RESEARCH ARTICLE
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Key Points:
- Detrital zircon U-Pb ages from Upper Mississippian strata in Kansas and Arkansas reveal a dominant source in the Appalachian region.
- Upper Mississippian strata in the U.S. midcontinent have age distributions that are similar to time-equivalent units across North America.
- East-to-west transport of sediments was driven by orogenesis, while north-to-south sediment dispersal was driven by glacioeustacy.

Supporting Information:
- Supporting Information SI
- Data S1
- Data S2

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1. Introduction

The Late Mississippian was a critical time interval across the globe, with major transitions taking place in tectonics, atmospheric and oceanic circulation, climate, eustacy, and ecosystems (Saunders & Ramsbottom, 1986; Ross & Ross, 1988; Hatcher et al., 1989; Isbell et al., 2003; Smith & Read, 2000; Montañez & Poulson, 2013; Qiao & Shen, 2015). During this time interval, Appalachian orogenesis (Alleghanian orogeny) initiates with the collision of Gondwana against the southeastern Laurentian margin, leading to the eventual formation of Pangaea (Hatcher et al., 1989; Heatherington et al., 2010). The expansion of continental glaciers also takes place, resulting in dramatic changes in paleoclimatic and frequent sea level fluctuations (Ross & Ross, 1988; Smith & Read, 2000). For the interior of the Laurentian Craton, these changes are recorded as a transition from stable carbonate platform deposition, which dominated for much of the Paleozoic, to widespread clastic deposition in the Pennsylvanian and Permian (Sloss, 1963; Lane, 1978; Smith & Read, 2000; Manger & Zachry, 2009; Park et al., 2010; Manger, 2014; Xie, O’Connor, et al., 2016).

In the U.S. midcontinent, Late Mississippian (Chesterian) sandstones preserve the earliest record of this evolving Carboniferous setting. In Kansas, the sandstones are part of N-S-oriented IVF systems that developed across a broad carbonate platform that covered much of the cratonic interior, including in Kansas, Missouri, and northern Arkansas (Lane, 1978; Manger, 2014; Manger & Zachry, 2009; Montgomery & Morrison, 1999). The sandstones represent an abrupt change to mixed carbonate-siliciclastic deposition during what is considered to be a relatively stable tectonic period in the midcontinent, one that predates the major and well-documented Pennsylvanian to Permian deformation across the region associated with the development of the Ancestral Rocky Mountains and of the Ouachita-Marathon fold-thrust belt (Adler et al., 1971; Leary et al., 2017; Montgomery & Morrison, 1999; Rascoe & Adler, 1983).
The presence of IVF systems and clastic detritus in a carbonate-shelf setting during the Late Mississippian raises two interesting issues. First, the provenance of the detritus is unknown. Although discrete sandbodies are preserved across the region, the northern reaches of these IVF systems in Kansas were eroded during Pennsylvanian deformation (Montgomery & Morrison, 1999). From the trend of the preserved sandstones, some workers have argued that sediments were sourced from local structural highs like the Central Kansas Uplift and Cambridge Arch to the north (Cirilo, 2002; Senior, 2012; Figure 1). However, Cambrian through Middle Mississippian carbonates would have covered much of the region and are more likely to have provided carbonate materials as locally derived sediments. The extent to which underlying Precambrian basement rocks would have been exposed as a potential source is unknown, although limited studies have pointed to highs like the Nemaha Ridge as a source of first-cycle zircons in age-equivalent units (Xie, Cains, et al., 2016; Xie, O’Connor, et al., 2016). A second and associated question relates to the role of

Figure 1. (a) Distribution of major basement age provinces in North America that may have been sources for Paleozoic sediments (modified from Ojakangas et al., 2001; Park et al., 2010; Gehrels et al., 2011; Xu et al., 2017). (b) Basement structure of the midcontinent (modified from Rascoe & Adler, 1983). Contours are in feet (1 feet ≈ 0.3045 m).
more distant clastic sources on the provenance of IVF systems and Upper Mississippian sandstones in the region. Gehrels et al. (2011) proposed a transcontinental sediment transport model whereby sandstones in the western part of Laurentia were sourced from the Appalachian orogen through a combination of westward flowing rivers, wind systems, and ocean currents. Although the Appalachian region is widely accepted as a source for Late Paleozoic sediments (Gehrels et al., 2011; Xie, Cains, et al., 2016; Xie, O’Connor, et al., 2016; Alsalem et al., 2017; Thomas et al., 2017; Bidgoli et al., 2018; Kissock et al., 2018; Jones et al., 2019; Wang & Bidgoli, 2019), the details of such long distance sediment transport require further study (see discussion in Thomas, 2011). For example, the role of recycling of Early and Middle Paleozoic strata along the hypothetical E-W route across Laurentia has not been fully explored. Sediment dispersal paths from the Appalachian region also require further investigation, as the N-S orientation of IVF systems in Kansas appears at odds with the E-W transport model. This suggests more complicated drainage systems and sediment routing from source to sink.

An increasing number of studies have focused their efforts on testing various aspects of the Gehrels et al. (2011) model (e.g., Finzel, 2014; Benyon et al., 2014; Lawton et al., 2015; Xie, O’Connor, et al., 2016; Xie, Cains, et al., 2016; Xie, Buratowski, et al., 2018, Xie, Anthony, & Busbey, 2018; Xu et al., 2017). However, most of these published investigations have focused on Pennsylvanian and younger strata. Investigations of Upper Mississippian strata have been limited (Xie, O’Connor, et al., 2016; Xie, Cains, et al., 2016), due, in part, to the restricted number of sandstones targets available for study under this carbonate- and shale-dominated background. Because these sandstones developed during a relatively stable period, with only limited clastic flux (Manger, 2014; Manger & Zachry, 2009; McGilvery et al., 2016), these sandstones should be sensitive to the evolving landscape across the craton and may provide important clues to the sources and transport history of clastic sediments.

This study examines the provenance of Upper Mississippian (Chesterian) sandstones using detrital zircon U-Pb geochronology. The data are acquired from seven samples obtained from boreholes in the Hugoton Embayment, in southwestern Kansas, that offer a rare opportunity to examine IVF systems, now buried >1,500 m in the subsurface. We also report ages obtained from Chesterian sandstones in northwestern Arkansas that represent some of the earliest pulses of clastic sediments to Arkoma Shelf (Winkelmann, 2007; McGilvery et al., 2016; Xie, O’Connor, et al., 2016). The new ages are compared to published detrital zircon ages from Early and Middle Paleozoic sandstones as well as from age-equivalent units across North America to evaluate patterns and drivers of sediment dispersal during this critical time interval. The analysis also provides insight into the relative roles of orogenesis, eustacy, and local topography in transcontinental sediment transport.

2. Geologic Background

The North American Craton (later the paleocontinent of Laurentia) occupied the center of the supercontinent Rodinia from the Late Proterozoic until breakup in the Precambrian-Cambrian. The multistage breakup of the supercontinent resulted in the opening of the Iapetus Ocean and the development of a passive margin along the southern and eastern margins of Laurentia (Aleinikoff et al., 1995; Park et al., 2010; Thomas et al., 2017). By the Ordovician, the majority of the craton was covered by shallow seas. Beginning in the Middle Ordovician, Appalachian orogenesis initiates and interrupts passive margin sedimentation along the eastern Laurentian margin. Elsewhere, in the interior of the craton, stable conditions continued with widespread deposition of shelf carbonates and intervening shales (Manger, 2014; Xie, O’Connor, et al., 2016). This pattern of deposition in the cratonic interior persisted until initiation of the Late Mississippian Alleghanian orogeny on the eastern margin of Laurentia, which increased the flux of clastics to the interior of the craton (Winkelmann, 2007; McGilvery et al., 2016; Xie, O’Connor, et al., 2016). Orogenesis continued on the margins of the craton throughout the Pennsylvanian, with development of the Appalachian-Ouachita-Marathon belt and associated uplifts, leading to the final assembly of the supercontinent of Pangaea in the Permian (Hatcher et al., 1989; Park et al., 2010; Thomas et al., 2017).

The Hugoton Embayment in southwestern Kansas is located in the center of the North American Craton and is considered as the shallow subsurface extension of the Anadarko Basin (Figure 1). In the Early and Middle Mississippian, the entire midcontinent was covered by epeiric seas and characterized by deposition of Kinderhook, Osage, and Meremec series carbonates and shales on a broad and relatively shallow platform.
During the latest Meramecian, sea level regression led to widespread subaerial exposure and fluvial incision of the carbonate platform, resulting in the development of deep, linear valleys across the Hugoton Embayment (Montgomery & Morrison, 1999; Cirilo, 2002; Senior, 2012; Figures 2 and 3). These valleys were subsequently filled, during a Late Mississippian (Chesterian) transgression, with dominantly fine- to very fine-grained sandstones. Near the center of the Hugoton Embayment, one such valley has been recognized in 3-D seismic, well log, and core data (Figures 2 and 3). The valley, more than 70 m deep in places, can be traced for over 160 km from Kansas into Oklahoma (Montgomery & Morrison, 1999; Cirilo, 2002; Senior, 2012). The valley fill is interpreted to have been deposited in an estuarine system, with more fluvial influence to the north and more tidal and marine influence to the south (Cirilo, 2002; Montgomery & Morrison, 1999; Senior, 2012), a pattern that is well exemplified by core and well log-based lithofacies from boreholes in three oil fields—located along the axis of the valley (Figures 2 and 3).

In the Pleasant Prairie South oilfield, Mary Jones #2 is one of only two boreholes with core from the Chesterian IVF, which consists of upward-fining sequences that grade from conglomerate to sandstone and siltstone. The sandstones are mainly well-sorted quartzarenites. Sedimentary structures and features in the core include laminations, trough cross-beds, and carbonized organic material (wood fragments), indicating a fluvial origin, and mud drapes, indicating minor tidal influence (Cirilo, 2002; Dubois et al., 2014; Senior, 2012).

The only core available for direct observation and sampling of the Eubank field comes from the MLP Black borehole that reveals a succession of tidally influenced estuarine deposits, with five major facies...
including marine shale, transgressive conglomerate, intertidal sand flat, estuarine bar margin, and estuarine bar facies (Dubois et al., 2014b). The estuary bar sandstones are the main oil-producing reservoir in the field and consists of fine- to very fine-grained quartzarenites and sublitharenites that are moderately well sorted with subrounded to rounded grains (Dubois, Williams, Youle, & Hedke, 2014b; Montgomery & Morrison, 1999).

Unlike the northern oilfields, the Shuck Oilfield is located in a deeper part of the Hugoton Embayment, and the youngest rocks of the transgressive fill were deposited beyond the extents of the incised valley. The lithofacies across the field are similar to the Eubank Field, with major lithofacies identified as marine shale, transgressive conglomerates, valley margin conglomerates, salt marsh, tidal flat, and estuarine bar facies (Dubois, Williams, Youle, & Hedke, 2014c). The estuary bar facies consist of fine- to very fine-grained, limey sandstone, interpreted to have been deposited in migrating sand bars in a subtidal estuary.

### 3. Geochronologic Provinces

Provenance analysis based on detrital zircon geochronology requires detailed knowledge of the age of potential source regions. Earlier geochronologic investigations provide a robust foundation for provenance analysis in North America (e.g., Gehrels et al., 2011; Sims, 1996; Van Schmus et al., 1993; Whitmeyer & Karlstrom, 2007). The North American Craton formed billions of years ago through the collision of microcontinental volcanic arcs and oceanic terrains (Hoffman, 1989). These collisions and accretionary events formed six major age provinces that may be sources of sediments. They include the Superior, Wyoming, Trans-Hudson, Penokean, Yavapai-Mazatzal, and midcontinental Granite-Rhyolite provinces (Whitmeyer & Karlstrom, 2007; Gehrels et al., 2011; Figure 1). In the following sections, we organize age provinces by geography.
3.1. Northern Provinces

The Archean basement of the Canadian Shield occupied the central part of the Laurentian Craton and was formed from microcontinent collisions in the Paleoproterozoic (1,960–1,800 Ma) that eventually formed a major orogenic belt (Whitmeyer & Karlstrom, 2007). The Superior and Wyoming provinces, the southernmost components of the Canadian Shield, are the closest Archean sources to the study area (Figure 1a). The Superior province was formed by the collision of a 2,700–2,800 Ma arc with an Archean block of 3,500 Ma (Hoffman, 1989 and references therein). The Wyoming province mainly consists of 2,500–2,700 Ma granite and gneiss. The Trans-Hudson province, between Superior and Wyoming provinces, is an orogenic belt made up of 1,800–1,900 Ma metasedimentary rocks (Hoffman, 1989 and references therein). Similar age magmatic rocks are also distributed along the southern margin of the Superior province, in the Penokean province (Sims, 1996; Van Schmus et al., 1993).

3.2. Eastern Provinces (Appalachian Region)

The Appalachian region is characterized by the superposition of multiple tectonic events that include the Grenville orogeny, Late Proterozoic to Early Paleozoic rifting and magmatic events, and the Paleozoic Appalachian orogenic series (Taconic, Acadian, and Alleghenian orogenies; Hatcher et al., 1989; Hauser, 1996; Aleinikoff et al., 1995; Hatcher, 2005; Cawood & Nemchin, 2001; Park et al., 2010; Thomas et al., 2017). The Grenville province (900–1,300 Ma) is the residual basement of a large orogenic belt that formed from continental collision during the formation of the Rodinia supercontinent (Tohver et al., 2006; Whitmeyer & Karlstrom, 2007). Synrift magmatic rocks are related to the breakup of Rodinia and a series of rifts and associated magmatic events in Late Proterozoic to Early Paleozoic (Aleinikoff et al., 1995; Hatcher, 2005; Lukert & Banks, 1984; Wehr & Glover, 1985). Taconic and Acadian orogenic terranes are also distributed along the eastern margin of North America (Park et al., 2010) and resulted from collisions between east Laurentia and an arc system and the Avalonia terrane in the Ordovician (~465–455 Ma; McLennan et al., 2001) and Devonian (~400–350 Ma), respectively. During these two orogenic events, volcanic and metamorphic activities were continuous (from ca. 350 to 500 Ma; Becker et al., 2005; McLennan et al., 2001). These terranes are inferred to have provided considerable sediment to the Appalachian foreland clastic wedge (McLennan et al., 2001; Becker et al., 2005).

3.3. Midcontinent Provinces

The Midcontinent consists of the Yavapai-Mazatzal (1,600–1,800 Ma) and Granite-Rhyolite (1,300–1,550 Ma) provinces. The Yavapai-Mazatzal province is a combination of two basement provinces. The Yavapai province is made up of 1,760–1,700 Ma arc rocks that were accreted to the North American continent at about 1,700 Ma, whereas the Mazatzal province is mainly composed of 1,800–1,700 Ma accretionary wedge rocks that were added to the southern Yavapai province in the latest Paleoproterozoic (Bowring & Karlstrom, 1990; Van Schmus et al., 1993). The adjacent Granite-Rhyolite province was distributed along the southeastern margin of the Laurentian Craton—from present-day northern Mexico to northeastern Canada—with an age range 1,550–1,300 Ma (Whitmeyer & Karlstrom, 2007).

3.4. Others

Rift-related igneous and sedimentary rocks associated with the Precambrian Midcontinent Rift System and Cambrian Southern Oklahoma Aulocogen also contribute to the fabric of the basement in North America (Cannon, 1994; Donaldson & Irving, 1972; Hauser, 1996). The Midcontinent Rift System is made up of bimodal igneous rocks that reflect a short-lived (1,115–1,085 Ma) pulse of back-arc extension and magmatism during the Grenville orogeny (Ojakangas et al., 2001). Cambrian intrusive and volcanic rocks, including gabbro and basalt, also developed along the Southern Oklahoma fault system (Arbuckle and Wichita uplifts in Figure 1b), collectively known as the 550–530 Ma Southern Oklahoma Aulocogen (Bowring & Hoppe, 1982; Hanson et al., 2013; Hogan & Gilbert, 1998; Thomas, 2014; Thomas et al., 2016; Wright et al., 1996).

4. Samples and Methods

Seven core samples were collected from three boreholes, the Mary Jones #2, MLP Black, and Hitch Unit 8-3 boreholes, located in the axis of the IVF complex in the Pleasant Prairie South, Eubank, and Shuck oilfields, respectively (Figure 3). Figure 3 shows the log characteristics, lithofacies interpretations based on the log properties, and generalized stratigraphy of the sampled boreholes. The figure also shows the relative...
Table 1
Sample Coordinates, Unit Age, Depth, and Simplified Lithology

| Sample name   | Coordinates | Unit          | Depth (m) | Description                        |
|---------------|-------------|---------------|-----------|-----------------------------------|
| Mary Jones    | 37.73445,   | Chesterian    | 1593.8 - 1594.1 | Oil-stained, fine- to very fine-grained quartzarenite |
|               | -101.0228   |               |           |                                   |
| MLP Black     | 37.46191,   | Chesterian    | 1670.9 - 1671.5 | Fine- to very fine-grained, moderately to well-sorted, and subangular to well-rounded quartzarenites and sublitharenites |
|               | -101.026909 | Chesterian    | 1666.3 - 1667.0 |                                   |
| Hitch         | 37.18061,   | Chesterian    | 1903.5 - 1903.9 | Fine- to very fine-grained, moderately well-sorted, subangular to subrounded sandstones |
|               | -100.99427  | Chesterian    | 1888.8 - 1889.5 |                                   |
| Hitch 61504   |             | Chesterian    | 1874.6 - 1875.4 |                                   |
| 17BS1         | 36.1748,    | Chesterian    | N/A       | Fine-grained, subangular to angular, moderately sorted, siliceous quartzarenite |
|               | -93.9429    | Batesville    |           |                                   |
| 17WS1         | 35.9276,    | Chesterian    | N/A       | Medium-grained, subrounded to rounded, well-sorted, siliceous quartzarenite |
|               | -94.1841    | Wedington     |           |                                   |

Positions of core and selected samples in each well. Core samples were selected from sand-rich intervals and were generally well-sorted, subrounded, fine- to medium-grained quartzarenites (Figure 3). We also collected two samples of age-equivalent units, the Chesterian Batesville and Wedington sandstones, from outcrops in northwestern Arkansas. The details of the core and outcrop samples are provided in Table 1.

Samples were processed using standard mechanical, electromagnetic (Frantz iodynamic magnetic separator), and heavy liquids (methylene iodide) techniques for separation and concentration of zircon. For core samples, an additional processing step was to wash and remove any coring fluid or hydrocarbon residues. Once separated, zircons from sample splits were evaluated under binocular microscope, mounted onto epoxy pucks (25-mm diameter) using double-sided tape (tape mount) for U-Pb spot analysis, and photographed for archive.

Laser ablation inductively coupled plasma mass spectrometry analyses were carried out at UTCChron Geo- and Thermochronometry Laboratories at the University of Texas at Austin and Isotope Geochemistry Laboratories at the University of Kansas. GJ1 with a $^{206}$Pb/$^{238}$U age of 600.4 ± 0.65 Ma is the primary reference material used to address calibration drift and both downhole isotopic and elemental fractionation (Jackson et al., 2004) and was analyzed once for every five to eight unknowns. Pak 1 was used as a secondary zircon standard with thermal ionization mass spectrometry ages of 43.0 Ma for the analysis at University of Texas at Austin. The Plesovice and Fish Canyon Tuff zircons with the age of 337.13 ± 0.37 Ma (Sláma et al., 2008) and 28.402 ± 0.023 Ma (Schmitz & Bowring, 2001; Wotzlaw et al., 2013) reported from chemical abrasion thermal ionization mass spectrometry were analyzed as the secondary reference materials for the analysis at the University of Kansas.

U-Pb data reduction of the samples from Kansas and Arkansas was completed using Iolite (Hellstrom et al., 2008; Paton et al., 2011) and the open-source software package ET Redux (McLean et al., 2016), respectively. $^{206}$Pb/$^{238}$U ages were used for grains younger than 850 Ma, and $^{207}$Pb/$^{206}$Pb ages were used for grains older than 850 Ma. All ages are reported using 2σ absolute propagated uncertainties. Standard GJ1 yields a $^{206}$Pb/$^{238}$U weighted average age of 601.8 ± 2.4 Ma (mean square weighted deviation (MSWD) = 0.75, n = 51). The Plesovice and Fish Canyon Tuff zircon references yielded weighted mean $^{206}$Pb/$^{238}$U dates of 339.8 ± 7.3 Ma (MSWD = 0.91, n = 20) and 28.93 ± 0.71 Ma (MSWD = 1.4, n = 20), respectively, and fall into the uncertainty ranges of the reported ages. For zircon U-Pb ages older than 850 Ma, the discordance was calculated based on $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{206}$Pb ages. For zircon ages younger than 850 Ma, the discordance was calculated based on $^{206}$Pb/$^{238}$U and $^{207}$Pb/$^{235}$U ages. For the Kansas IVF core samples, grains with greater than 10% discordance or 5% reverse discordance were excluded. For the Arkansas outcrop samples, which were generally poorer in data quality, we use lower discordance (20%) and analytical error (15%) cutoffs for older grains (>850 Ma).

To compare the new detrital zircon data with published data sets, we use a range of visualization and statistical tools in our analysis. The age data are presented and qualitatively compared using probability density (Ludwig, 2008) and kernel density estimation plots (Vermeesch, 2012; 2013; Vermeesch et al., 2016) and pie charts. More quantitative comparison of samples is accomplished through cumulative probability plots,
which can reveal differences in the proportions of grains among samples (Gehrels et al., 2011), and through Kolmogorov‐Smirnov (K‐S) tests (Press et al., 1986), which are a measure of the statistical significance of differences between age distributions, with \(P\) values as the major criterion and 0.05 as the cutoff. A \(P\) value less than the cutoff suggests that age distributions of two samples are not the same at a confidence level >95% (Guynn & Gehrels, 2006). Multidimensional scaling (MDS) analysis (Vermeesch, 2013; Vermeesch et al., 2016) was also used to evaluate similarities and differences among samples through grouping of samples with similar U-Pb age distributions.

5. Results

Of the 976 detrital zircon grains analyzed from core samples from southwestern Kansas, a total of 865 grains yielded ages within the discordance and error criteria. The full suite of isotopic measurements, U–Pb ages (Supporting Information Tables S1 and S2), and associated Concordia plots (Figure S1) are provided in the supplement. The detrital zircon age results are plotted as probability density and kernel density estimation plots (Ludwig, 2008; Vermeesch, 2012) in Figure 4, with the range of known age provinces highlighted. In general, the samples show major groups of Middle to Late Mesoproterozoic (~1,300–900 Ma) and Paleozoic (~500–350 Ma) ages and more minor groups of Late Paleoproterozoic (~1,800–1,600 Ma), Early

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**Figure 4.** U-Pb detrital zircon probability density (red lines) and kernel density estimation plots (blue lines; Vermeesch, 2012) of samples from the (a) Hugoton Embayment, southwest Kansas, and (b) Arkoma Shelf, northwestern Arkansas. Diagrams were constructed using Isoplot (Ludwig, 2008). (c) Kernel density estimation plots comparing detrital zircon U-Pb ages from Chesterian incised valley fill in the Hugoton Embayment (upper curve) with compiled detrital zircon ages from Late Paleozoic successions in the Appalachian Foreland (based on Thomas et al., 2017 and references therein).
Mesoproterozoic (~1,550–1,300 Ma), and Archean (>2,500 Ma) ages. Visual inspection of the age spectra of the samples and K-S statistical comparisons (Table 2), with P values generally less than 0.05, suggest they are statistically indistinguishable. The MDS plots (Figure S2) also group the samples together and suggest a high degree of similarity between age spectra. Outcrop samples from northwestern Arkansas yielded a total of 172 grains within discordance and error criteria. The age results, while similar to the Kansas sample in terms of the major age groups (~1,300–900 and ~500–350 Ma), also contained abundant numbers of Late Paleoproterozoic (~1,800–1,600 Ma) and Early to Middle Mesoproterozoic (~1,550–1,300 Ma) ages and minor groups of Neoproterozoic to Early Cambrian (650–500 Ma) and Paleoproterozoic and older grains (>1,800 Ma). The details of the age results are described below.

5.1. Pleasant Prairie South Field, Mary Jones #2

Two samples of fine-grained sandstone were analyzed from the Mary Jones #2 borehole (Figure 4). However, one grain from the Mary Jones 5229 sample resulted in a concordant age of 191.7 ± 3.6, much younger than the depositional age of the unit and likely the result of sample contamination, perhaps from rock cuttings derived from higher in the borehole being circulated downhole. Therefore, this age is excluded from our analyses. Overall, the two samples yield very similar age distributions (Figure 4a), with pronounced groups of Middle to Late Mesoproterozoic (ca. 1,300–900 Ma) and Paleozoic (ca. 500–350 Ma) ages. A total of 108 zircons from the Mary Jones 5229 sample yielded ages ranging from 364 ± 22 to 3,267 ± 14 Ma, with the ~1,300–900 Ma age group accounting for 65% and a subordinate ~500–350 Ma age group accounting for 9% of the grains. The 120 zircons from the Mary Jones 5194 sample range in age from 359 ± 7 to 2,881 ± 20 Ma, with the same dominant population of grains of ~1,300–900 Ma accounting for 60% and the subordinate cluster (~500–350 Ma) accounting for 15% of grains. K-S statistical comparison of the two samples yields a P value of 0.507 (>0.05; Table 2), suggesting that the two samples have similar age distributions (Gehrels et al., 2011; Press et al., 1986).

5.2. Eubank Field, MLP Black #4-3

Two samples of fine-grained sandstone from the MLP Black 4-3 borehole were dated. A total of 131 concordant ages from sample MLP Black 5482 range from 352 ± 6 to 2,775 ± 27 Ma (Figure 4a). A major age cluster of Middle to Late Mesoproterozoic (1,300–900 Ma) ages accounts for 54%, and the subordinate group of Paleozoic (500–350 Ma) ages constitutes 16% of the grains. Late Paleoproterozoic (~1,800–1,600 Ma) and Archean (>2,000 Ma) ages also form two minor groups (~11% and ~7% of grains, respectively). The sample also contains small numbers of grains from other age groups (e.g., 1,550–1,300 and 900–500 Ma). A total of 123 concordant ages from sample MLP Black 5467 range from 336 ± 5.4 to 2,816 ± 18 Ma (Figure 4a). Overall, ~1,300–900 Ma ages dominate (~54%), while ~500–350 Ma zircons are the second most abundant age group (~19%). Late Paleoproterozoic (~1,800–1,600 Ma) and Early to Middle Mesoproterozoic (~1,550–1,300 Ma) ages account for 10% and 7% of grains, respectively, with rare grains from other age groups. These two samples yield a P value of 0.421 (Table 2), suggesting similar provenance (Press et al., 1986; Gehrels et al., 2011).
5.3. Shuck Field, Hitch Unit #8-3

Three samples of fine-grained sandstone from the borehole Hitch Unit #8-3 were analyzed. The samples yield similar ages with major groups of Middle to Late Mesoproterozoic (~1,300–900 Ma) and Paleozoic (~500–350 Ma) ages (Figure 4a). The sample Hitch 6245 yielded a total of 129 concordant ages, ranging from 402 ± 6 to 2,821 ± 20 Ma. The dominant age group of ~1,300–900 Ma accounts for 67%, and a Paleozoic cluster of ~500–350 Ma accounts for 10% of the ages. Late Paleoproterozoic (~1,800–1,600 Ma) ages account for another 10% of the zircons. Other age clusters are made up by 5% or fewer grains. Sample Hitch 6197 yielded 132 concordant ages that range from 369 ± 9 to 3,226 ± 21 Ma (Figure 4a). Ages of ~1,300–900 and ~500–350 Ma form the two major clusters accounting for 47% and 30% of grains, respectively. Early to Middle Mesoproterozoic (~1,550–1,300 Ma) grains account for 10% of the grains. Rare grains from other age groups (7% or below) are also present. The Hitch 6150 sample yielded 121 concordant ages ranging from 375 ± 8 to 2,847 ± 20 Ma (Figure 4a). The ~1,300–900 Ma ages are the dominant age cluster (52%) with the Paleozoic grains of ~12%. The $P$ values derived from K-S comparisons of the samples range from 0.010 to 0.394 (Table 2), suggesting the age distributions are similar.

5.4. NW Arkansas Outcrop Samples

Samples 17BS1 and 17WS1 were collected from outcrops in northwestern Arkansas. Ages from these samples have relative low analytical quality, with high discordance and errors (Figure 4b and Table S1) that may be a consequence of the grain mounting procedure (tape mounts). Only 90 concordant ages resulted from 177 analyses of the 17BS1 sample, with a $P$ value of 0.379 (Table 3) from K-S tests showing the consistency of the original and filtered age distributions. The concordant ages range from 404 ± 10 to 3,055 ± 66 Ma and contain two major clusters of ~1,300–350 Ma accounts for 10% of the ages. Late Paleoproterozoic (~1,800–1,600 Ma) ages account for another 10% of the zircons. Other age clusters are made up by 5% or fewer grains. Sample 17WS1 yielded 82 concordant ages from 110 analyses, with a $P$ value of 1.00 (Table 3), suggesting consistency between the original and filtered ages. The data range from 411 ± 13 to 2,853 ± 39 Ma, with 500–350 Ma (21%) and ~1,300–900 Ma (41%) age groups accounting for more than 60% of the concordant ages (Figure 4b). The remaining grains are made up of ~1,800–1,600 Ma (16%), ~1,550–1,300 Ma (10%), and >1,800 Ma (8%) ages and a minor group of ~650–500 Ma (4%) zircons (Figure 4b).
6. Discussion

6.1. Provenance of Chesterian IVF Sandstones

Detrital zircon age distributions from Chesterian core samples from the Hugoton Embayment have pronounced age clusters of 900–1,300 and 350–500 Ma that correspond to the age ranges of the Appalachian Grenville and Taconic-Acadian orogenies, respectively. The bimodal pattern, observed in the histogram and probability density plots (Figure 4), along with the K-S tests (Table 2) and MDS analysis (Figures S2 and S3) indicate that all seven samples are similar and were likely derived from the same provenance.

In Figure 4c, the age data from Chesterian core samples are combined into a single kernel density estimation plot (Vermeech, 2012). In addition to the pronounced Grenville and Taconic-Acadian age groups, the age spectrum shows that zircons sourced from northern and midcontinent age provinces are rare or absent in the IVF sandstones. The low content of Yavapai-Mazatzal (1,800–1,600 Ma) and Granite-Rhyolite (1,550–1,300 Ma) ages, in particular, excludes major derivation from local midcontinent basement. The results seem to suggest that structural highs like the Central Kansas Uplift and Cambridge Arch remained covered during the Late Mississippian, a conclusion also supported by structural analysis that suggests that the main phase of deformation and potential breaching of these structures occurred later, in the Pennsylvanian (Adler et al., 1971; Rascoe & Adler, 1983).

The strong Grenville and Acadian-Taconic age peaks observed in the zircon age spectra for the Chesterian IVF sandstones point to more distant or potentially recycled sources for sediments. Both the Grenville and Taconic-Acadian orogenies occurred in the Appalachian region, and comparison of our data with data from the Alleghanian Appalachian Foreland Basin, a proxy for sediment sources and likely zircon age distributions derived from the orogen, shows a high degree of similarity (Thomas et al., 2017 and references therein). The almost mirror image in age spectra between sandstones from the Hugoton Embayment and Appalachian signature derived from synorogenic clastic wedge sediments (Thomas et al., 2017), shown in Figure 4c, strongly suggests that the Appalachian region was the primary source of sediments. However, it is worth noting that the percentages of Yavapai-Mazatzal grains (1,800–1,600 Ma; up to 10%) in some samples are higher than in Appalachian sources and may point to some limited contributions from local basement uplifts such as Nemaha Uplift (Xie, O’Connor, et al., 2016). The high percentages of the Grenville grains may also reflect contributions from the Midcontinent rift system, which contains bimodal igneous rocks that formed during a short-lived Grenville-age pulse (1,115–1,085 Ma; Ojakangas et al., 2001).

6.2. Recycling of Early Paleozoic Sandstones

Although an Appalachian age signature is clear in the Chesterian IVF sandstones, zircons are durable and can be eroded and transported through multiple sedimentary cycles. Thus, it is necessary to also evaluate the possibility of recycled grains in our age data sets. Several pre-Mississippian sandstones that could be sources of zircons are present west and northwest of the Hugoton Embayment (Figure 5). These sandstones include Cambrian and Lower Ordovician quartz arenites (e.g., Jordan sandstone; Runkel et al., 2007) and the widely distributed Middle Ordovician St. Peter sandstone, a supermature arenite (Konstantinou et al., 2014; Figure 5). A compilation of published detrital zircon geochronologic data from these Early Paleozoic sandstones is presented in Figure 5.

The age spectrum for Cambrian sandstones shown in Figure 5a is compiled from seven samples collected in Wisconsin, Minnesota, and Missouri that have similar age distributions (Konstantinou et al., 2014; Li, 2016). The Archean component (>2,500 Ma) dominates the age spectrum whereas other age groups, particularly the Grenville (900–1,300 Ma), are limited. By comparison, the zircon data from five samples of Early Ordovician sandstone are bimodally distributed, with both Archean (>2,500 Ma) and Grenville (1,300–900 Ma) ages strongly represented (Figure 5b; Konstantinou et al., 2014; Li, 2016). The pattern, with strong Archean and Grenville age groups, is repeated for the Middle Ordovician St. Peter sandstone, the most well studied and areally extensive of the Early Paleozoic sandstones (Konstantinou et al., 2014; Ibrahim, 2016; Figures 5c–g). It should be noted that there is some geographic variability in the age spectra for the St. Peter sandstone, particularly for zircons <2,000 Ma and most notably for the Grenville age group (Figures 5c–g). Comparison of these age spectra with the compiled age distribution for the Taconic synorogenic wedge (Gray & Zeitler, 1997; Cawood & Nemchin, 2001; McLennan et al., 2001; Eriksson et al., 2004; Park et al., 2010; Thomas et al., 2017) suggests that the Appalachian area was an important source
of sediments and Grenville-age zircons during the Early to Middle Ordovician; however, its influence and contributions were not uniform.

Overall, the compilation suggests that the Superior province in the north was an important and continuous provenance area for Early and Middle Paleozoic sedimentary rocks that is largely absent in the Appalachian foreland and in the Chesterian samples from this study. This difference precludes the possibility of recycling of Early Paleozoic sedimentary rocks as a dominant source of sediments to the Hugoton Embayment and Arkoma Shelf. The compilation also demonstrates that Grenville grains are rare or absent in the Cambrian sandstones and that transportation of sediments from the Appalachian area initiated in the Early Ordovician, and its dominance as a sediment source persisted through the Paleozoic.

6.3. Comparison with Age-Equivalent Units Across North America

In contrast to the Pennsylvanian, with intense tectonic activity, widespread clastic sedimentation, and generally more complicated local environments (Sloss, 1963; Manger & Zachry, 2009; Thomas, 2011; Manger, 2014; Xie, O’Connor, et al., 2016; Alsalem et al., 2017; Xie, Buratowski, et al., 2018, Xie, Anthony, & Busbey, 2018), the Late Mississippian was a relatively stable period with only limited clastic flux, particularly in the midcontinent (Manger & Zachry, 2009; Manger, 2014; McGilvery et al., 2016; Xie, O’Connor, et al., 2016). In the following sections, we compile and summarize published detrital zircon data from Middle to Late Paleozoic basins that contain Upper Mississippian clastic strata. We focus on sandstones from the Appalachian Foreland Basin, Black Warrior Basin, Illinois Basin, Ozark Dome, Arkoma Shelf, and Grand Canyon and use the data to trace changes in age distributions and provenance across Laurentia in Late Mississippian.

6.3.1. Appalachian Foreland

The Late Paleozoic Appalachian orogen is the principal source of clastic sediments transported westward into the Appalachian Foreland Basin and farther west into the interior of the craton (Gehrels et al., 2011; Park et al., 2010; Thomas et al., 2017). Nearest this presumed source area, Ordovician Taconic synorogenic clastic wedges show unimodal age distributions of Grenville grains (Figure 5h), whereas Devonian Acadian...
synorogenic clastic wedges and subsequent Upper Mississippian clastic wedges show pronounced bimodal distributions of Grenville and Taconic‐Acadian ages. The age distributions suggest the Appalachian orogen remained a stable sediment source region, yielding zircon grains with similar age distribution with negligible variation since Devonian (Figure 6).

6.3.2. Black Warrior Basin
The Black Warrior Basin, in the southern midcontinent, is the easternmost foreland basin to the Ouachita orogenic system. The basin resides near the intersection of this system with the southern Appalachian orogenic system and thus, the provenance of Chesterian sandstones within the basin is debated (Mars & Thomas, 1999; Xie, Cains, et al., 2016). Detrital zircons from the Lewis sandstone, at the base of the Chesterian section, contain Taconic‐Acadian and Grenville grains that define two prominent age peaks, consistent with major derivation from the Appalachian region (Xie, Cains, et al., 2016; Kissock, 2016; Ozark Dome data are from Li (2016); and Arkoma Shelf data are from Xie, Cains, et al. (2016), Pickell (2012), and this study.

6.3.3. Illinois Basin and Ozark Dome
The Illinois Basin is an intracratonic basin, separated from the Appalachian Foreland in the east by the Cincinnati Arch (Quinlan & Beaumont, 1984; Root & Onasch, 1999; Figure 7). The basin resides near the intersection of this system with the southern Appalachian orogenic system and thus, the provenance of Chesterian sandstones within the basin is debated (Mars & Thomas, 1999; Xie, Cains, et al., 2016). Detrital zircons from the Lewis sandstone, at the base of the Chesterian section, contain Taconic‐Acadian and Grenville grains that define two prominent age peaks, consistent with major derivation from the Appalachian region (Xie, Cains, et al., 2016; Figure 6). The unit also contains two major clusters of Granite‐Rhyolite and Yavapai‐Mazatzal ages, suggestive of more local influence on the provenance of the sandstone.

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6.3.3. Illinois Basin and Ozark Dome
The Illinois Basin is an intracratonic basin, separated from the Appalachian Foreland in the east by the Cincinnati Arch (Quinlan & Beaumont, 1984; Root & Onasch, 1999; Figure 7). The basin is located across the transcontinental drainage system proposed by Gehrels et al. (2011). Due to its proximity to the
Appalachian orogen, sandstones developed in this basin should be sensitive to sediments sourced from the Appalachian foreland. For example, detrital zircon data of the Devonian Dutch Creek sandstone, a set of quartz arenites developed in a shelf environment, are characterized by major Archean (67%) and subordinate Grenville (16%) age clusters, suggesting that sediment may be recycled from the Ordovician St. Peter Sandstone (Wallenberg et al., 2016). The Lower Mississippian Borden siltstone is dominated by Granite-Rhyolite ages (1,550–1,300 Ma; 68% of grains) with a peak at 1,460 Ma that matches the age of the Wolf River Batholith in the north, a local source for sediments that was exposed during Early Carboniferous (Gregorich et al., 2018). By comparison, Late Mississippian (Chesterian) incised valley systems, similar to those in the Hugoton Embayment, are dominated by Taconic-Acadian and Grenville grains. The Aux Vases sandstone at the base of Chesterian is incised into St. Genevieve limestone and marks the first appearance of these Appalachian-dominated sediments (Rothschild et al., 2016).

Similar provenance shifts also occurred on the margin of the Ozark Dome, west of the Illinois Basin (Li, 2016). The Aux Vases sandstone, present on the eastern limit of the dome, is a medium-grained orthoquartzite, interbedded with limestone and shale (Thompson, 1995) that appears to be correlated with similar strata in the Illinois Basin. Detrital zircon U-Pb ages from the Aux Vases are dominated by Taconic-Acadian and Grenville grains that are distinct from the Upper Devonian Bushberg sandstone, which is characterized by pronounced Grenville and Archean age peaks (Li, 2016; Figure 6).

6.3.4. Arkoma Shelf
The Arkoma Shelf, south of the Ozark Dome, was also characterized by carbonate and shale deposition in the Late Mississippian, prior to Laurentia-Gondwana convergence and development of the Arkoma Foreland Basin (Manger & Zachry, 2009; Manger, 2014; Xie, O’Connor, et al., 2016). During this period,
two sets of Chesterian sandstones developed and are interbedded with carbonates and shales, among which the Batesville sandstone is interpreted as the first major pulse of quartz-rich clastic detritus, derived from the north-northeast by coastal currents (Handford, 1995; McGilvery et al., 2016). The stratigraphically younger Wedington sandstone formed as a constructive delta that dispersed clastic sediments from northwest to southeast across a part of the shelf (Winkelmann, 2007; Xie, O’Connor, et al., 2016; Figure 7). Compilation of Chesterian data from this study and from Xie, Cains, et al. (2016) suggests that the Archean-dominated age distribution of Early Paleozoic sandstones (Pickell, 2012) gives way to the bimodal “Appalachian” age distribution in the Late Mississippian and suggests that the Arkoma Shelf experienced a provenance change similar to other sites in North America (Figure 6).

6.3.5. Grand Canyon

Farther west, the age spectrum of Early Paleozoic and Devonian rocks from the Grand Canyon is dominated by the regional basement made up of the Yavapai-Mazatzal and Granite-Rhyolite provinces. In contrast, the age distribution of the upper Mississippian Surprise Canyon Formation, like other age-equivalent units across Laurentia, changes dramatically to a more bimodal distribution, characteristic of the Appalachian orogen (Figure 6). These Chesterian units in the Grand Canyon also consist of nonmarine and marine sediments that fill erosional valleys cut into the Lower to Upper Mississippian Redwall limestone (Billingsley & Beus, 1985), similar to IVF systems in the Hugoton Embayment.

6.3.6. Summary

As illustrated in Figure 6, the detrital zircon age distributions of pre-Mississippian (mostly Devonian) sandstones are variable, whereas Upper Mississippian sandstones across the continent have age spectra that mirror the signature of the Appalachian region. We speculate that these discontinuous and sporadically preserved sandstones may have been components of a transcontinental sediment dispersal system that initially developed in the Late Mississippian.

6.4. Spatial Analysis and Constraints on Sediment Distribution Pathways

K-S tests, MDS plots, and cumulative probability and kernel density estimation plots are used to evaluate similarities and differences between age distributions of the Chesterian IVF sandstones and temporally equivalent strata (Table 3; Figures S3, 8, and 9). As shown in these plots, detrital zircon ages from Late Mississippian sandstones across North America are similar and are dominated by Grenville and Taconic-Acadian grains (50–73%). The shift to these relatively uniform age distributions and provenance, especially when compared to Middle Paleozoic sandstones, seems to occur simultaneously across Laurentia (Figure 6), suggesting a shared provenance region, most likely in the Appalachian region (Gehrels et al., 2011; Xie, O’Connor, et al., 2016; Xie, Cains, et al., 2016). However, as illustrated in Figures 6, 8, and 9 and via statistical analysis (Table 2 and Figure S3), age distributions have some variability, suggesting that sediment dispersal from the Appalachian region was more complicated than would be expected from a simple river system draining the orogen from east to west.

In the presumed regional source area of the Appalachian Foreland Basin, the Late Mississippian temporal equivalents are synorogenic clastic-wedge deposits of the Mauch Chunk Group (Park et al., 2010; Thomas, 2011; Thomas et al., 2017). In Figure 9, it can be seen that Mauch Chunk samples (Park et al., 2010; Thomas et al., 2017), from different parts of the foreland basin, all contain large numbers of Grenville grains, commonly greater than 50%. However, variations exist in the relative proportions of Grenville and Taconic-Acadian age zircons that could be interpreted to reflect either recycling of sediments derived from the orogenic basement or sediments directly sourced from the Taconic-Acadian synorogenic magmatic and metamorphic rocks (Park et al., 2010; Thomas et al., 2017). For example, from south to north, the percentage of 1,600–1,800 Ma grains diminishes from 13% to 4% and to 2% and >1,800 Ma grains decreases from 13% to 7% and to 1% (Figure 9). These changes in the relative quantity of grains could suggest that the northernmost samples of the synorogenic clastic wedge, made up predominantly of Grenville grains and generally lacking grains older than 1,500 Ma, may be more representative of the “Appalachian signature” defined by Thomas et al. (Thomas et al., 2017; Figure 4). However, more detailed analysis of the roles of zircon fertility of the source rocks and mixing and dilution effects during transport must be accounted for. The data from the IVF sandstones in the Hugoton Embayment show a relatively large percentage of Grenville (57%) and Taconic-Acadian grains (16%), but only 8% of grains have ages >1,500 Ma (Figure 9). K-S tests suggest
these samples are most similar to the northernmost samples of the Mauch Chunk Group in the Appalachian Foreland Basin and to samples of the Aux Vases sandstone from the margin of the Ozark Dome (the basal Chesterian sandstone interval also developed in the Illinois Basin). The ages from the IVF sandstones are also similar to age data from the sample of the Wedington sandstone analyzed in this study. These similarities are also illustrated in the MDS plot through grouping of samples (Figure S3). It should be noted that published data for the Wedington sandstone from Xie, O’Connor, et al. (2016) also show large percentage of Grenville grains (52%) but fewer Paleozoic grains. Differences between our Wedington sample and that of Xie, O’Connor, et al. (2016) may relate to number of grains analyzed (N = 559 vs. N = 82 in this study). By comparison, the other Upper Mississippian samples show more complex age distributions, with fewer Grenville grains (32–46%) and higher and relatively uniform proportions of Yavapai-Mazatzal grains (15–19%), similar to samples from the southern Appalachians (Figures 8 and 9). These age distributions have composite characteristics that suggest influence from both the regional Appalachian provenance and the local midcontinent provenance associated with structural highs like the

Figure 8. Cumulative probability and kernel density estimation plots for the Upper Mississippian samples from this study and other sites across the United States.
The Early to Middle Mississippian was characterized by epeiric seas that covered much of the Laurentian interior (Manger & Zachry, 2009; Manger, 2014; Xie, O’Connor, et al., 2016). This is interpreted to have been a tectonically quiescent period on the eastern margin (between Acadian and Allegheny orogenies; Park et al., 2010). During this period, thick and extensive carbonate deposits developed across the midcontinent. This carbonate/shale blanket offers a relatively simple background for sediment dispersal in the Late Mississippian (Figure 10). From the Late Mississippian onward, the collision between Laurentia and Gondwana resulted in intense deformation and uplift along the eastern margin of the craton (Hatcher et al., 1989). The resulting topographic gradient across Laurentia may have created the conditions necessary for the birth of one or more large-scale westward-flowing river systems. The development of these Late Mississippian river systems may have been similar to the birth of the Yangtze River and other rivers associated with the uplift of Tibet (Zheng et al., 2013; Wang et al., 2017, 2018, 2019). The domination of the Appalachian age signature in Upper Mississippian sandstones across the continent, and strong similarity between samples from the Hugoton Embayment, Illinois Basin, and Arkoma Shelf and northernmost Appalachian synorogenic wedge sediments, suggests that a relatively uniform transcontinental river system likely developed in the north. The existence of such a river system could explain why N-S-oriented, southward-flowing drainage systems across the midcontinent lack the Archean signature of the northern age provinces and of Early Paleozoic sandstones and instead contain sediments more consistent with a source in the Appalachian orogen (Figures 9 and 10).

The more variable age distributions documented for other Upper Mississippian units (e.g., Chesterian in Black Warrior Basin and Batesville sandstone on the Arkoma Shelf) may be a direct influence of the Southern Appalachians and restricted structural highs such as the Ozark Dome and the now buried Nemaha Uplift and the Ozark Dome, which may have been exposed in the Late Mississippian (Xie, O’Connor, et al., 2016; Xie, Cains, et al., 2016).
and 9; Table 3). Likewise, the provenance of the Grand Canyon may reflect a combination of sediments derived from a transcontinental river system and local influence from the early uplifts associated with the Ancestral Rocky Mountains (Gehrels et al., 2011).

6.5. Relationship to IVF Systems

The recognition of somewhat similar provenance for Upper Mississippian strata across Laurentia certainly suggests the establishment of major transcontinental sediment delivery systems in the Late Mississippian. However, IVF systems across the midcontinent suggest that the sediment distribution pathways and processes are more complicated than can be represented by a simple east-west transport model. The IVF systems in the Hugoton Embayment and Illinois Basin are similar, with N-S-oriented incised valleys and sedimentary fill that suggests north-to-south (or inland to offshore) transport of sediments. The NW-SE constructive delta of Wedington sandstone on the Arkoma Shelf (Price, 1981; Winkelmann, 2007; Xie, O'Connor, et al., 2016) may have been fed by a similar drainage. This pattern indicates that sediment delivery, particularly to the shelf, was not completed through a single step. The sediments were first delivered to the north, perhaps through a major east to west flowing river with its provenance in the orogen, and subsequently delivered to the south by other river systems and processes.

For the Illinois Basin, Smith and Read (2000) proposed that incised valleys were formed by changes in the magnitude of eustatic fluctuations associated with abrupt increases in ice volume, tied to the expansion of continental glaciers. For the Hugoton Embayment, the IVF systems are also believed to be a consequence of transgressive-regressive cycles associated with sea level fluctuations (Ross & Ross, 1988). Fluvial systems across the region incised deep valleys during low stands in sea level and transported sediments from the north, southward, to the continental shelf. Sediments preserved within the incised valleys are interpreted to have been deposited and/or reworked during the transgressive part of the cycle. These sea level changes may be ultimately linked to changes in atmospheric and oceanic circulation associated with the closure of the equatorial seaway between Laurentia and Gondwana and the uplift of the Alleghanian Plateau (Smith & Read, 2000). Therefore, sediment dispersal in North America is ultimately tied to the Laurentia-
Gondwana collision and was established into two steps: (1) east to west transcontinental sediment delivery was driven by direct collision and uplift along the eastern margin of the continent and (2) north to south (or inland to offshore) sediment delivery through incised valleys was controlled by associated eustatic changes. This tectonic and depositional framework established in the Late Mississippian was inherited by Pennsylvanian and Permian depositional systems but under a more intense tectonic regime and likely with more complicated sediment dispersal systems.

7. Conclusion

In this study, we report 1,037 new concordant detrital zircon U-Pb ages from Upper Mississippian sandstones collected from core in southwestern Kansas and from outcrops in northwestern Arkansas. Based on the new data and comparisons with detrital zircon data from Paleozoic sandstones and time-equivalent units across the US, we draw several key conclusions:

1. Detrital zircon U-Pb ages from samples of Chesterian IVF sandstones from the Hugoton Embayment are similar and include two pronounced age clusters of Middle to Late Paleoproterozoic (1,300–900 Ma) and Paleozoic (500–350 Ma), which correspond to Grenville and Acadian-Taconic orogenies, and suggest major derivation from an Appalachian source region. Other age groups like the Yavapai-Mazatzal grains (1,800–1,600 Ma) and high number of Grenville grains indicate subordinate contributions from the local basement uplifts and the Midcontinent rift system.

2. Late Mississippian sandstones preserved in and/or along the Appalachian Foreland Basin, Black Warrior Basin, Illinois Basin, Ozark Dome, Arkoma Shelf, Hugoton Embayment, and Grand Canyon were likely derived from a fairly uniform E-W transcontinental river system; however, complications exist within the system due to local structural highs.

3. Sediment dispersal in North America can be interpreted as a response to the Laurentia-Gondwana collision and was established into two steps. East to west transcontinental sediment delivery was driven by collision and uplift along the eastern margin of the continent, whereas north to south (or inland to offshore) sediment delivery through incised valleys (Hugoton Embayment and Illinois Basin), one of the dispersal patterns, was controlled by associated glacioeustatic sea level fluctuations.

Data Availability Statement

The data used are listed in the references, tables, and supporting information. The full suite of data is also available through the IEDA (Interdisciplinary Earth Data Alliance) EarthChem Library (www.earthchem.org) at https://doi.org/10.1594/IEDA/111376.

References

Adler, F. J., Henslee, H. T., Hicks, I. C., Larson, T. G., Rascoe, B., & Caplan, W. M. (1971). Basement structure of the Mid-continent. AAPG Memoir, 15(2), 1000–1004.

Aleinikoff, J. N., Zartman, R. E., Walter, M., Rankin, D. W., Lyttle, P. T., & Burton, W. C. (1995). U-Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains. Geology, 15(5), 454–458. https://doi.org/10.1130/0091-7613(1995)013<0454:UZAMSW>2.3.CO;2

Billingsley, G. H., & Beus, S. S. (1985). The Surprise Canyon Formation, an Upper Mississippian and Lower Pennsylvanian(? ) rock unit in the Grand Canyon, Arizona. U.S. Geological Survey Bulletin, 1605A, A27–A33.

Bowring, S. A., & Hoppe, W. J. (1982). U/Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains. Oklahoma Geological Survey Guidebook, 21, 54–59.

Bowring, S. A., & Karlstrom, K. E. (1990). Growth, stabilization and reactivation of Proterozoic lithosphere in the southwestern United States. Geology, 18(12), 1203–1206. https://doi.org/10.1130/0091-7613(1990)018<1203:GSRoPO>2.3.CO;2

Cannon, W. F. (1994). Closing of the Midcontinent rift: A far—field effect of Grenvillian compression. Geology, 22(2), 155–158. https://doi.org/10.1130/0091-7613(1994)022<0155:CDOMR2>2.3.CO;2

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References

Aleinikoff, J. N., Zartman, R. E., Walter, M., Rankin, D. W., Lyttle, P. T., & Burton, W. C. (1995). U-Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains. Geology, 15(5), 454–458. https://doi.org/10.1130/0091-7613(1995)013<0454:UZAMSW>2.3.CO;2

Billingsley, G. H., & Beus, S. S. (1985). The Surprise Canyon Formation, an Upper Mississippian and Lower Pennsylvanian(? ) rock unit in the Grand Canyon, Arizona. U.S. Geological Survey Bulletin, 1605A, A27–A33.

Bowring, S. A., & Hoppe, W. J. (1982). U/Pb zircon ages from Mount Sheridan gabbro, Wichita Mountains. Oklahoma Geological Survey Guidebook, 21, 54–59.

Bowring, S. A., & Karlstrom, K. E. (1990). Growth, stabilization and reactivation of Proterozoic lithosphere in the southwestern United States. Geology, 18(12), 1203–1206. https://doi.org/10.1130/0091-7613(1990)018<1203:GSRoPO>2.3.CO;2

Cannon, W. F. (1994). Closing of the Midcontinent rift: A far—field effect of Grenvillian compression. Geology, 22(2), 155–158. https://doi.org/10.1130/0091-7613(1994)022<0155:CDOMR2>2.3.CO;2
Caswood, P. A., & Nemchin, A. A. (2001). Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians. *Geological Society of America Bulletin*, 113(9), 1234–1246. https://doi.org/10.1130/0016-7606(2001)113<1234:PFDETOS>2.0.CO;2

Cirillo, L. L. (2002). Transgressive estuarine fill of an incised paleovalley, Upper Mississippian Chesterian series, Shuck field area, Seward County, Kansas (Master’s thesis). Houston, TX: University of Houston.

Donaldson, J. A., & Irving, E. (1972). Grenville front and rifting of the Canadian Shield. *Nature*, 237(78), 139–140.

Dubois, M. K., Williams, E. T., Hedke, D. E., Senior, P. R., & Youle, J. C. (2014). Pleasant Prairie South reservoir characterization, modeling and simulation. A technical report in Watney W. L. (Ed.) Final report for DOE Award Number: DE-FE0002056, Modeling CO2 sequestration in saline aquifer and depleted oil reservoir to evaluate regional CO2 sequestration potential of Ozark Plateau aquifer system, South-Central Kansas. https://doi.org/10.2172/1262271

Dubois, M. K., Williams, E. T., Youle, J. C., & Hedke, D. E. (2014b). Eubank North Unit reservoir characterization, modeling and simulation. A technical report in Watney W. L. (Ed.) Final report for DOE Award Number: DE-FE0002056, Modeling CO2 sequestration in saline aquifer and depleted oil reservoir to evaluate regional CO2 sequestration potential of Ozark Plateau aquifer system, South-Central Kansas. https://doi.org/10.2172/1262271

Dubois, M. K., Williams, E. T. Youle, J. C. & Hedke, D. E. (2014c). Shuck Field Chester incised valley fill reservoir characterization, modeling and simulation. A technical report in Watney W. L. (Ed.) Final report for DOE Award Number: DE-FE0002056, Modeling CO2 sequestration in saline aquifer and depleted oil reservoir to evaluate regional CO2 sequestration potential of Ozark Plateau aquifer system, South-Central Kansas. https://doi.org/10.2172/1262271

Eriksson, K. A., Campbell, I. H., Palin, J. M., Allen, C. M., & Bock, B. (2004). Evidence for multiple recycling in Neoproterozoic through Paleozoic strata in the Grand Canyon, Arizona. *Lithosphere*, 6(1), 151–160. https://doi.org/10.1016/j.lithos.2012.06.003

Finzel, E. S. (2014). Detrital zircons from Cretaceous midcontinent strata reveal an Appalachian Mountains–Cordilleran foreland basin connection. *Lithosphere*, 6(5), 378–382. https://doi.org/10.1130/L140.1

Gehrels, G. E., Blakey, R., Karlstrom, K. E., Timmons, J. M., Dickinson, B., & Pecha, M. (2011). Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona. *Lithosphere*, 3(3), 183–200. https://doi.org/10.1130/L121.1

Gray, M. B., & Zeitler, P. K. (1997). Comparison of clastic wedge provenance in the Appalachian foreland using U/Pb ages of detrital zircons. *Tectonics*, 16(1), 151–160. https://doi.org/10.1029/96TC02911

Gregortich, H., Mclaughlin, P. L., Malone, D., & Craddock, J. (2018). Evidence for long distance eolian transport of 1460 Ma zircons in the Borden siltstone, Illinois Basin, USA. An abstract presented at the GSA annual meeting, Indianapolis, IN.

Guy, J., & Gehrels, G. (2006). Comparison of detrital zircon age distribution using the K-S test. K-S test instruction of the Arizona LaserChron Center. Retrieved from https://drive.google.com/file/d/0B9ezu34PS8eZWMzOwUzOTfZDgyZi00NDRlLWE4ZCtCTbTjNTM5OTU1MGUz/view?hl=en

Handford, C. R. (1995). Basalplains patterns and the recognition of lowstand exposure and drowning; a Mississippian-ramp example and its seismic signature. *Journal of Sedimentary Research, 65*(6b), 323–337.

Hanson, R. E., Puckett, R. E. Jr., Keller, G. R., Brueseke, M. E., Bulen, C. L., Mertzman, S. A., et al. (2013). Intraplate magmatism related to opening of the southern Lapetus Ocean: Cambrian-Wiuchi igneous province in the Southern Oklahoma rift zone. *Lithos*, 174, 57–70. https://doi.org/10.1016/j.lithos.2012.06.003

Hatcher, R. D. Jr. (2005). *Southern and Central Appalachians*. London, UK: Elsevier.

Hatcher, R. D. Jr., Thomas, W. A., & Geiser, P. A. (1989). Alleghanian orogen. In R. D. Hatcher, Jr., W. A. Thomas, & G. W. Viele (Eds.), *The Appalachian Ouachita orogen in the United States* (Vol. F-2, pp. 233–318). Boulder, CO: Geological Society of America.

Hauser, E. C. (1996). Midcontinent rifting in a Grenville environment. In B. A. Pliujm, & F. A. Catacosinos (Eds.), *Basement and basins of eastern North America* (pp. 65–75). Boulder, CO: Geological Society of America Special Papers.

Heatherington, A. L., Mueller, P. A., & Wood, J. (2010). Alleghanian plutonism in the Susawanne terrane, USA: Implications for late Paleozoic tectonic models. *Memoir - Geological Society of America*, 206, 607–620.

Hellstrom, J., Paton, C., Woodhead, J., & Hergt, J. (2008). Iolite: Software for spatially resolved LA-(Quad and MC)-ICP-MS analysis. Laser ablation ICP-MS in the Earth Sciences. *MAC Short Course Series*, 40, 343–348.

Hoffman, P. F. (1989). Precambrian geology and tectonic history of North America. In A. W. Bally (Ed.), *The geology of North America—An overview* (pp. 447–512). Boulder, CO: Geological Society of America.

Hogan, J. P., & Gilbert, M. C. (1998). The Southern Oklahoma Aulacogen: A Cambrian analog for mid-Proterozoic AMCG (Anorthosite-Mangerite-Charnockite-Granite) complexes? In: Hogan J.P., and Gilbert M.C. (eds) Basement tectonics 12. Proceedings of the international conferences on basement tectonics, vol 6. Springer, Dordrech. doi: 10.1007/978-0-411-01598-9_3

Ibrahim, D. M. (2016). High-resolution sequence stratigraphy and detrital zircon provenance of the Ordovician Ancell group in the Iowa and Illinois Basins: Insight into the evolution of midcontinental intracontinental basins of North America (Doctoral dissertation). Retrieved from Iowa Research Online. (https://doi.org/10.17077/etd.0rat94k). Iowa City, IA: University of Iowa.

Isbell, J. L., Lenaker, P. A., Askin, R. A., Miller, M. F., & Babcock, L. E. (2005). Reevaluation of the timing and extent of late Paleozoic glaciation in Gondwana: Role of the transantarctic mountains. *Geology*, 33(11), 977–980. https://doi.org/10.1130/G19810.1

Jackson, S. E., Pearson, N. J., Griffin, W. L., & Belousova, E. A. (2004). The application of laser ablation-inductively coupled plasma mass spectrometry to in situ U-Pb zircon geochronology. *Chemical Geology*, 211(1-2), 47–69. https://doi.org/10.1016/j.chemgeo.2004.06.017

Jones, A., Sturmer, D. M., Bidgoli, T. S., & Müller, A. (2019). Sediment Routing and Provenance of Shallow to Deep Marine Sandstones in the Late Paleozoic Oquirrh Basin, Utah. *Geological Society of America Annual Meeting Abstracts with Program, 51*(5). https://doi.org/10.1130/abs/2019AM-337719

Kissick, J. K. (2016). Detrital zircon evidence for the unroofing of the northern Appalachians in early-middle Pennsylvaniaian sandstones of North America (Master's thesis). Retrieved from Iowa Research Online (https://doi.org/10.17077/etd.ktJ5ap87). Iowa City, IA: University of Iowa.

Kissick, J. K., Finzel, E. S., Malone, D. H., & Craddock, J. P. (2018). Lower-Middle Pennsylvaniaian strata in the North American midcontinent record the interplay between erosional unroofing of the Appalachians and eustatic sea-level rise. *Geosphere*, 14(1), 141–161. https://doi.org/10.1130/GEOS15121.1

Konstantinou, A., Wirth, K. R., Vervoort, J. D., Malone, D. H., Davidson, C., & Craddock, J. P. (2014). Provenance of quartz arenites of the early Paleozoic Midcontinent region, USA. *Journal of Geology*, 122(2), 201–216. https://doi.org/10.1086/675327

Lane, H. R. (1978). The Burlington shelf (Mississippian, north-central United States). *Geologica et Palaeontologica*, 12, 165–176.
Lawton, T. F., Buller, C. D., & Parr, T. R. (2015). Provenance of a Permian erg on the western margin of Pangea: Depositional system of the Kungurian (late Leonardian) Castle Valley and White Rim sandstones and subjacent Cutler Group, Paradox Basin, Utah, USA. *Geosphere*, 11(5), 1475–1506. https://doi.org/10.1130/GES01174.1

Leary, R. J., Umhoefer, P., Smith, M. E., & Riggs, N. (2017). A three-sided oregen: A new tectonic model for Ancestral Rocky Mountain uplift and basin development. *Geology*, 45(8), 735–738.

Li, B. (2016). Paleogeogra detrital zircon geochronology of Upper Cambrian to Lower Mississippian siliciclastic strata of the Ozark Dome and vicinity (Master’s thesis) (http://scholarsmine.mst.edu/masters_theses/7741). Rolla, MO: Missouri University of Science and Technology.

Ludwig, K. R. (2008). Isoplot 3.6. Berkeley Geochronology Center, Special Publication, 4, 77

Lukert, S., & Onasch, C. M. (1999). Structure and tectonic evolution of the transitional region between the central Appalachian foreland and the Superior region, Northwestern Arkansas. *AAPG Midcontinent Section Meeting Field Trip*, October 10-11.

Mars, J. C., & Thomas, W. A. A. (1999). Sequential filling of a late Paleozoic foreland basin. *Journal of Sedimentary Research, 69*(6), 1191–1208. https://doi.org/10.2110/jsr.69.1191

McGillivary, T. A., Manger, W. L., & Zachry, D. L. (2016). Summary and guidebook to the depositional and tectonic history of the Carboniferous succession Northwest Arkansas. *AAPG Midcontinent Section Meeting Field trip*, September 30-October 2.

McLean, N. M., Bowring, J. F., & Gehrels, G. (2016). Algorithms and software for U-Pb geochronology by LA-ICPMS. *Geochemistry, Geophysics, Geosystems*, 17, 2480–2496. https://doi.org/10.1002/2015GC006097

McLennan, S. M., Bock, B., Compston, W., Hemming, S. R., & McDaniel, D. K. (2001). Detrital zircon geochronology of Taconian and Acadian foreland sedimentary rocks in New England. *Journal of Sedimentary Research, 71*(2), 305–317. https://doi.org/10.1306/072600710305

Montañez, I. P., & Poulsen, C. J. (2013). The Late Paleozoic ice age: An evolving paradigm. *Annual Review of Earth and Planetary Sciences, 41*(1), 629–656. https://doi.org/10.1146/annurev-earth-031208.100118

Montgomery, S. L., & Morrison, E. (1999). South Eubank field. Haskell County, Kansas: A case of field redevelopment using subsurface mapping and 3-D seismic data. *AAPG Bulletin*, 83(3), 393–409.

Ojakangas, R. W., Morey, G. B., & Green, J. C. (2001). The Mesoproterozoic Midcontinent Rift System, Lake Superior Region, USA. *AAPG Bulletin*, 14(3), 421–442.

Park, H., Barbeau, D. L. Jr., Rickenbaker, A., Bachmann-Krug, D., & Gehrels, G. (2010). Application of foreland basin detrital zircon geochronology to the reconstruction of the Southern and Central Appalachian Orogen. *Journal of Geology, 118*(1), 23–44.

Paton, C., Heilström, J., Paul, B., Woodhead, J., & Hecht, J. (2011). Jolie: Freeware for the visualization and processing of mass spectrometric data. *Journal of Analytical and Atomic Spectrometry, 26*(12), 2508–2518. https://doi.org/10.1039/c1ja10172b

Pickell, M. (2012). Detrital zircon geochronology of Middle Ordovician siliciclastic sediment on the Southern Laurentian Shelf (Master’s thesis), College Station, TX: Texas A&M University.

Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. (1986). *Numerical recipes: The art of scientific computing*, Cambridge, UK: Cambridge University Press.

Price, C. R. (1981). Transportational and depositional history of the Wedington sandstone (Mississippian), Northwest Arkansas (Master’s thesis), Fayetteville, AR: University of Arkansas.

Qiao, L., & Shen, S. Z. (2015). A global review of the Late Mississippian (Carboniferous) Gigantoproductus (Brachiopoda) faunas and their paleogeographical, paleoecological and paleoclimatic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 433(1), 262–263. https://doi.org/10.1016/j.palaeo.2015.05.031

Quinlan, G. M., & Beaumont, C. (1984). Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North America. *Canadian Journal of Earth Sciences, 21*(9), 973–996. https://doi.org/10.1139/e84-103

Rascoe, B. J., & Adler, F. J. (1983). Permo-Carboniferous hydrocarbon accumulations, Midcontinent, USA. *AAPG Bulletin, 67*(6), 979–1001.

Root, S., & Onasch, C. M. (1999). Structure and tectonic evolution of the transitional region between the central Appalachian foreland and interior cratonic basins. *Tectonophysics*, 305(1–3), 205–223. https://doi.org/10.1016/S0040-1951(99)00222-0

Ross, C. A., & Ross, J. R. (1988). Late Paleozoic transgressive deposition. In D. K. Wilgus (Ed.), *Sea level changes: An integrated approach* (pp. 227–247). SEPM Special Publication 42.

Rothscheld, T. J., Malone, D. H., Craddock, J. P., & Devera, J. (2016). Detrital zircon geochronology of Chesterian sandstones in the Illinois Basin, USA. Paper presented at the Conference on Geological Society of America. Denver, CO

Runkel, A. C., Miller, J. F., McKay, R. M., Palmer, A. R., & Taylor, J. F. (2007). High paleogeography in an intermontane region: How do we interpret these rare earth element patterns and what are their implications? *Geology*, 35(11), 943–946. https://doi.org/10.1130/G24490A.1

Senior, P. J. (2012). Depositional environment, reservoir properties, and EOR potential of an incised-valley-fill sandstone, Pleasant Prairie Oilfield, Haskell County, Kansas (Master’s thesis). Retrieved from KU ScholarWorks (https://kuscholarworks.ku.edu/handle/1808/10086). Lawrence, KS: University of Kansas.

Smits, P. K. (1996). Early Proterozoic Penokean orogen. In P. K. Sim, & L. M. H. Carter (Eds.), *Archean and Proterozoic geology of the Lake Superior region* (pp. 28–30). USA: U.S. Geological Survey.

Smola, J., Kosler, J., Condon, D. J., Crowley, J. L., Gerdes, A., Hanchan, J. M., et al. (2008). Plešovice zircon—A new natural reference material for U-Pb and Hf isotopic microanalysis. *Chemical Geology*, 249(1-2), 1–35. https://doi.org/10.1016/j.chemgeo.2007.11.005

Smith, L. B. Jr., & Read, J. F. (2000). Rapid onset of late Paleozoic glaciation on Gondwana: Evidence from Upper Mississippian strata of the Midcontinent, United States. *Geology, 28*(3), 279–282. https://doi.org/10.1130/0016-760X(2000)28<279:ROPLGA>2.0.CO;2
Thomas, W. A. (2011). Detrital-zircon geochronology and sedimentary provenance. *Lithosphere*, 3(4), 304–308. https://doi.org/10.1130/L1.1

Thomas, W. A. (2014). A mechanism for tectonic inheritance at transform faults of the Iapetan margin of Laurentia. *Geoscience Canada*, 41(3), 321–344. https://doi.org/10.12789/geo.canada.2014.41.048

Thomas, W. A., Gehrels, G. E., Greb, S. F., Nadon, G. C., Satkoski, A. M., & Romero, M. C. (2017). Detrital zircons and sediment dispersal in the Appalachian foreland. *Earth and Planetary Science Letters*, 444, 220–230. https://doi.org/10.1016/j.epsl.2015.11.030

Thomas, W. A., Gehrels, G. E., & Romero, M. C. (2016). Detrital zircons from crystalline rocks along the Southern Oklahoma fault system, Wichita and Arbuckle Mountains, USA. *Geosphere*, 12(4), 1224–1234. https://doi.org/10.1130/GES01316.1

Thompson, T. L. (1995). The stratigraphic succession in Missouri. Missouri Department of Natural Resources, Division of Geology and Land Survey, 2nd series.

Tohver, E., Teixeira, W., Ben, V. D. P., Gerais, M. C., Bettencourt, J. S., & Rizzotto, G. (2006). Restored transect across the exhumed Grenville orogen of Laurentia and Amazonia, with implications for crustal architecture. *Geology*, 34(8), 669–672. https://doi.org/10.1130/G22534.1

Van Schmus, W. R., Bickford, M. E., & Anderson, J. L. (1993). Transcontinental Proterozoic provinces. In J. C. Reed, Jr., M. E. Bickford, & R. S. Houston (Eds.), *Precambrian: discontinuous U. S.* (pp. 171–334), Boulder, CO: Geological Society of America.

Vermeesch, P. (2012). On the visualisation of detrital age distributions. *Chemical Geology*, 312, 190–194.

Vermeesch, P. (2013). Multi-sample comparison of detrital age distributions. *Chemical Geology*, 341, 140–146. https://doi.org/10.1016/j.chemgeo.2013.01.010

Vermeesch, P., Resentini, A., & Garzanti, E. (2016). An R package for statistical provenance analysis. *Sedimentary Geology*, 336, 14–25. https://doi.org/10.1016/j.sedgeo.2016.01.009

Wallenberg, A., Malone, D. H., Day, J. E., & Devera, J. (2016). Detrital zircon geochronology of the Devonian Dutch Creek sandstone in the Southern Illinois Basin. An abstract presented at the GSA annual meeting, Denver, CO.

Wang, W., & Bidgoli, T. S. (2019) Detrital zircon analysis of Late Mississippian Wallenberg, A., Malone, D. H., Day, J. E., & Devera, J. (2016). Detrital zircon geochronology of the Devonian Dutch Creek sandstone in the Southern Illinois Basin. An abstract presented at the GSA annual meeting, Denver, CO.

Wang, W., Bidgoli, T. S. (2019) Detrital zircon analysis of Late Mississippian-Early Pennsylvanian sediments and implications for the reliability of double-dating in provenance analysis in the central U.S. *Geological Society of America Abstracts with Programs*, 51(5). https://doi.org/10.1130/abs/2019AM-340383

Wang, W., Bidgoli, T. S., Yang, X., & Ye, J. (2018). Source-to-sink links between East Asia and Taiwan from detrital zircon geochronology of the Oligocene Huagang Formation in the East China Sea Shelf Basin: Geochemistry, Geophysics, Geosystems, 19(10), 3673–3688. https://doi.org/10.1029/2018GC007576

Wang, W., Yang, X., Bidgoli, T. S., Ye, J., & Zeng, Z. (2019). Detrital zircon geochronology reveals source-to-sink relationships in the Pearl River Mouth Basin, China. *Sedimentary Geology*, https://doi.org/10.1016/j.sedgeo.2019.04.004

Wang, W., Ye, J., Bidgoli, T., Yang, X., Shi, H., & Shu, Y. (2017). Using detrital zircon geochronology to constrain Paleogene provenance and its relationship to rifting in the Zhu 1 Depression, Pearl River Mouth Basin, South China Sea. *Geochemistry, Geophysics, Geosystems*, 18(11), 3976–3999. https://doi.org/10.1002/2017GC007110

Wehr, F., & Glover, L. (1985). Stratigraphy and tectonics of the Virginia-North Carolina Blue Ridge: Evolution of a late Proterozoic-early Paleozoic hinge zone. *Geological Society of America Bulletin*, 96(3), 285–295. https://doi.org/10.1130/0016-7606(1985)96<285:SAOTV>2.0.CO;2

Whitmeyer, S. J., & Karlstrom, K. E. (2007). Tectonic model for the Proterozoic growth of North America. *Geosphere*, 3(4), 220–259. https://doi.org/10.1130/GES00055.1

Winkelmann, W. (2007). Wedington isopachous Map. Southwestern Energy, document for internal circulation.

Wotzlaw, J. F., Schaltegger, U., Frick, D. A., Dungan, M. A., Gerdes, A., & Günther, D. (2013). Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. *Geology*, 41(8), 867–870. https://doi.org/10.1130/G34366.1

Wright, J. E., Hogan, J. P., & Gilbert, M. C. (1996). The Southern Oklahoma Aulacogen: Not just another BLIP. *American Geophysical Union Transactions*, 77, F845.

Xie, X., Anthony, J. M., & Bushey, A. B. (2018). Provenance of Permian Delaware Mountain Group, central and southern Delaware Basin, and implications of sediment dispersal pathway near the southwestern terminus of Pangea. *International Geology Review*, 61, 361–380.

Xie, X., Buratowski, G., Manger, W. L., & Zachey, D. (2018). U-Pb detrital zircon geochronology of the Middle Bloyd sandstone (Morrowan) of northern Arkansas (USA): Implications for Early Pennsylvanian sediment dispersal in the Laurentian Foreland. *Journal of Sedimentary Research*, 88(7), 795–810. https://doi.org/10.1115/jsr.2018.47

Xie, X., Cairns, W., & Manger, W. L. (2015). U-Pb detrital zircon evidence of transcontinental sediment dispersal: Provenance of Late Mississippian Wedington sandstone member, NW Arkansas. *International Geology Review*, 58(15), 1951–1966. https://doi.org/10.1080/00206814.2016.1193775

Xie, X., O’Connor, P. M., & Absleben, H. (2016). Carboniferous sediment dispersal in the Appalachian–Ouachita juncture: Provenance of selected late Mississippian sandstones in the Black Warrior Basin, Mississippi, United States. *Sedimentary Geology*, 342, 191–201. https://doi.org/10.1016/j.sedgeo.2016.07.007

Xu, J., Stockli, D. F., & Snedden, J. W. (2017). Enhanced provenance interpretation using combined U-Pb and (U-Th)/He double dating of detrital zircon grains from lower Miocene strata, proximal Gulf of Mexico Basin, North America. *Earth & Planetary Science Letters*, 475, 44–57. https://doi.org/10.1016/j.epsl.2017.07.024

Zheng, H., Clift, P. D., Wang, F., Tada, R., Jia, J., He, M., & Jourdan, F. (2013). Pre-Miocene birth of the Yangtze River. *Proceedings of the National Academy of Sciences*, 110(19), 7556–7561. https://doi.org/10.1073/pnas.1216244110