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

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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 (12) 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 the 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 and 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 orogenetic 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 (DZs) 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 the U.S. 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
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.

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 Biddle (2019). L—Lower; Ls—Limestone; Mid—Middle; Miss.—Mississippian; Mtn—Mountain; Penn.—Pennsylvania; Ss—Sandstone; U—Upper.
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., Boorman, 1953; Briggs and Cline, 1967; Morris, 1971, 1974b, 1989; Graham et al., 1976; Morris et al., 1979; 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 DZs 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) summarized 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 superrterraneans (Ganderia, Avalonia, and Carolina) to Laurentia; and (3) the ca. 330–275 Ma Alleghanian-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) distinguished the southern Appalachian segment (south of the New York promontory) from the northern segment based on observations that show Alleghanian 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.

<p>| TABLE 1. SOURCES FOR DETRITAL ZIRCON AGE GROUPS IN LOWER PENNSYLVANIAN OUACHITA DEEP-SEA FAN DEPOSITS |</p>
<table>
<thead>
<tr>
<th>Age group name</th>
<th>Age range (Ma)</th>
<th>Primary source</th>
<th>Common geographic and stratigraphic sources for reworked ages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paleozoic Appalachian province (Taconic, Acadian, and Alleghanian orogens)</td>
<td>500–300</td>
<td>Appalachian-Ouachita orogen</td>
<td>Paleozoic Appalachian-Ouachita foreland-basin strata</td>
</tr>
<tr>
<td>Neoproterozoic peri-Gondwanan terranes, Iapetus Rift, Wichita Mountains</td>
<td>800–500</td>
<td>Gondwanan margin of the Appalachian-Ouachita orogen, Wichita Mountains of Oklahoma</td>
<td>Paleozoic Appalachian-Ouachita foreland-basin strata</td>
</tr>
<tr>
<td>Mesoproterozoic Grenville province</td>
<td>1250–950</td>
<td>Appalachian orogen, extending into central and western Texas and northwestern Mexico; Midcontinental Rift (1.1 Ga)</td>
<td>Paleozoic sandstones of the U.S. midcontinent, Appalachian-Ouachita foreland-basin strata</td>
</tr>
<tr>
<td>Mesoproterozoic Midcontinent Anorogenic Granite-Rhyolite province</td>
<td>1550–1300</td>
<td>Northeast-southwest trend across the eastern U.S. midcontinent, plus numerous intrusions into Yavapai-Mazatzal basement in the Rocky Mountains</td>
<td>Paleozoic sandstones of the U.S. midcontinent, Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.</td>
</tr>
<tr>
<td>Paleoproterozoic Yavapai-Mazatzal orogens</td>
<td>1800–1600</td>
<td>Northeast-southwest trend across the central U.S. midcontinent to the southwestern U.S., including the central and southern Laramide Rockies and the Mogollon Rim of central Arizona</td>
<td>Paleozoic passive margin strata of the western U.S., Ouachita Basin of Arkansas</td>
</tr>
<tr>
<td>Paleoproterozoic Penokean orogen</td>
<td>2000–1800</td>
<td>South-central Canada (Manitoba and Saskatchewan) and Great Lakes region of the U.S. (especially Wisconsin)</td>
<td>Common in low concentrations throughout the area and in all stratigraphic units</td>
</tr>
<tr>
<td>Archean Superior and Wyoming provinces</td>
<td>&gt;2500</td>
<td>Northern U.S. midcontinent to present-day northern Rocky Mountains province</td>
<td>Common in low concentrations throughout the area and in all stratigraphic units</td>
</tr>
</tbody>
</table>

Note: Summarized from Becker et al. (2005), Whitmeyer and Karlstrom (2007), Dickinson and Gehrels (2009), Park et al. (2010), Laskowski et al. (2013), and Blum et al. (2017).
Ingersoll et al. (1995) and Coleman (2000) referred 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 >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<sup>6</sup> km<sup>2</sup> 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, 2020).

Previous Work on Early Pennsylvanian Sediment Routing

Within the previously described 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, 1989; Mack et al., 1983; Thomas, 1988; Gleason et al., 1994), with additional workers considering the Himalayan-Bengal system to be a modern analog for sediment dispersal (Graham et al., 1975, 1976; Ingersoll et al., 1995, 2003). Early provenance studies describe sandstone petrography (Morris, 1994), with additional workers considering the Himalayan-Bengal system to be a modern analog for sediment dispersal (Graham et al., 1975, 1976; Ingersoll et al., 1995, 2003). Early provenance studies describe sandstone petrography (Morris, 1971, 1974b, 1989; Morris et al., 1979) 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 compose 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 ca. 450 Ma (see Patchett et al., 1999). However, Nd data reflect only 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 (Goyenche et al., 2006), DeGray Lake Spillway (Ali-Siyabi, 2000; Slatt et al., 2000a; Schlichtemeier, 2011), and Big Rock Quarry (Olariu et al., 2008, 2011; Funk et al., 2012). Near 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 provides 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 seems 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 12 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; Table 2): Big Rock Quarry (see Olariu et al., 2008, 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 12 samples were then mounted and analyzed at the ALC employing methods outlined by Gehrels (2012). U-Pb analyses 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).

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were conducted on the Element 2 single-collector laser ablation–inductively coupled plasma–mass spectrometer (LA-ICP-MS). The maximum uncertainty filter for \(^{206}\text{Pb}/^{238}\text{U}\) ages was 10%. The maximum uncertainty filter for \(^{208}\text{Pb}/^{206}\text{Pb}\) ages was also 10%, but only applied to analyses with \(^{204}\text{Pb}/^{238}\text{U}\) ages >400 Ma. Maximum discordance and reverse discordance cutoffs were 20% and 5%, respectively, for analyses with \(^{208}\text{Pb}/^{206}\text{Pb}\) 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

Detrital zircon 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, 2020) provide \(e_{HR}^{Hf}\) 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 \(e_{HR}^{Hf}\) 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 12 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

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Location</th>
<th>Outcrop details</th>
<th>Stratigraphic position</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>(n)</th>
<th>Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>PennJ1</td>
<td>DeGray Lake Spillway</td>
<td>South</td>
<td>Jackfork, upper</td>
<td>34.216240</td>
<td>93.095775</td>
<td>800*</td>
<td>A</td>
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<tr>
<td>PennJ2</td>
<td>DeGray Lake Spillway</td>
<td>Middle</td>
<td>Jackfork, upper</td>
<td>34.218915</td>
<td>93.095732</td>
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<tr>
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<td>North</td>
<td>Jackfork, upper</td>
<td>34.219597</td>
<td>93.096074</td>
<td>295</td>
<td>A</td>
</tr>
<tr>
<td>PennJ4</td>
<td>Kirby</td>
<td>K1*</td>
<td>Jackfork, lower</td>
<td>34.230034</td>
<td>93.641180</td>
<td>301</td>
<td>A</td>
</tr>
<tr>
<td>PennJ5</td>
<td>Kirby</td>
<td>K2*</td>
<td>Jackfork, lower</td>
<td>34.227850</td>
<td>93.640335</td>
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<td>A</td>
</tr>
<tr>
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<td>K5*</td>
<td>Jackfork, middle</td>
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<td>93.642940</td>
<td>298</td>
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<td>Kirby</td>
<td>K7*</td>
<td>Jackfork, middle</td>
<td>34.217020</td>
<td>93.647230</td>
<td>293</td>
<td>A</td>
</tr>
<tr>
<td>PennJ8</td>
<td>Kirby</td>
<td>K9*</td>
<td>Jackfork, upper</td>
<td>34.213860</td>
<td>93.645590</td>
<td>294</td>
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<tr>
<td>PennJ9</td>
<td>Kirby</td>
<td>JVS section 1*</td>
<td>JVS, lower</td>
<td>34.210835</td>
<td>93.643860</td>
<td>305</td>
<td>A</td>
</tr>
<tr>
<td>PennJ10</td>
<td>Kirby</td>
<td>JVS section 3 (western roadcut)*</td>
<td>JVS, lower</td>
<td>34.204597</td>
<td>93.642370</td>
<td>299</td>
<td>A</td>
</tr>
<tr>
<td>PennJ11</td>
<td>Big Rock Quarry</td>
<td>Quarry top</td>
<td>Jackfork, upper</td>
<td>34.783440</td>
<td>92.303071</td>
<td>298</td>
<td>B</td>
</tr>
<tr>
<td>PennJ12</td>
<td>Big Rock Quarry</td>
<td>Quarry bottom</td>
<td>Jackfork, upper</td>
<td>34.777308</td>
<td>92.302858</td>
<td>286</td>
<td>B</td>
</tr>
</tbody>
</table>

Note: Cluster—one of two groups of samples shown in Figure 7B; \(n\)—number of grains; JVS—Johns Valley Shale.

*Total number of grains from sample PennJ1 (the original PennJ1A analyses and the PennJ1B higher-\(n\) upgrade).
†See Zou et al. (2017) for Kirby roadcut details.
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

### Detrital Zircon U-Pb Age Distributions

We obtained 3550 concordant DZ U-Pb ages from samples PennJ1A through PennJ12, which represent a mean of 295 concordant analyses per sample, plus an additional 503 concordant U-Pb ages from sample PennJ1B using the rapid-acquisition “higher-n” approach described above (sample analytical data available in the Supplemental Material1). 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 data set 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 composing 6.2% of the total, followed by the Penokean–Trans-Hudson ages (4.0%) and peri-Gondwanan ages (3.0%) (Fig. 5).

Kernel density estimate 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 samples 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 (74.4%) 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 (samples 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 the larger percent-ages 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 samples 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 samples PennJ4 and PennJ5 plot farthest away.

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1Supplemental 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, and contact editing@geosociety.org with any questions.
Youngest Detrital Zircon U-Pb Ages from Jackfork Group Samples

We anticipated that constraining the maximum depositional age (MDA) for the Jackfork Group would be difficult, unlike for the underlying Mississippian Stanley Group, which contains ash beds (Niem, 1977; Shaulis et al., 2012). Indeed, from 3550 concordant U-Pb ages, only samples 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 MDAs.

Our attempt to identify more young volcanogenic grains by obtaining 503 additional concordant U-Pb ages from sample 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, >45 m.y. 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; 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 sample PennJ8 has the two most evolved values in the data set (−19.3 ± 1.5 [1σ] and −17.0 ± 0.7 [1σ]). When comparing mean εHf values of Appalachian- (n = 78) versus peri-Gondwanan-age (n = 25) 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).
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) Two-dimensional 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 ($\varepsilon_{\text{Hf}}$) 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 $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). The mean $\varepsilon_{\text{Hf}}$ value for all grains from the four samples and the standard error is $-2.0 \pm 1.0$ (1σ). Shading represents the 95% density contour (2σ) for $\varepsilon_{\text{Hf}}$ 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 Table S3 (text footnote 1).


### 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 samples PennJ1A to PennJ10 from the DeGray Lake Spillway and Kirby, is dominated by Appalachian and Grenville ages, whereas cluster B, which includes samples 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 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 (samples 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 Group 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 U.S. 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; Jocelk et al., 2019), whereas Yavapai-Mazatzal age crystalline rocks would have been buried by older Paleozoic sedimentary rocks of the northern U.S. midcontinent (Kostantinou 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 sample PennJ1A grains from

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### TABLE 3. SUMMARY OF εHf VALUES FOR SPECIFIC U-Pb AGE GROUPS

<table>
<thead>
<tr>
<th>Location, sample no.</th>
<th>317.5 Ma*</th>
<th>485–370 Ma</th>
<th>800–500 Ma</th>
<th>All ages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>Error (1σ)</td>
<td>No. of grains</td>
<td>Range</td>
</tr>
<tr>
<td>Kirby</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PennJ10, JVS</td>
<td>—</td>
<td>—</td>
<td>18</td>
<td>+8.1 to −11.7</td>
</tr>
<tr>
<td>PennJ8, JU</td>
<td>—</td>
<td>—</td>
<td>18</td>
<td>+3.4 to −19.3</td>
</tr>
<tr>
<td>PennJ4, JL</td>
<td>—</td>
<td>—</td>
<td>21</td>
<td>+7.0 to −14.0</td>
</tr>
<tr>
<td>DeGray Lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PennJ1A, JU</td>
<td>+0.3</td>
<td>0.8</td>
<td>20</td>
<td>+12.4 to −9.7</td>
</tr>
<tr>
<td>Total</td>
<td>77</td>
<td>+12.4 to −19.3</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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 PennJ1A).

†Standard error.

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*317.5 Ma* is the age of the DeGray Lake Spillway samples (cluster A) which includes samples PennJ1A to PennJ10 from the DeGray Lake Spillway and Kirby, is dominated by Appalachian and Grenville ages, whereas cluster B, which includes samples 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 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).

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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 sample PennJ1A grains from
TABLE 4. MEAN εHf VALUES FROM THE OUACHITA, APPALACHIAN, ILLINOIS, AND FOREST CITY BASINS

<table>
<thead>
<tr>
<th>Age distributions (Ma)</th>
<th>Ouachita (317–784 Ma)</th>
<th>Appalachian (330–711 Ma)</th>
<th>Illinois (307–833 Ma)</th>
<th>Forest City (320–624 Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of grains</td>
<td>Mean</td>
<td>Error (1σ)</td>
<td>No. of grains</td>
</tr>
<tr>
<td>Appalachian (307–500)</td>
<td>78</td>
<td>-1.8</td>
<td>1.0</td>
<td>48</td>
</tr>
<tr>
<td>Peri-Gondwanan (501–833)</td>
<td>25</td>
<td>-2.8</td>
<td>0.9</td>
<td>16</td>
</tr>
<tr>
<td>Total</td>
<td>103</td>
<td>-2.0</td>
<td>1.0</td>
<td>64</td>
</tr>
</tbody>
</table>

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

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 ± 0.9 [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–age DZs 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 grain of approximate Early Pennsylvanian age (ca. 322 Ma) in Pennsylvania-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, 2017), but zircons of Pennsylvanian age are modestly more common in Middle to Upper Pennsylvanian deposits 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 Group. 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, plutos 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.

![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 DZs collected from Iowa (n = 14), Missouri (n = 4), Illinois (n = 3), Ohio (n = 2), Oklahoma (n = 1), and Virginia (n = 1).](http://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/18/1/350/5515757/350.pdf)
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 Group 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 Gondwana 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 Group 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 United States to the midcontinent. Similarly 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 Detrital Zircon 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, 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 Pennsylvania 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 Bloyd Formation 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) (Alsaleh 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, 2008), 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 supports the interpretation that the Ouachita Basin was the primary terminal sink for sediment derived from eastern Laurentia, from the Appalachians to the U.S. 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 U.S. midcontinent to the Ouachita Basin would have most likely obstructed westward sediment transport throughout the extent of the contributing drainage area for the Jackfork Group 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 United States 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 United States (Dickinson and Gehrels, 2003; Gehrels et al., 2011; Gehrels et al., 2014; Nair et al., 2018; Chapman and Laskowski, 2019). However, we note that wind-transported particles >1 µm generally fall out within 1000 km of the source area (e.g., Schütz 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).
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 (text footnote 1) for sample name key.
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 DZs 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 hundreds 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 yr (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-shef paleovalleys during sea-level lowstands 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 × 10^3 m^3 yr^-1 range (Stone and Stapor, 1996), whereas longshore sand transport along Australia’s Gold Coast is ~5 × 10^3 m^3 yr^-1 (Pattearson and Patterson, 1983; Boyd et al., 2008). By comparison, between 1950 and 2010 CE, the Mississippi River delivered approximately two 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 United States 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.

## CONCLUSIONS

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 10 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. DZ 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 DZs 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, 2020); the intermediate εHf values characteristic of the Ouachita Basin do not in themselves clearly discriminate different crustal sources but provide additional characterization of Appalachian 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 flank systems of the Appalachian foredeep, the generally northeast-to-southwest–flowing flank systems of the Appalachian backbeufge, and the generally north-to-south–flowing flank systems of the U.S. 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 U.S. part of the Appalachian orogen.

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