dominated by the provincial Appalachian signature, whereas to the west, the DZ U-Pb record is slightly more cosmopolitan because sediment was derived from erosion of the Ouachita fold and thrust belt, which represents sediments initially deposited in the Ouachita deepwater trough that included recycled sediments from Paleozoic sedimentary rocks of the northern US (Blum et al., 2017).

Beginning in the Late Cretaceous, the Sevier foreland basin in the US was undergoing Laramide deformation, but Late Cretaceous to Early Paleocene fluvial systems with headwaters in the fold and thrust belt continued to flow eastward into and through evolving Laramide topography to the western shore of the Western Interior Seaway. With withdrawal of the seaway, Sevier and Laramide-derived rivers flowed east and south, directly to the western GoM in Texas, or continued eastward to join an ancestral Mississippi River and its Appalachian-derived tributaries within the Mississippi embayment (Blum et al., 2017). DZ U-Pb data from the Paleocene Wilcox Group, which extends across the Gulf of Mexico coastal plain from Texas to Alabama, show two dominant sediment-routing systems. The western GoM was fed by a large fluvial system that drained the SW US: the cosmopolitan DZ U-Pb age distribution includes a small recycled APG age group, but is dominated by the Western Cordillera magmatic arc and Great Plains orogens age groups. Farther east within the Mississippi embayment, a west-derived and east-derived tributary network converged to form an ancestral Mississippi River. West-derived tributaries of this ancestral Mississippi River had headwaters that extended into and beyond the central and northern Rocky Mountains, and delivered sediments with a cosmopolitan recycled

APG age group to the Mississippi embayment and central GoM, where it comprises ~58% of the total age distribution, with the remainder dominated by zircons from the magmatic arc and Great Plains orogens age groups, which comprise ~10% and ~17%, respectively. East-derived tributaries delivered sediment with the provincial Appalachian signature and primary APG age group to the Mississippi embayment (~82% of the total; Fig. 3).

Headwaters of the Paleocene fluvial system that delivered sediment from the SW US to the western GoM were tectonically dismembered by the Oligocene, and the southwestern extent of GoM drainage was thereafter restricted to the southern Rockies in Colorado, New Mexico, and northern Mexico (Blum et al., 2017). However, DZ U-Pb data from Oligocene and Miocene strata show the pattern of convergence of west- vs. east-derived river systems within lowlands of the central US and the the Mississippi embayment continued (Blum et al., 2017; Xu et al., 2017). Moving forward in time, samples of Plio-Pleistocene age from the Mississippi embayment reflect this convergence as well. Samples from the western lower Mississippi valley margins in Missouri and Arkansas show a cosmopolitan DZ U-Pb signature, where the recycled APG age group comprises ~60% of the total, the Great Plains orogens age group comprises 20–25%, and the Western Cordillera magmatic arc age group comprises ~15–18%. By contrast, samples from the eastern valley margin in Illinois and Kentucky are dominated by the provincial primary APG age group, which comprises 78% of the total, contributions from the Great Plains orogens comprise <10% of the total, and there is no contribution from the MWC magmatic arc.

The modern Mississippi Valley also shows mixing of western and eastern signatures (Blum et al., 2017). DZ U-Pb data from the Rocky-Mountain-sourced Missouri, Platte, Kansas, and Arkansas Rivers, which provide most of the sediment load for the lower Mississippi River

(Meade and Moody, 2010), have a cosmopolitan age distribution that includes the recycled APG age group (~30% of the total), as well as contributions from the Great Plains orogens (~15–20%) and the Western Cordillera magmatic arc (~18% of the total) age groups. Contributions from the Great Plains orogens were likely augmented by erosion of basement rocks exposed in the Laramide Rockies, but Missouri River sediment supply is known to be dominated by erosion and recycling of Sevier foreland-basin strata (Meade and Moody, 2010), such that each of the contributing DZ U-Pb age groups in the Missouri system are likely recycled from older sedimentary rocks. By contrast, samples from the Ohio-Tennessee River system are exclusively dominated by the provincial Appalachian signature, derived directly from the Appalachians or by recycling in the Appalachian foreland-basin system (Fig. 3 and 4).

Discussion and Conclusions

The provincial Appalachian DZ U-Pb signature reflects the integrated contributions of sediment from the Appalachian cordillera (Fig. 3) and dominates the provenance of the Appalachian foreland-basin system and the associated Ouachita deepwater trough. Moreover, this signature was dispersed more broadly across North America during the late Paleozoic through middle Mesozoic where it became an important component of the Western Laurentian passive margin. Today, some 350 Myrs after the Appalachian signature commenced its journey to the west, 70–85% of the DZ U-Pb ages in modern rivers that drain the Appalachians still belong to the provincial APG age group.

By the middle-late Jurassic, ca. ~160 Ma, development of the MWC resulted in uplift of Western Laurentian margin strata, incorporation of sandstones containing the Appalachian signature into the eastward-migrating Sevier fold and thrust belt, and the initiation of eastward-flowing river systems. The APG age group was then recycled, diluted with contributions from the Paleoproterozoic Great Plains orogens and the Western Cordillera magmatic arc, and a very cosmopolitan DZ U-Pb signature was transported back to the east by rivers systems within the Sevier foreland-basin system. Today, some 150 Myrs after the recycled APG age group began making its way back to the east, the lower Mississippi River delivers a mixture of the recycled and primary APG age groups to the Gulf of Mexico, which collectively represent ~40% of the total DZ U-Pb age distribution.

The modern provenance fingerprint for the Mississippi River and Gulf of Mexico basin therefore reflects a convergence of primary and recycled sources that include sediments produced during the Nuna, Rodinia and Pangea supercontinent cycles, as well as the most recent orogenic system in western North America. The journey back to the east resulted in the Appalachian DZ U-Pb signature, and presumably Appalachian-sourced sediment, comprising important constituents in major Mesozoic and Cenozoic North American depocenters, including the middle Jurassic through Late Cretaceous Sevier foreland basin in the western US, the Cretaceous foreland-basin phase of the Western Canadian Sedimentary Basin, and the Late Cretaceous through Cenozoic Gulf of Mexico passive margin. Eastward propagation of the recycled APG age group took place in a stepwise manner that reflects major tectonic and geodynamic changes, as follows:

(1) During the middle to late Jurassic through Late Cretaceous, the recycled APG age group was dispersed by east-flowing rivers throughout the Sevier foreland-basin fill in the US.

Jurassic-Cretaceous Morrison, Lytle, and Dakota samples display APG characteristics, including a bimodal Grenville signature (Fig. 3). These samples also demonstrate a relatively high percentage of peri-Gondwanan-ages, a Mesozoic-long, western tendency that suddenly began in the Permian (Gehrels et al., 2011; Liu and Stockli, 2019), decreased during the Cretaceous, and abruptly ended in the Cenozoic (Fig. 3 and 4).

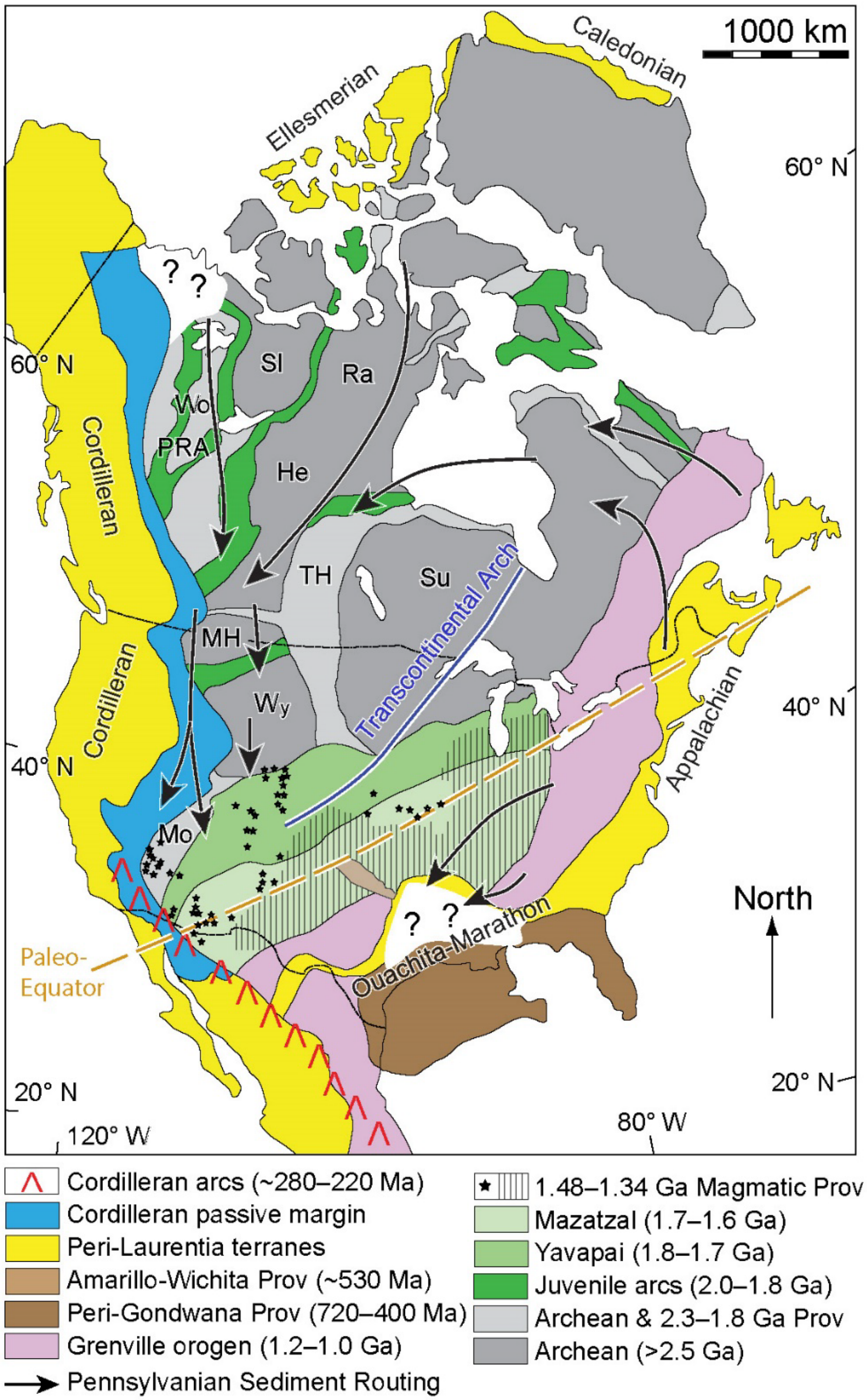
(2) During the Early Cretaceous, the foreland-basin system was not generally flooded by the Western Interior Seaway. Hence the recycled APG age group, derived from the west, converged with the primary APG age group supplied by Appalachian-sourced rivers flowing from the east, and routed sediments to the Western Canadian Sedimentary Basin. The foreland-basin system coincided with an axis of dynamic subsidence that has been inferred to have migrated eastward across the central US in the wake of flat-slab subduction along the western margin (Liu, 2015; Wang et al., 2020).

(3) From the Albian through the Late Cretaceous, the Western Interior Seaway flooded, facilitated by both Sevier fold and thrust belt loading and dynamic subsidence (Liu et al., 2011; 2014). During times when the Seaway was at its greatest extent, the recycled APG was delivered only to the western shoreline, and the primary APG was sequestered along the eastern shoreline (Fig. 2, 3, and 4).

(4) With withdrawal of the Seaway in the latest Cretaceous and early Paleocene, and the proposed evolution of mantle-driven dynamic topography, major river systems were steered southward to the Cenozoic GoM passive margin (Liu, 2015; Wang et al., 2020).

Late Cretaceous to Paleocene drainage reorganization produced the modern template for sediment routing to the GoM as the primary depocenter for the eastern 3/4ths of southern North America. There is no more routing of Appalachian-sourced sediment to the West, but the recycled Appalachian signal delivered from the west is generally more significant than the Western Cordillera DZ U-Pb signature per se. We suggest the longevity and magnitude of the Appalachian signature throughout the Phanerozoic is due to the crustal concatenation of supercontinent-cycle provincial terranes and argue that the primary and recycled Appalachian-Grenville DZ U-Pb age groups are the most important components of North American sediment routing throughout the Phanerozoic.

Figures



1000 km
Caledonian
Ellesmerian
60° N
? ?
60° N
Sl
Ra
Wo
PRA
He
Cordilleran
TH
Su
Transcontinental Arch
MH
Wy
Cordilleran
40° N
40° N
Appalachian
Mo
North
? ?
Ouachita-Marathon
Paleo-Equator
20° N
20° N
120° W
80° W
Cordilleran arcs (~280–220 Ma)
Cordilleran passive margin
Peri-Laurentia terranes
Amarillo-Wichita Prov (~530 Ma)
Peri-Gondwana Prov (720–400 Ma)
Grenville orogen (1.2–1.0 Ga)
Pennsylvanian Sediment Routing
1.48–1.34 Ga Magmatic Prov
Mazatzal (1.7–1.6 Ga)
Yavapai (1.8–1.7 Ga)
Juvenile arcs (2.0–1.8 Ga)
Archean & 2.3–1.8 Ga Prov
Archean (>2.5 Ga)

Figure 1. Continental-scale sediment routing interpretations for Middle Pennsylvanian time based on Embry (1988), Peterson (1988), Patchett et al. (1999), Beranek et al. (2010), Gottlieb et al. (2014), Lawton et al. (2015), and Leary et al. (2020). Basemap of North American basement age provinces adapted and modified from Hoffman et al. (1989), Whitmeyer and Karlstrom (2007), Gehrels et al. (2011), Gehrels and Pecha (2014), and Leary et al. (2020). He—Hearne province; MH—Medicine Hat province; Mo—Mojave province; PRA—Peace River Arch region; Ra—Rae province; Sl—Slave province; Su—Superior province; TH—Trans-Hudson province; Wo—Wopmay province; Wy—Wyoming province.

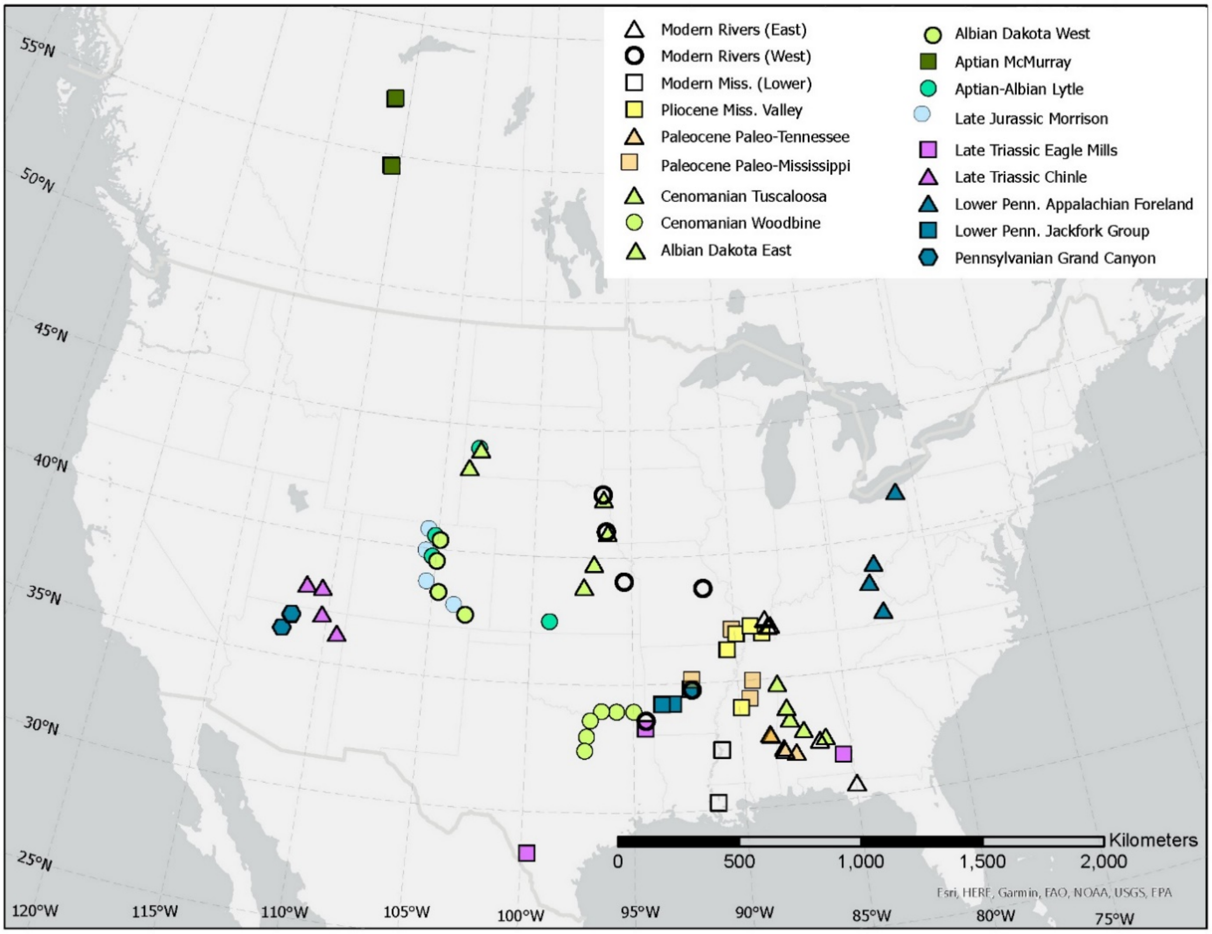


Figure 2. Map of North America showing DZ samples that exemplify the late Paleozoic-early Mesozoic westward propagation of the Appalachian signature and the subsequent return to the East. Dark Blue — Pennsylvanian; Purple — Triassic; Light Blue — Jurassic; Green — Cretaceous; Orange— Paleocene; Yellow — Pliocene; Black open circle — modern. General affiliation: Northern-derived—octagon; eastern-derived — triangle; mixed and/or central — square; western-derived — circle. See appendix for location information and references.

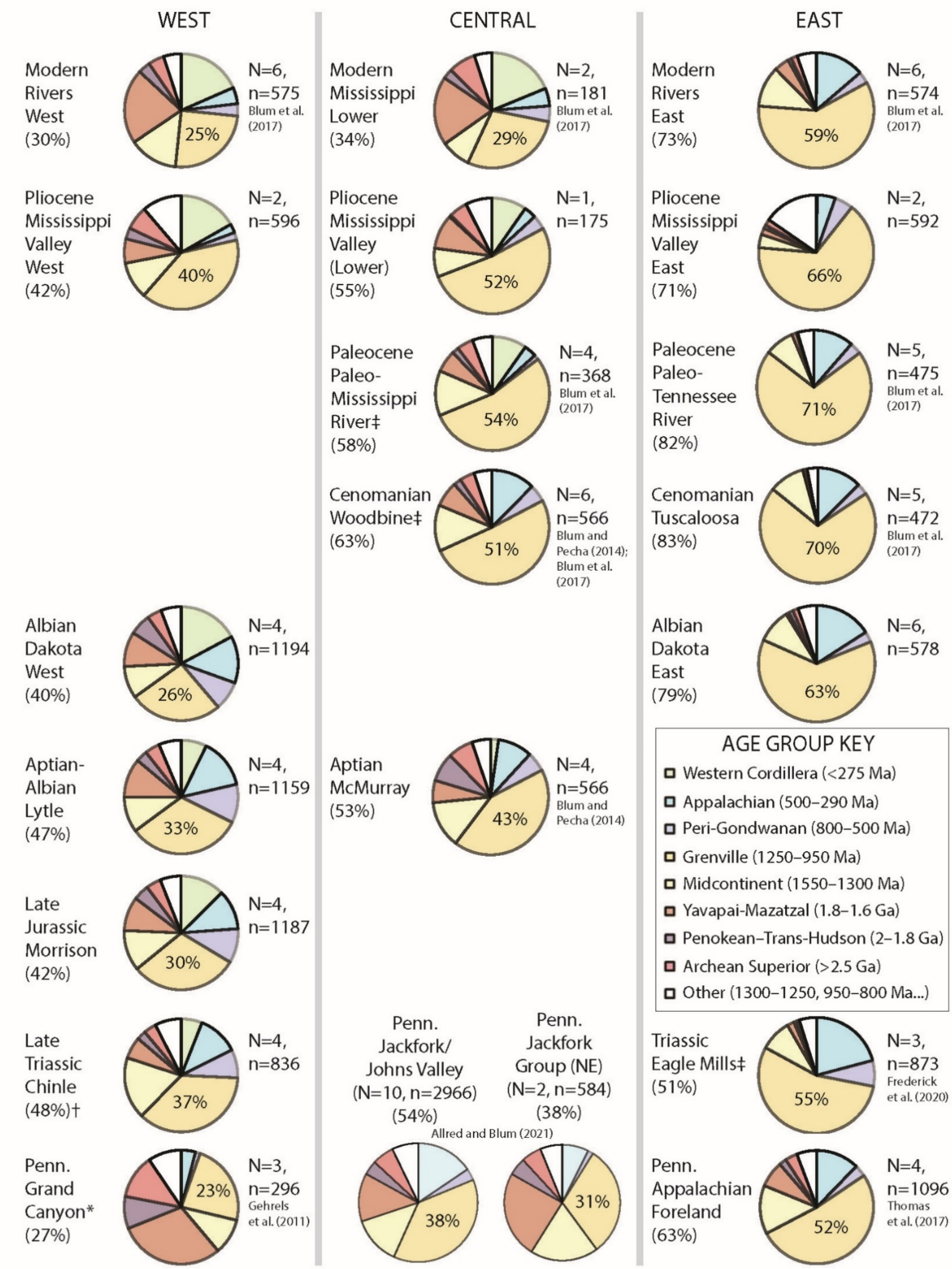
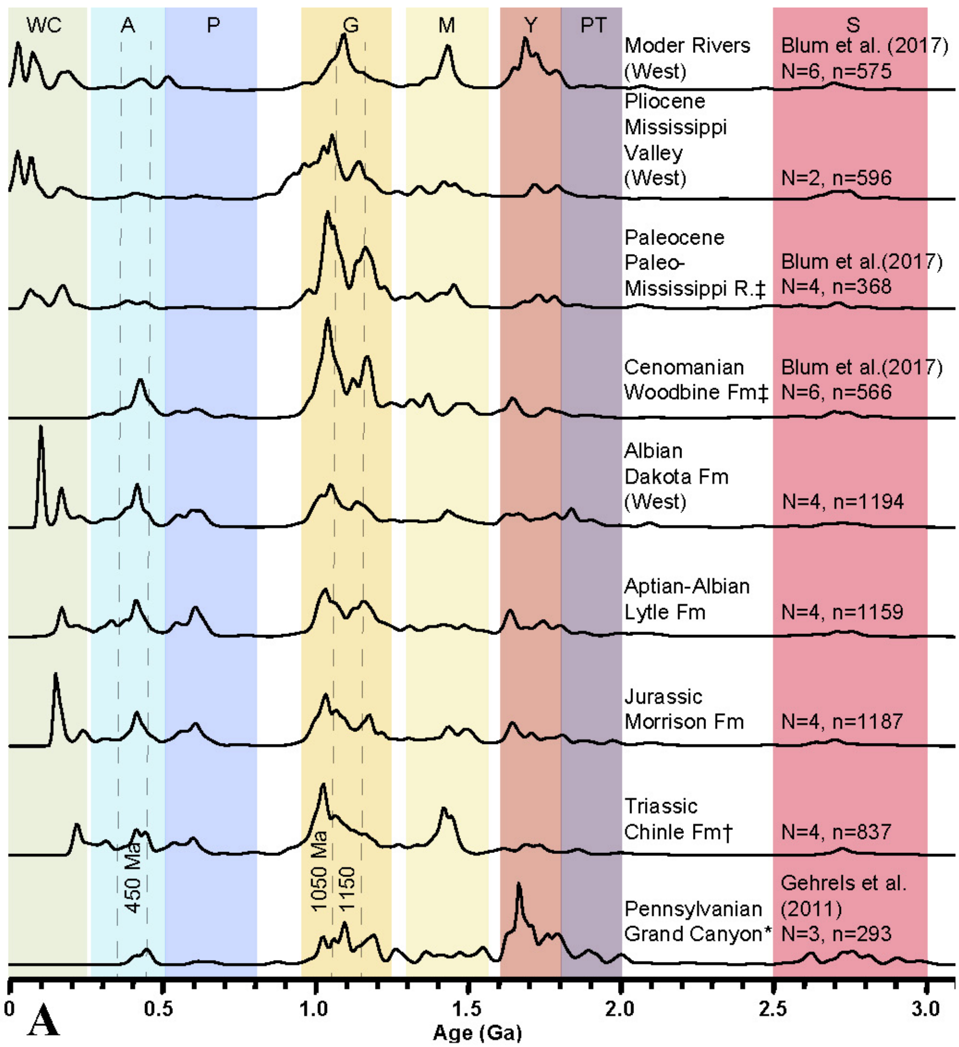

WEST
CENTRAL
EAST
Modern Rivers West (30%)
N=6, n=575 Blum et al. (2017)
25%
Modern Mississippi Lower (34%)
N=2, n=181 Blum et al. (2017)
29%
Modern Rivers East (73%)
N=6, n=574 Blum et al. (2017)
59%
Pliocene Mississippi Valley West (42%)
N=2, n=596
40%
Pliocene Mississippi Valley (Lower) (55%)
N=1, n=175
52%
Pliocene Mississippi Valley East (71%)
N=2, n=592
66%
Paleocene Paleo-Mississippi River‡ (58%)
N=4, n=368 Blum et al. (2017)
54%
Paleocene Paleo-Tennessee River (82%)
N=5, n=475 Blum et al. (2017)
71%
Cenomanian Woodbine‡ (63%)
N=6, n=566 Blum and Pecha (2014); Blum et al. (2017)
51%
Cenomanian Tuscaloosa (83%)
N=5, n=472 Blum et al. (2017)
70%
Albian Dakota West (40%)
N=4, n=1194
26%
Albian Dakota East (79%)
N=6, n=578
63%
AGE GROUP KEY
Western Cordillera (<275 Ma)
Appalachian (500–290 Ma)
Peri-Gondwanan (800–500 Ma)
Grenville (1250–950 Ma)
Midcontinent (1550–1300 Ma)
Yavapai-Mazatzal (1.8–1.6 Ga)
Penokean–Trans-Hudson (2–1.8 Ga)
Archean Superior (>2.5 Ga)
Other (1300–1250, 950–800 Ma...)
Aptian-Albian Lytle (47%)
N=4, n=1159
33%
Aptian McMurray (53%)
N=4, n=566 Blum and Pecha (2014)
43%
Late Jurassic Morrison (42%)
N=4, n=1187
30%
Late Triassic Chinle (48%)†
N=4, n=836
37%
Penn. Jackfork/ Johns Valley (N=10, n=2966) (54%)
Penn. Jackfork Group (NE) (N=2, n=584) (38%)
Allred and Blum (2021)
38%
31%
Triassic Eagle Mills‡ (51%)
N=3, n=873 Frederick et al. (2020)
55%
Penn. Grand Canyon* (27%)
N=3, n=296 Gehrels et al. (2011)
23%
Penn. Appalachian Foreland (63%)
N=4, n=1096 Thomas et al. (2017)
52%

Figure 3. Pie charts that show percentages of age groups for units from the Pennsylvanian to the Holocene, arranged by relative geography of North America (West to East). The Central column has samples located in the midcontinent or samples of a mixed provenance; the symbol ‡ denotes samples that may not perfectly fit in this three-column classification. Percentages in parenthesis indicate the Appalachian signature (Grenville + Appalachian) per unit. Grenville percentages labeled on charts. The symbol * denotes western samples that preceded the MWC; † denotes that the average of four Chinle samples, although two samples have Grenville and Appalachian ages representing 59% of the total ages.


WC
A
P
G
M
Y
PT
S
Moder Rivers (West)
Blum et al. (2017) N=6, n=575
Pliocene Mississippi Valley (West)
N=2, n=596
Paleocene Paleo-Mississippi R.‡
Blum et al.(2017) N=4, n=368
Cenomanian Woodbine Fm‡
Blum et al.(2017) N=6, n=566
Albian Dakota Fm (West)
N=4, n=1194
Aptian-Albian Lytle Fm
N=4, n=1159
Jurassic Morrison Fm
N=4, n=1187
Triassic Chinle Fm†
N=4, n=837
450 Ma
1050 Ma
1150
Pennsylvanian Grand Canyon*
Gehrels et al. (2011) N=3, n=293
0
0.5
1.0
1.5
2.0
2.5
3.0
Age (Ga)
A

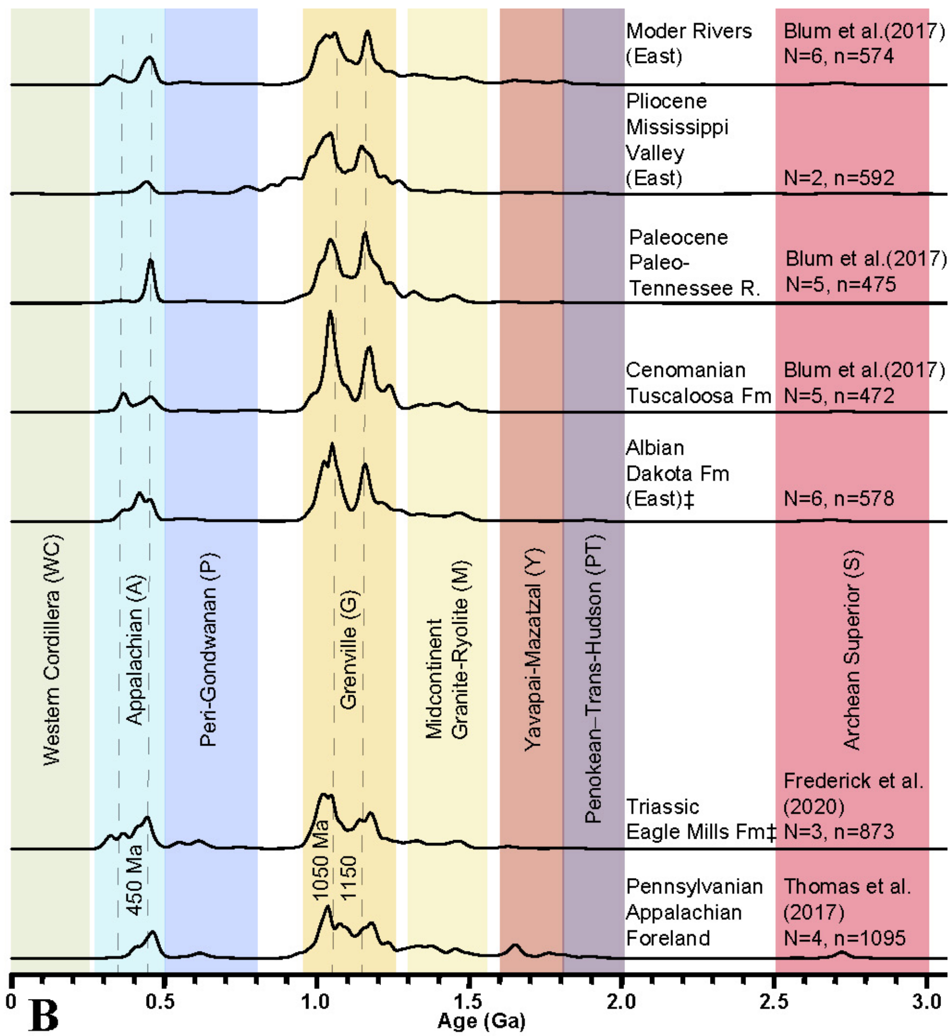
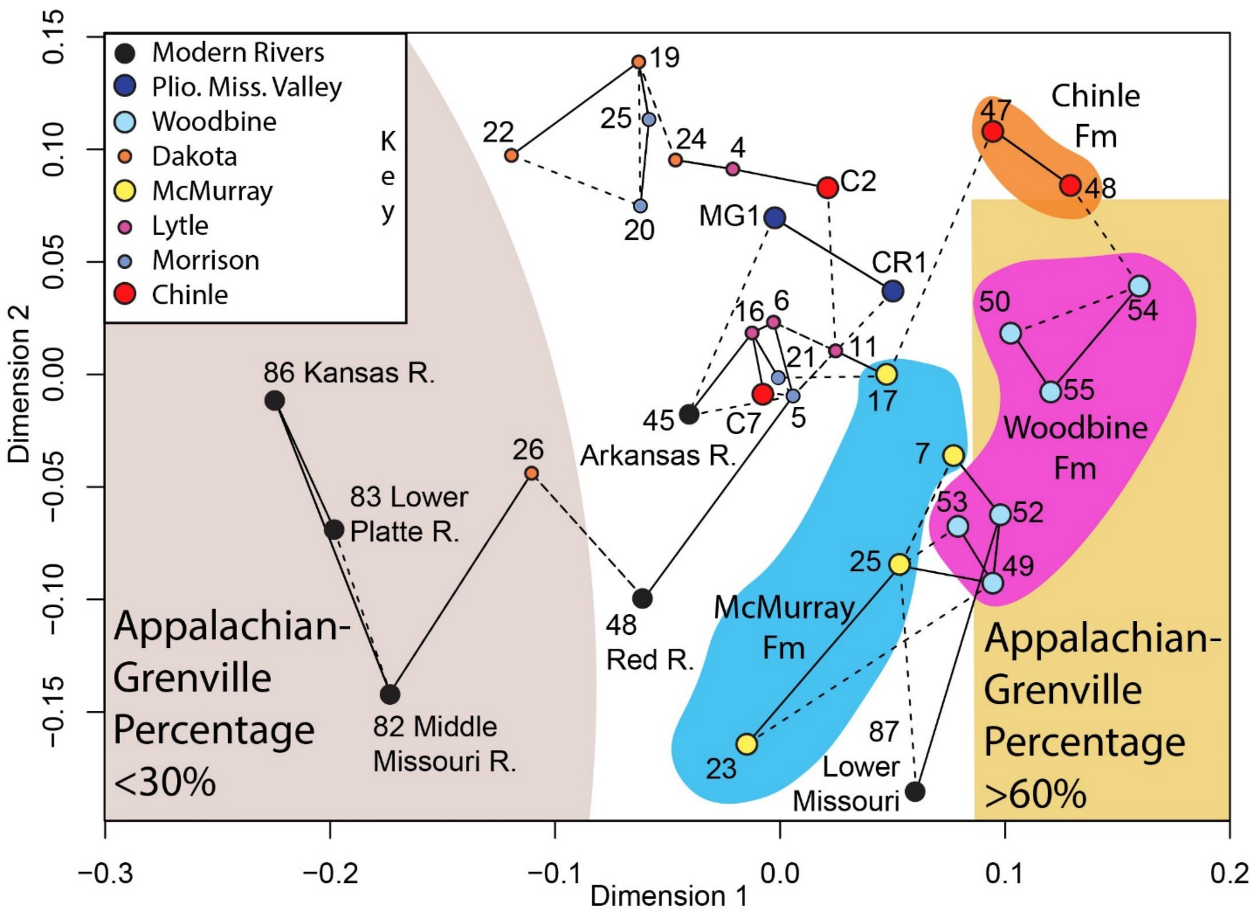


Figure 4. Normalized kernel density estimates (KDE, bandwidth, 10 M.y.) for samples from the West (A) and East (B). Vertical dashed lines at 350, 450, 1050, and 1150 Ma for reference. The symbol * denotes western samples preceding the MWC; the symbol ‡ denotes samples that may not perfectly fit this West-East classification.

Supplemental Materials



Supplemental Material Figure. Multi-dimensional scaling (MDS) plot for select DZ samples from western and central North America, which typifies the recycled Appalachian signature and the primary Appalachian signature. The greater the distance between samples, the more dissimilar samples are. Samples in the orange, blue and bright purple polygons typify the primary Appalachian signature (>60%). Except for the Lower Missouri, all samples to the left of the above-mentioned polygons have the recycled APG signature. The Lower Missouri River sample has an anomalously high percentage of Grenville ages (53%), but a low Appalachian percentage (1%), and plots to the right. Samples from the East are excluded from this plot, all of which typify the primary Appalachian signature.

Table S7: DZ U-Pb Isotopic Data (Chinle, Morrison, Lytle, Dakota)

Table S8: DZ U-Pb Isotopic Data (Rapid Acquisition, Pliocene Mississippi Valley 4 samples)

Table S9: DZ U-Pb Isotopic Data (Rapid Acquisition, Pliocene Mississippi Valley EB-1)

Table S10: DZ and MDS Sample Key

See Appendix for supplemental files S7-S10

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Chapter 5: Summary

Detrital zircons (DZ) are insensitive to chemical alternation during erosion and transport (Vermeesch, 2012), and thus DZ U-Pb analysis is an ideal tool for large-scale provenance studies (Dickinson and Gehrels, 2010). As a result the number of DZ studies has increased exponentially over the last few decades (Gehrels, 2014). As this technique became more widespread, DZ U-Pb provenance analysis has faced criticism regarding the role of DZ recycling in the rock record (e.g., Dickinson et al., 2009; Schwartz et al., 2019). As with any method, DZ must be contextualized with other geological data, yet DZ provenance analysis still provides a quantitative approach to sedimentology.

Concurrently, clastic sedimentology has experienced a paradigm shift from a multi-decadal focus on facies models and sequence stratigraphy to a broader process-based emphasis on quantifying sediment routing and storage within entire source-to-sink systems. Much progress has been made quantifying properties of modern systems (e.g., Syvitski and Milliman, 2007; Sømme et al., 2009; Blum et al., 2013; Romans et al., 2016; Nyberg et al., 2018a; Nyberg et al., 2018b), including quantitative relationships between fluxes and properties within and between different parts of the system, from tectonic highland source terranes to deepwater sinks.

Chapters 2 and 3 demonstrate that DZ provenance analysis dovetails with the source-to-sink approach by elucidating linkages between source areas and sediment sinks. Like studies of late Cenozoic deep-sea fans (e.g., Fildani et al., 2016; Mason et al., 2017; Blum et al., 2018; Mason et al., 2019), which show that DZ from basin-floor fans fingerprint paleodrainage feeder fluvial systems, DZ results from Early Pennsylvanian fluvial and marginal-marine environments of eastern Laurentia (Chapter 3) and deep-sea fans (Chapter 2) also demonstrate fidelity between source-to-sink. The results of this DZ U-Pb provenance analysis of a late Paleozoic fluvial-to-deepwater system indicate that this approach is applicable to other ancient deep-sea fan deposits in other basins.

After the culmination of the Appalachian-Ouachita orogenic system, Appalachian- and Grenville-age DZ were disseminated across Laurentia, dominating the subsequent DZ record of North America. The first Appalachian-age DZ to reach western Laurentia may have been derived from the northern Appalachians in the U.S. and Canada, and perhaps from as far north as the Ellesmerian orogen in northern Canada (Leary et al., 2020), which is in contrast to previously interpreted sources from the southern Appalachians (Gehrels et al., 2011; Chapman and Laskowski, 2019). The results of an east-to-west comparison of DZ samples across North America (Chapter 4) demonstrate a persistent, continent-wide Appalachian signature (composed of a high percentage of Appalachian- and Grenville-age DZ), including a recycled Appalachian signature from samples in western North America. Western samples, representative of west-to-east flowing Jurassic to Holocene rivers, frequently are composed of >40% Appalachian- and Grenville-age DZ, accompanied by western age groups (e.g., Yavapai-Mazatzal and Western Cordillera). The examination of DZ U-Pb data from Pennsylvanian to modern stratigraphic units (Chapter 4) illustrates the broader trajectory of primary and, especially, recycled Appalachian DZ U-Pb signals. This trajectory reflects major tectonic and geodynamic events, and has dominated the stratigraphic record of sediment dispersal to North American Mesozoic and Cenozoic sedimentary basins. The longevity and magnitude of the Appalachian DZ U-Pb signature is attributed to the close affinity of two source terranes formed by supercontinent cycles.

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Appendix

Supplemental Material Tables

Chapter 2

Please visit **https://doi.org/10.1130/GEOS.S.16709722** to access the supplemental material for Chapter 2.

Chapter 3

Table S1: DZ U-Pb Isotopic Data

Table S2: DZ Hf Isotopic Data

Table S3: Petrographic Data

Table S4: MDS Sample Key

Table S5: Sources for DZ Age Groups

Table S6: DZ Percentage per Age Group

Chapter 4

Table S7: DZ U-Pb Isotopic Data (Chinle, Morrison, Lytle, Dakota)

Table S8: DZ U-Pb Isotopic Data (Rapid Acquisition, Pliocene Mississippi Valley 4 samples)

Table S9: DZ U-Pb Isotopic Data (Rapid Acquisition, Pliocene Mississippi Valley EB-1)

Table S10: DZ and MDS Sample Key

Note that Supplemental Material Figures from Chapter 3 and 4 are listed with Chapter 3 and 4 Supplemental Materials (before References).