Palaeogeography, Palaeoclimatology, Palaeoecology xxx (xxxx) 110750

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Exploring the influence of Late Mississippian to Middle Pennsylvanian tectonics on sediment transport through detrital zircon geochronology, southwestern Kansas and northwestern Arkansas

Wei Wang[a, b, c], Tandis S. Bidgoli[b, *], Daniel M. Sturmer[d]

[a] School of Earth Resources, China University of Geosciences, Wuhan 430074, Hubei, China
[b] Department of Geological Sciences, University of Missouri, Columbia, MO 95211, USA
[c] Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, China University of Geosciences, Wuhan 430074, China
[d] Department of Geology, University of Cincinnati, Cincinnati, OH 45221, USA

ARTICLE INFO

Editor: Howard Falcon-Lang

Keywords:
U-Pb
Ancestral Rocky Mountains
Carboniferous
Appalachian
Alleghanian
Transcontinental sediment

ABSTRACT

This study explores the influence of the Alleghanian-Ouachita-Marathon Orogeny and Ancestral Rocky Mountains (ARM) uplifts on sediment dispersal in the Carboniferous through sandstone compositions and detrital zircon provenance analysis. We focus on Upper Mississippian to Middle Pennsylvanian siliciclastic intervals in two areas: (1) the Hugoton Embayment in southwestern Kansas, where six samples of Upper Mississippian and Lower Pennsylvanian sandstone were collected from two boreholes and (2) the Arkoma Shelf and foreland basin in northwestern Arkansas, where nine samples were collected from Lower through Middle Pennsylvanian outcrops. We report 1544 new concordant ages, 582 ages from Kansas core and 962 ages from Arkansas outcrop samples. U—Pb age spectra are characterized by major Grenville (900–1300 Ma) and Taconic-Acadian (350–500 Ma) age clusters and minor components of older age groups, suggesting a persistent source in the Appalachians tied to the Alleghanian orogeny. However, by Early Pennsylvanian, the Hugoton Embayment samples see the Appalachian source partially replaced by Yavapai-Mazatzal (1800–1600 Ma) and Granite-Rhyolite (1550–1300 Ma) grains, major components of the local basement, that suggest contributions from nearby ARM uplifts. In contrast, contributions from midcontinent basement sources are limited in the Arkoma Shelf and foreland basin samples. Sandstone composition data are also consistent across all Arkoma Shelf and Upper Mississippian Hugoton Embayment samples; whereas, Lower Pennsylvanian Hugoton samples show increases in feldspar and volcanic lithic grains, consistent with input from local midcontinent age provinces. Comparison with published data suggests a similar change in provenance, from extraregional to local sediment sources, is observed across western Laurentia where ARM deformation was active. Together, new and published data support development of a major transcontinental sediment dispersal system in the Late Mississippian, controlled by Alleghanian orogenesis on the eastern Laurentian margin; however, by the Early Pennsylvanian this system was disrupted by development of the ARM.

1. Introduction

The tectonic landscape of the Carboniferous was complex, with orogenesis occurring along much of the Laurentian margin. The Appalachian orogenic series culminated in the Alleghanian orogeny on the eastern margin of Laurentia, and the southern margin of the continent saw the east-to-west closure of the Rheic Ocean and deformation tied to the Ouachita-Marathon orogeny (Hatcher Jr et al., 1989; Hatcher, 2002). These events and the development of mountains that may have been similar to the scale of modern-day Tibet had profound effects on the landscape. It has been proposed that a major consequence of this changing tectonic landscape was the establishment of transcontinental sediment transport systems, whereby sandstones as far west as in the Grand Canyon of Arizona were sourced from the Appalachian orogen through a system of westward flowing rivers and wind and ocean currents (Gehrels et al., 2011; Chapman and Laskowski, 2019; Wang and Bidgoli, 2019; Lawton et al., 2021). Although an Appalachian source for Mississippian and younger sediments is evident and widely accepted (Gehrels et al., 2011; Xie et al., 2016; Alsalem et al., 2017; Thomas et al., 2017; Kissock et al., 2018; Jones et al., 2019; Wang and Bidgoli,

* Corresponding author.
E-mail address: bidgolit@missouri.edu (T.S. Bidgoli).

https://doi.org/10.1016/j.palaeo.2021.110750
Received 1 June 2021; Received in revised form 26 October 2021; Accepted 2 November 2021

2019; Chapman and Laskowski, 2019; Thomas et al., 2020; Waite et al., 2020), the details of this continental-scale sediment transport system remain enigmatic. In particular, the role of deformation occuring in the interior of Laurentia on Carboniferous sediment dispersal and provenance has remained elusive.

While the influence of Alleghanian orogenesis on Carboniferous sediment dispersal is well discussed (e.g., Chapman and Laskowski, 2019; Thomas et al., 2020), during this same period, the interior of the craton was experiencing the far-field effects of convergence along its margins (Curtis, 1958; Mallory, 1958; Kluth, 1986; Kluth and Coney, 1981; Ye et al., 1996; Dickinson and Lawton, 2003; Lawton et al., 2017; Leary et al., 2017). Intraplate stress transmission resulted in the development of a series of dominantly NNW- to NW-trending basement-cored structural highs, known as the Ancestral Rocky Mountains (ARM), and adjacent basins, that span much of the central and western USA (Fig. 1A). The most prominent of these ARM uplifts, the Front Range and Uncom-

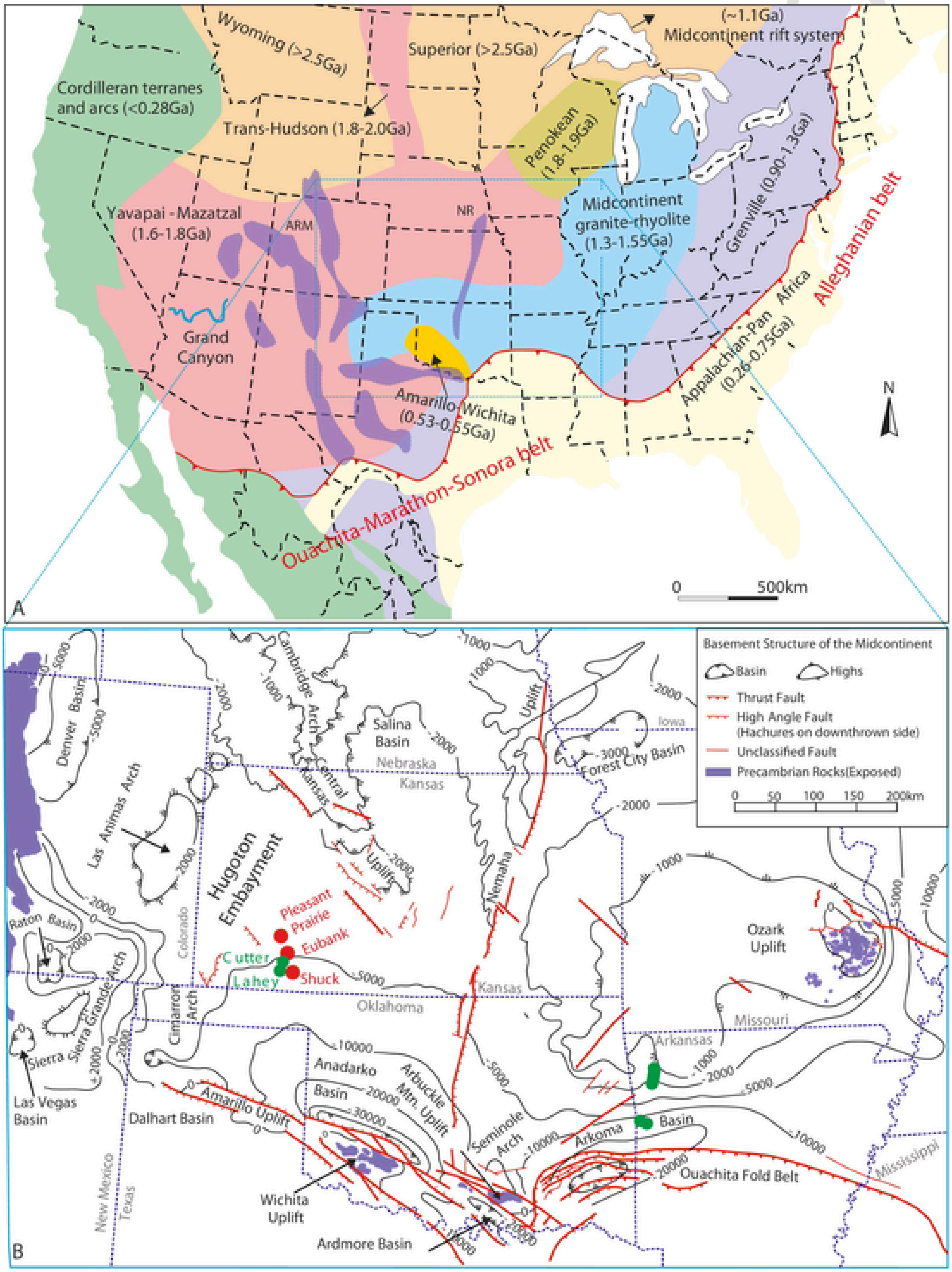


Fig. 1. (A) Distribution of major age provinces in central and southern North America and location of Kansas and Arkansas study regions (red boxes) (modified from Park et al., 2010; Gehrels et al., 2011; and Xu et al., 2017). Major tectonic elements shown in red. ARM uplifts shown in purple. (B) Basement structure of the midcontinent (modified from Rascoe and Adler, 1983). Contours are in feet (1 ft ≈ 0.3045 m). Chester (red) and Morrow (green) oil fields and outcrop sites are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

paghre uplifts, have kilometers of vertical displacement, and the products of their erosion were preserved in nearby basins (Eardley, 1951; Kluth and Coney, 1981; Barbeau, 2003; Leary et al., 2020). But other structures, generally believed to belong to the ARM, like the buried Nemaha Ridge in Kansas and Oklahoma, are more subtle features and their influence on provenance and sediment routing is not clear (Fig. 1; Xie et al., 2018; Thomas et al., 2020).

Since publication of the Gehrels et al. (2011) model, a large number of studies have explored the provenance of sediments across Laurentia and different aspects of the continental-scale transport model. The provenance of Carboniferous sandstones in eastern Laurentia, including in the Appalachian foreland basin and nearby intracratonic basins like the Michigan and Illinois basins is well studied (e.g., Xie et al., 2016; Li, 2016; Rothschild et al., 2016; Thomas et al., 2017; Xie et al., 2018; Kissock et al., 2018; Thomas et al., 2020). Similarly, a great deal of effort has gone into understanding the influences of local and extraregional sediment transport to many of the ARM and temporally equivalent basins in western Laurentia (e.g., Sweet and Soreghan, 2010; Nair et al., 2018; Leary et al., 2020). However, the intervening region in the central USA is poorly studied, in part, because few sandstones are available for study along the carbonate-shale dominated shelf, and many of the age-equivalent formations are now buried in the subsurface.

This study explores the influence of the Alleghanian-Ouachita-Marathon orogeny and Ancestral Rocky Mountains uplifts on sediment dispersal in the Carboniferous through sandstone compositional and detrital zircon provenance analysis. We focus on two areas that reside along proposed transcontinental sediment transport routes: (1) the Hugoton Embayment in southwestern Kansas, where Upper Mississippian and Lower Pennsylvanian sandstones form a stacked incised valley fill complex and one of the few targets for study within the carbonate-shale-dominated sequence and (2) the Arkoma Shelf in northwestern Arkansas, where Upper Mississippian through Middle Pennsylvanian sandstones capture the transition from a carbonate shelf to a clastic-dominated foreland. The new ages are compared to published detrital zircon data from age-equivalent sandstones across North America to evaluate the role of extraregional versus local provenance and the influence of the ARM orogen and related uplifts on continental-scale sediment transport.

2. Geological setting

2.1. Tectonic background

The Carboniferous was a dynamic time interval in North America, with major changes taking place in tectonics, climate, and sedimentation linked to the Laurentia-Gondwana collision and the eventual amalgamation of the Pangean supercontinent (Ziegler, 1990; Trappe, 2000; Stampfli et al., 2013). Orogenesis was concentrated along the eastern, southern, and western margins of Laurentia (Fig. 1a). On the eastern margin, deformation culminated in the Alleghanian orogeny, the last major collision of the Appalachian series, overprinting the earlier Taconic (Ordovician) and Acadian (Devonian–Early Mississippian) orogenies (Hatcher Jr et al., 1989; Hatcher, 2002). Along the southern Laurentian margin, the Alleghanian belt merges into the Ouachita-Marathon system. The orogenic system formed during late subduction-collision of the Laurentian margin beneath Gondwana (South America) (Graham et al., 1975; Drake et al., 1989; Granath, 1989; Poole et al., 2005; Nance and Linnemann, 2008). However, there is debate on the plate margin configuration, with some studies suggesting that Laurentia was in the upper plate of the subduction system prior to collision and final closure (Domeier and Torsvik, 2014). This belt of deformation continues into Mexico, through Chihuaha and Sonora, and may become transpressional (e.g., Dickinson and Lawton, 2003; Leary et al., 2017). Along the western margin of Laurentia, the Antler orogeny and subsequent deformation is documented; however, the underlying cause of this recognized period of deformation is debated (e.g., Nilsen and Stewart, 1980; Speed and Sleep, 1982; Trexler Jr et al., 2003, 2004; Lawton et al., 2017).

In addition to orogenesis along the Laurentian margin, the interior of the craton was also the site of deformation related to the ARM orogen. The ARM are a complex zone of intraplate strain that may be linked to one or more of the above described zones of convergence (Fig. 1; e.g., Curtis, 1958; Mallory, 1958; Kluth, 1986; Kluth and Coney, 1981; Ye et al., 1996; Dickinson and Lawton, 2003; Lawton et al., 2017; Leary et al., 2017). The basement-involved structural highs and adjacent basins of the ARM orogen span a large swath of the central and western USA and northern Mexico, and include prominent fault-controlled structural highs with kilometers of vertical displacement (e.g., the Front Range and Uncompaghre uplifts) to more subtle arches and troughs that may be reactivated Precambrian basement features (e.g., Nehama Ridge) (Eardley, 1951; Kluth and Coney, 1981; Barbeau, 2003). The main phase of ARM activity spans the Pennsylvanian to early Permian, however, the timing of initiation is not well-constrained or uniform and may have been as early as Late Mississippian (Kluth, 1998; Ye et al., 1996; Dickinson and Lawton, 2003; Leary et al., 2017; Sweet et al., 2021).

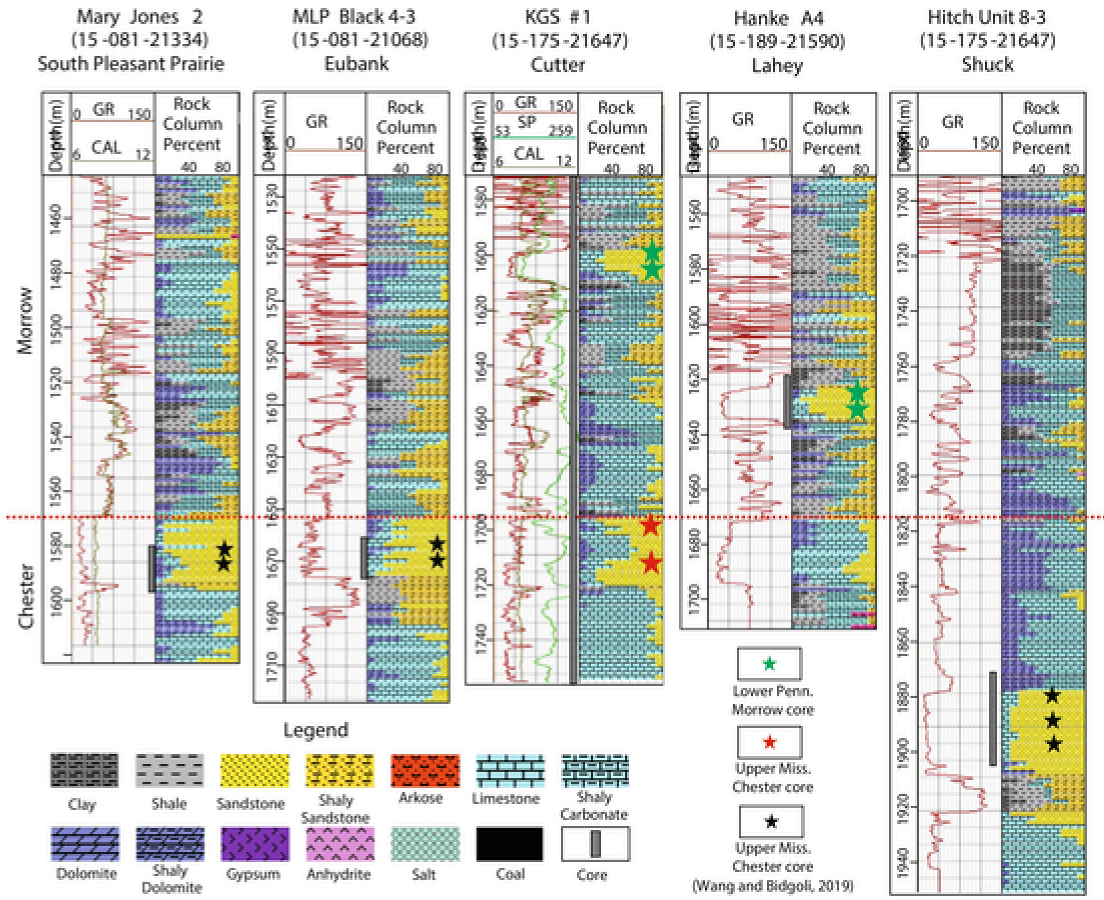
2.2. Carboniferous depositional systems in the midcontinent

In the Early to Middle Mississippian, in the southern midcontinent was a broad tropical carbonate platfrom. This platform, the Burlington Shelf, extended from present-day Kansas into Missouri and northern Arkansas (Lane and De Keyser, 1980; Gutschick and Sandberg, 1983; Manger, 2014; Xie et al., 2016). Deposition in southwestern Kansas and northwestern Arkansas was characterized by interbedded shallow-water limestone and shale during Kinderhookian through Meremecian (Tournaisian to middle Visean) time (Figs. 2 and 3; Rascoe and Adler, 1983; Montgomery and Morrison, 1999). However, by the Late Mississippian to Early Pennsylvanian, the shelf was increasingly invaded by siliciclastic sediments (Montgomery and Morrison, 1999; Bowen and Weimer, 2003; McGilvery et al., 2016; Xie et al., 2016). In Arkansas, the carbonate shelf was eventually replaced by a siliciclastic-dominated foreland basin (Sutherland, 1988).

2.2.1. Incised valley fill systems in southwestern Kansas

In southwestern Kansas, sandstones occur in incised valley fill systems that developed during two time intervals: the Late Mississippian and the Early Pennsylvanian (Montgomery and Morrison, 1999; Cirilo, 2002; Bowen and Weimer, 2003; Senior, 2012). Across the Hugoton Embayment, a shallow extension of Andarko Basin, a Chesterian (Serpukhovian) incised valley fill system is well-documented in several oil and gas fields (Fig. 1b). This incised valley fill system developed during a regressive-transgressive cycle, cutting a valley more than 70 m deep in places, that can be tracked in subsurface datasets (e.g., wells and seismic data) for over 160 km from Kansas into Oklahoma (Montgomery and Morrison, 1999; Cirilo, 2002; Senior, 2012). In the Pleasant Prairie field, the northernmost part of the preserved incised valley fill system, fluvial sandstones are documented in core. Farther south, in the Eubank and Shuck fields, core study reveals more tidally-influenced estuarine environments, relative to the Pleasant Prairie field to the north, with estuary bar sandstones as the major reservoir (Montgomery and Morrison, 1999; Cirilo, 2002; Senior, 2012). A north-to-south paleoflow direction is inferred for this and other incised valley fill systems in the midwest (Smith and Reed, 2000; Wang and Bidgoli, 2019). These paleovalleys may represent local fluvial systems that connect to more substantial trunk rivers of the transcontinental transport system (e.g., Wang and Bidgoli, 2019; Lawton et al., 2021).

Although carbonate sedimentation continued across much of the midcontinent through the Pennsylvanian, the Morrowan (Bashkirian) saw some of lowest Carboniferous sea levels, resulting in multiple re-



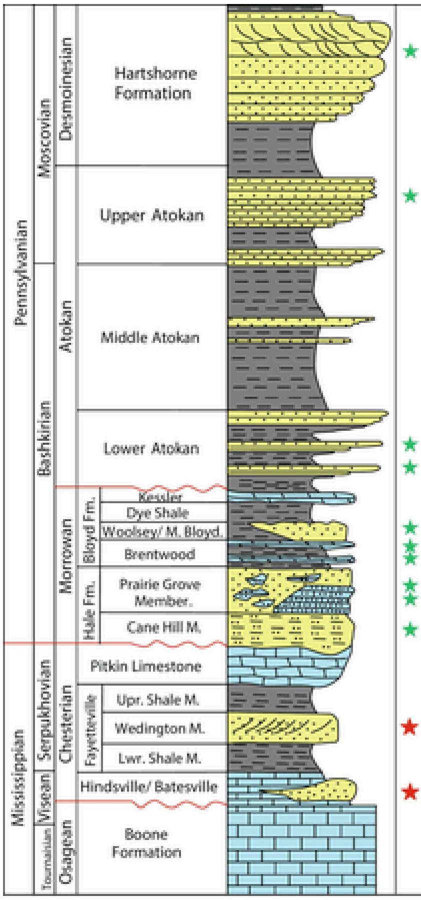
Sample Name	Coordinates	Age / Unit	Depth (m)	Description / Sandstone Compositions	Source
HAN 1 HAN 2	37.3531, -101.0789	Bashkirian Morrow ss.	1628.2-1628.9 1623.7-1624.4	Coarse-grained feldspathic arenite with 30-70% quartz, 30-45% feldspar, and up to 25% lithics	this study
MOR 1 MOR 2	37.3810, -101.0722	Bashkirian Morrow ss.	1608.6-1608.7 1601.7-1602.3	Medium- to coarse-grained feldspathic arenite with 30-80% quartz and 20-70% feldspar, and up to 10% lithics	
CHS 1 CHS 2		Serpukhovian Chester ss.	1712.5-1712.8 1694.4-1694.7	Fine- to very fine-grained, moderately to well sorted, subangular to subrounded feldspathic arenite, with 35-50% qtz. & 50-65% fs.	
MaryJones5229 MaryJones5194	37.7344, -101.0228	Serpukhovian Chester ss.	1593.8-1594.1 1583.1-1583.4	Fine to very fine grained quartzarenite	Wang & Bidgoli, 2019
MLPBlack5482 MLPBlack5467	37.4619, -101.0269	Serpukhovian Chester ss.	1670.9-1671.5 1666.3-1667.0	Fine to very fine grained, moderately to well sorted, and sub-angular to well-rounded quartzarenites and sublitharenites	
Hitch6245 Hitch6197 Hitch61504	37.18061, -100.9942	Serpukhovian Chester ss.	1903.5-1903.9 1888.8-1889.5 1874.6-1875.4	Fine to very-fine grain, moderately well-sorted, subangular to subrounded quartzarenites and sublitharenites	

Fig. 2. The stratigraphic correlation of Kansas boreholes used in this study and Wang and Bidgoli (2019). Stars correspond to core sample depths. Stratigraphic tops data are from the Kansas Geological Survey (http://www.kgs.ku.edu/). Inset table provides each sample's coordinates, age, depth, description, and source.

gressive-transgressive cycles and the development of incised valley fill successions (Ross and Ross, 1988; Sonnenberg et al., 1990). These deposits, which extend from southeastern Colorado and southwestern Kansas into Oklahoma and Texas, are coarse-grained sandstones interspersed between marine mudstones (Sonnenberg et al., 1990; Rader, 1990; Bowen and Weimer, 2003).

2.2.2. *Incursions of terrigenous clastics in northwestern Arkansas*

In northwestern Arkansas, a broad and stable carbonate platform occupied the passive continental margin from the early Paleozoic through the Middle Mississippian (Rascoe and Adler, 1983; Sutherland, 1988). However, toward the end of the Mississippian, the depositional pattern on the shelf changed and intermittent incursions of terrigenous clastics became increasingly common. The earliest record of these changes includes the Batesville and Wedington sandstones (Fig. 3, Garner, 1967; Sutherland, 1988; Xie et al., 2016). Detrital zircon provenance analysis of these sandstones suggests a major source in the Appalachian region (Xie et al., 2016; Wang and Bidgoli, 2019). Although carbonate sedimentation continued through the Early Pennsylvanian, the Morrowan (Bashkirian) saw a significant increase in clastic detritus to the shelf. This transition to a mixed carbonate-siliclastic system is recognized in the Hale and Bloyd formations (Fig. 3, Henbesi, 1953), which reflect a third-order transgressive-regressive cycle (McGilvery et al., 2016). The Cane Hill Member of the Hale Formation, which consists of tidally-influenced sandstone and shale interbeds, formed during the initial transgression of the shelf, following a major sea-level draw down in the Early Pennsylvanian (Liner, 1979; Sutherland, 1988). Continued sea-level rise and establishment of longshore currents led to the deposition of inner shelf to shoreface sandstones of the Prairie Grove Member of the Hale Formation (Liner, 1979; Sutherland, 1988). The Brentwood



Sample	Coordinates	Age	Unit	Description	Source
17HF01	35.1875, -94.2885	Desmoinesian (Moscovian)	Hartshorne	Fine-grained quartzarenite	this study
17AF03	35.2207, -94.4105	Upper Atokan (Mocovian)	Alma-Carpenter	Fine-grained feldspathic arenite	this study
17AF02	35.8262, -94.1852	Lower Atokan (Bashkirian)	Cecil Spiro	Fine-grained feldspathic arenite	this study
17AF01	35.8974, -94.1889				
Middle Bloyd Mbr.		Morrowan (Bashkirian)	Middle Bloyd	Med. to coarse-grained quartzarenite / sublitharenite	Xie et al., 2018
17BF02	35.9204, -94.1997		Brentwood	Medium- to coarse-grained, calcareous feldspathic arenite	this study
17BF01	36.0145, -94.1933				
17PG02	36.0145, -94.1933		Prairie Grove	Medium-grained, calcareous, feldspathic sublitharenite	this study
17PG01	36.0145, -94.1933				
17CH01	36.0061, -94.1962		Cane Hill	Fine-grained, feldspathic arenite	this study
Wedington Mbr.		Chesterian (Serpukhovian)	Wedington	Fine- to medium-grained quartzarenite	Xie et al., 2016
17WS01	35.9276, -94.1841			Medium-grained, quartzarenite	Wang & Bidgoli, 2019
17BS01	36.1748, -93.9429		Batesville	Fine-grained, quartzarenite	

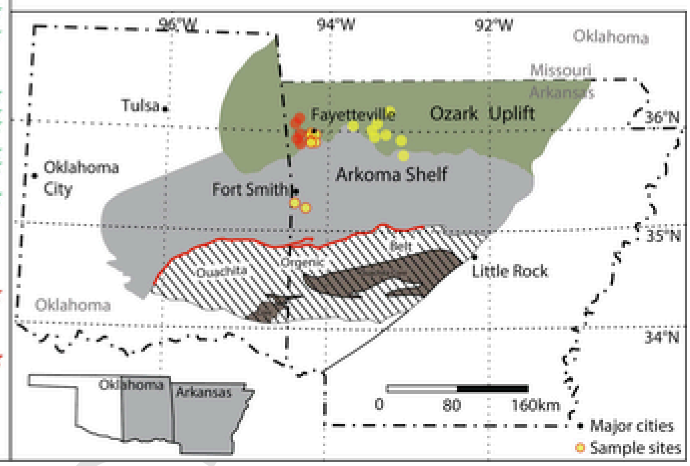


Fig. 3. (A) Stratigraphic column representing Carboniferous strata in northwestern Arkansas (modified from McGilvery et al., 2016). Wavy red lines between formations correspond to unconformities and stars correspond to sampled intervals. (B) Table summarizing each sample's coordinates, age, description, and other information. (C) Simplified geological elements of the study region (based on Rascoe and Adler, 1983; Houseknecht et al., 2014) with sample sites from Xie et al., 2016 (red stars) and 2018 (yellow stars), Wang and Bidgoli (2019), and this study (yellow circles with red rim). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Member of the lower Bloyd Formation overlies the Prairie Grove and consists of alternating quartz sand-rich grainstone/packstone and black shale that represent maximum flooding of the shelf (McGilvery, 1980; McGilvery et al., 2016). Terrestrial siltstone, coal, and shale of the Woolsey Member of the Bloyd Formation reflect a subsequent regression, capped by the upper Morrowan (Bashkirian) Dye Shale and Kessler Limestone members of the Bloyd Formation (McGilvery, 1980; McGilvery et al., 2016).

In the Middle Pennsylvanian, continental collison along the southern Laurentian margin, led to development of the Ouachita fold-thrust belt (Drake et al., 1989; Granath et al., 1989). The stable shelf experienced rapid subsidence to form the Arkoma foreland basin (Fig. 3, Sutherland, 1988; Houseknecht et al., 2014; McGilvery et al., 2016). This transition is marked by a shift from tidally-influenced shoreface sandstones of the lower Atoka Formation to thick, slope channel complexes of the middle Atoka Formation (Coleman, 2000; Graham et al., 1975, 1976; Houseknecht, 1986). As subsidence diminished in the late Atokan (early Moscovian), remaining accomodation space was filled by upward thickening inner shelf to tidal flat and shoreface successions (Houseknecht, 1986). Foreland basin sedimentation culminated in the Desmoinesian (middle Moscovian to early Kasimovian) with deposition of the Hartshorne Formation, a fluvially-dominated deltaic system (Fig. 3, Houseknecht and Kacena, 1983).

2.3. Potential age provinces

The basement geochronology of North America is well established and can be divided into several major age provinces that are regarded as ultimate sources of detrital zircon grains (Fig. 1A, Whitmeyer and Karlstrom, 2007; Park et al., 2010; Gehrels et al., 2011). The age provinces of the northern Laurentian craton include Archean Superior and Wyoming provinces (>2500 Ma), the Trans-Hudson collisional province (2000–1800 Ma), and the Penokean accretionary province (1900–1800 Ma) along the southern margin of the Superior province (Hoffman, 1989; Van Schmus et al., 1993; Sims, 1996). Southern Laurentian age provinces include the Yavapai-Mazatzal province (1800–1600 Ma) and Grenville province (1300–900 Ma) in the southwest and Granite-Rhyolite province (1550–1300 Ma) in the southeast (Van Schmus et al., 1993; Whitmeyer and Karlstrom, 2007).

The Appalachian region along the eastern Laurentia margin has long been considered as a major source of sediments and consists of the Grenville province (1300–900 Ma), Gondwanan accreted terranes, including Pan-African–Brasiliano ages of 530–760 Ma and Eburnian–Trans-Amazonian ages of 1950–2160 Ma (Mueller et al., 2014; Thomas et al., 2017), Iapetan *syn*-rift rocks (765–530 Ma; Thomas, 2014) and Taconic-Acadian rocks (500–350 Ma). Thomas et al. (2017) characterized the detrital-zircon signature of the late Paleozoic Appalachian region as dominated by Grenville grains and significant numbers of Taconic-Acadian grains, but generally lacking in grains older than 1500 Ma.

3. Samples and methods

Six core samples of Upper Mississippian and Lower Pennsylvanian sandstones were collected from two boreholes, Cutter KGS #1 and Hanke A4, located in the axis of a stacked incised valley fill complex in southwestern Kansas (Fig. 1B). Samples were selected from sand-rich intervals, with Chesterian (Serpukhovian) samples being well-sorted, subrounded, fine-grained quartz arenites and Morrowan (Bashkirian) samples being distinctly coarser and more feldspathic (Fig. 2). In addition to these samples, nine samples were collected from sand-rich Upper Mississippian to Middle Pennsylvanian outcrops in northwestern Arkansas. The selected lithostratigraphic units are fine- to medium-grained sandstones that capture the transition from a carbonate shelf in the Osagean to mixed carbonate-siliclastic system from the Chesterian through Morrowan (Serpukhovian to Bashkirian), to a clastic-dominated foreland basin later in the Pennsylvanian (Fig. 3).

Point counting was completed on 19 thin sections following the Gazzi-Dickinson point counting methods (e.g., Dickinson and Suczek, 1979; Dickinson et al., 1983). Each thin section was stained for calcite. A minimum of 400 grains were counted for each thin section. Counts were broken out into 23 different mineral/grain types, including four quartz varieties (monocrystalline, undulatory, polycrystalline, and chert), potassium feldspar, plagioclase, and lithic (volcanic, sedimentary, and metamorphic) grains. The data were then normalized and plotted on QFL, QmFLt, QpLvLs, and QmPK tectonic discrimination diagrams (e.g., Dickinson and Suczek, 1979; Dickinson et al., 1983). The complete list of minerals and grain types counted and components included in each plot is included in Supplemental Table 1.

We used standard mineral separation techniques to isolate zircon and other heavy minerals from the whole-rock samples. This included use of a jaw crusher and disk mill to crush and pulverize samples, a Gemeni table and Frantz Isodynamic® magnetic separator to concentrate minerals of interest, and heavy liquids (methylene iodide) to isolate zircon. Once separated, at least 120 grains per sample were selected from sample splits, under a binocular microscope, and mounted onto epoxy pucks (25 mm diameter) with double-sided tape (tape mount) so that grains could be recovered for future analyses.

Detrital zircon dating was performed using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at the University of Kansas, Isotope Geochemistry Laboratory using a PhotonMachines Analyte G.2193 nm ArF excimer laser ablation system coupled with a ThermoFinnigan Element2 ICPMS (inductively coupled plasma mass spectrometer). The laser was set to 2.0 Jcm-2 fluence and 10 Hz repetition rate resulting in 15 μm pit depth at 20 μm spot diameter. Zircon GJ1 with a $^{206}Pb/^{238}U$ age of 600.4 ± 0.65 Ma and a 608.5 Ma $^{207}Pb/^{206}Pb$ age was used as the primary reference material used to correct calibration drift and downhole isotopic and elemental fractionation (Jackson et al., 2004). It was analyzed once for every 5–8 unknowns throughout each sample run. Single GJ1 analyses typically produced $^{206}Pb/^{238}U$ within 1–2% of the reported calibration age. The Plešovice and Fish Canyon Tuff zircons were used as secondary, calibration validation zircon reference materials, with chemical abrasion-thermal ionization mass spectrometry [CA-TIMS] $^{206}Pb/^{238}U$ ages of 337.13 ± 0.37 Ma (Sláma et al., 2008) and 28.402 ± 0.023 Ma (Wotzlaw et al., 2013), respectively. These published ages were reproduced to within 2% during the course of this study.

U-Pb data reduction was performed using Iolite 2.5 (Hellstrom et al., 2008; Paton et al., 2011). All grains with >10% discordance or > 5% reverse discordance were excluded from our interpretations, as were grains with >15% analytical error. Zircon grains older than 850 Ma were assessed by $^{207}Pb/^{206}Pb$ ages and the discordance was calculated based on $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages. Zircons grains younger than 850 Ma were assessed by $^{206}Pb/^{238}U$ ages and the discordance was calculated based on $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages. All ages reported use 2σ absolute propagated uncertainties.

To compare the new detrital zircon data with published datasets, we used several visualization and statistical tools. The age data are presented as histograms, probability density plots (Ludwig, 2008), kernel density estimation plots (Vermeesch, 2012; Vermeesch et al., 2016) and pie charts. Quantitative comparisons of samples were completed through Kolmogorov-Smirnov (K—S) tests (Press et al., 1986), which provide a measure of the statistical significance of differences between age distribution (Guynn and Gehrels, 2006), and cumulative probability analysis, which can reveal differences in the proportions of grains among samples (Gehrels et al., 2011). Multidimensional scaling analysis, a type of principal component analysis, was also used to visually represent similarities and differences among samples (Vermeesch, 2013; Vermeesch et al., 2016).

4. Results

4.1. Sandstone compositions

Point counting was completed on sixteen samples from the study area and the data were plotted on a series of ternary diagrams (e.g., Dickinson and Suczek, 1979; Dickinson et al., 1983; Garzanti, 2016; Supplemental Table 1). The samples are dominantly classified as feldspathic arenites with one sample a quartz arenite (Fig. 4a). Most of the samples only contain feldspar and quartz grains, with four samples having a significant lithic component. As a result, the samples dominantly plot in the basement uplift-transitional continental-carton interior fields, which corresponds to the continental block field of Garzanti (2016) (Fig. 4b and c). One sample plots in the dissected arc/magmatic arc field. For samples with lithic grains, nearly all of the grains are volcanic (Fig. 4d). Feldspar composition is variable, but in all samples, K-feldspar is more abundant than plagioclase (Fig. 4e). The largest differentiation is shown on the QmFLt diagram (Fig. 4f). The majority of samples still plot along the basement/craton side of the diagram, but a few samples plot in the arc-related and recycled fields (Fig. 4f).

4.2. Detrital zircon geochronology

Of the 2038 detrital zircon grains analyzed from the Kansas and Arkansas study area, a total of 1544 grains yielded U—Pb ages within the discordance and error criteria. The full suite of isotopic measurements, U—Pb ages, and statistical analyses are provided in Supplemental Tables 2 and 3. The detrital zircon age results are plotted as histograms and probability density plots (Ludwig, 2008; Vermeesch, 2012) in Fig. 5, with the ranges of known age provinces highlighted.

Core samples from Kansas yielded a total of 582 grains within discordance and error criteria. In general, Chesterian (Serpukhovian) samples contain major groups of Middle to Late Mesoproterozoic (~1300–900 Ma, Grenville) and Paleozoic (~500–350 Ma, Taconic-Acadian) ages and minor groups of Late Paleoproterozoic (~1800–1600 Ma, Yavapai-Mazatzal), Early Mesoproterozoic (~1550–1300 Ma, Granite-Rhyolite), and Archean (>2500 Ma) ages; whereas Morrowan (Bashkirian) samples contain larger proportions of Paleoproterozoic (~1800–1600 Ma) and Early Mesoproterozoic (~1550–1300 Ma) ages (Fig. 5 and Table 1).

Outcrop samples from northwestern Arkansas yielded a total of 962 grains within discordance and error criteria. The age results, while similar to the Kansas Chesterian (Serpukhovian) samples in terms of the major age groups (~1300–900 and ~ 500–350 Ma), also contained mainly Late Paleoproterozoic (~1800–1600 Ma) and Early to Middle Mesoproterozoic (~1550–1300 Ma) ages and minor groups of Neoproterozoic to Early Cambrian (650–500 Ma) and Paleoproterozoic and older grains (>1800 Ma; Fig. 5 and Table 1). The details of the dating results are described below and summarized in Table 1.

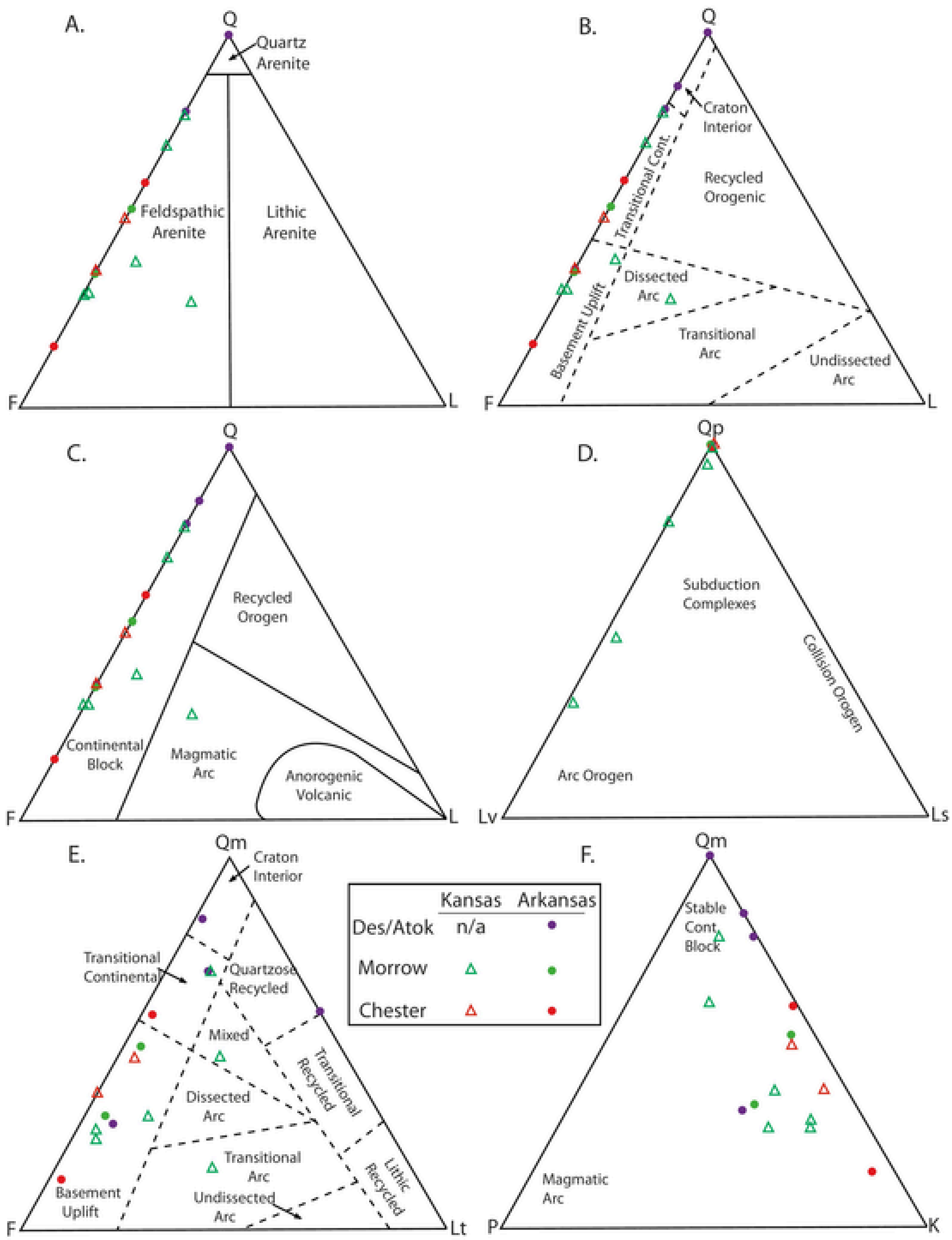


Fig. 4. Thin section point count data plotted on compositional and tectonic discrimination diagrams. (A) Sandstone composition plotted on QFL diagram. (B) QFL tectonic discrimination diagram (after Dickinson et al., 1983). (C) QFL tectonic discrimination diagram (after Garzanti, 2016). (D) QpLvLs discrimination diagram. (E) QmFLt discrimination diagram. (F) QmPK discrimination diagram. F, feldspar; K, potassium feldspar; L, lithic grains; Ls, sedimentary lithic grains; Lv, volcanic lithic grains; Lt, total lithic grains (including chert and polycrystalline quartz); P, plagioclase feldspar; Q, quartz (including chert); Qm, monocrystalline quartz; Qp, polycrystalline quartz (including chert).

4.2.1. Southwestern Kansas core samples

4.2.1.1. Upper Mississippian samples. Two samples of fine-grained sandstone were collected from the Cutter KGS#1 borehole in the Cutter oil field, located on the margin of a Chesterian (Serpukhovian) incised valley fill system (Figs. 1 and 2). The Chester 1 sample yields an age range of 393 to 3674 Ma, dominated by 393–498 Ma and 920–1272 Ma zircons. The Chester 2 sample's age distribution is similar to the Chester 1 (p = 0.197), with two major clusters of 371–501 Ma and 921–1214 Ma ages. Additionally, a single grain with an age of 273 ± 23 Ma, younger than the Late Mississippian age of the unit, may be the result of well-bore sample contamination, despite rigorous sample processing. Therefore, this age is not included in our interpretations.

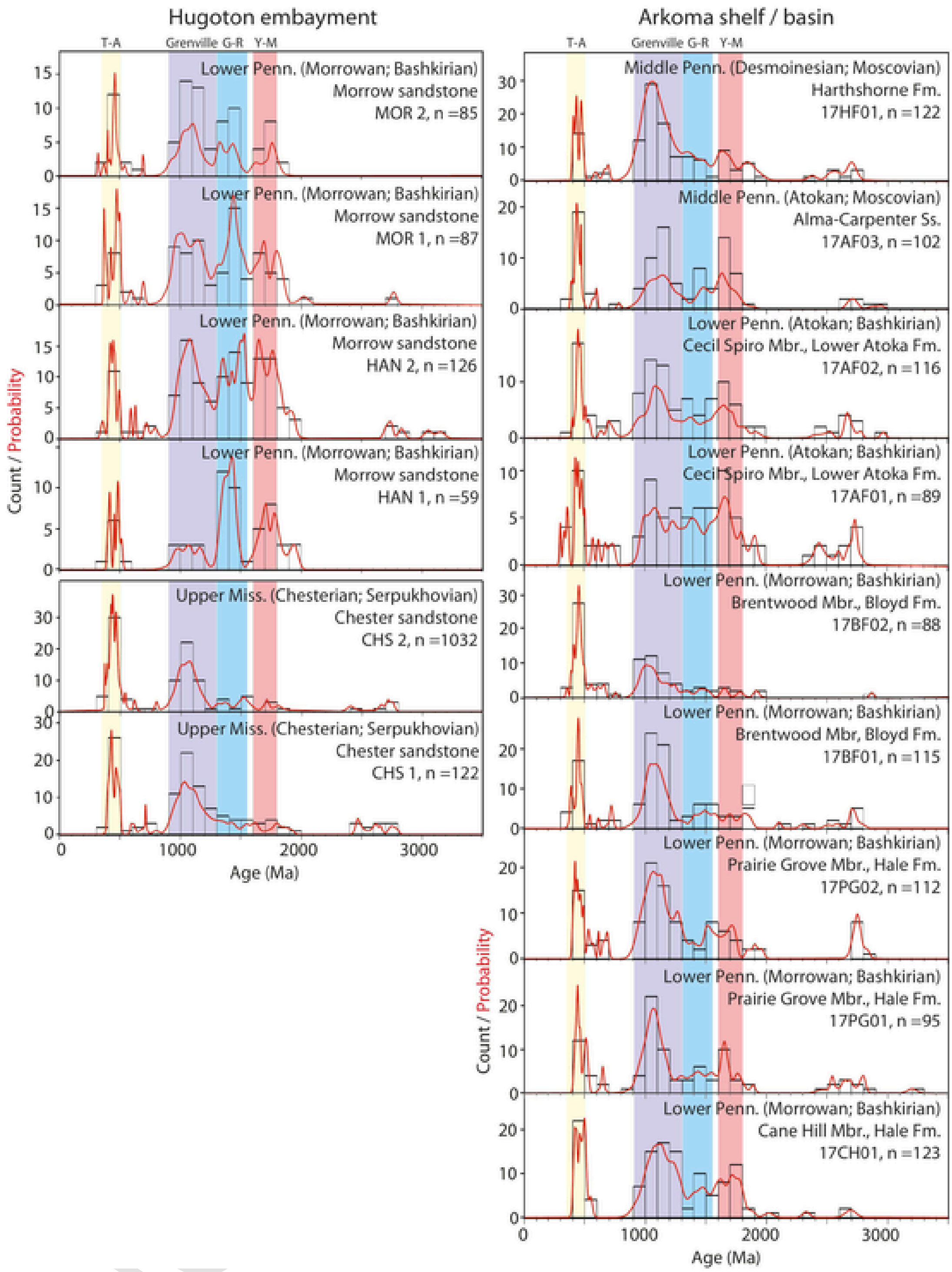


Fig. 5. Detrital zircon U—Pb age histogram (100 Ma bins) and PDP plots of core samples from Hugoton Embayment, southwestern Kansas, and outcrop samples from the Arkoma Shelf, northwestern Arkansas. Diagrams were constructed in Isoplot (Ludwig, 2008).

4.2.1.2. Lower Pennsylvanian samples. The Cutter KGS#1 borehole also penetrates the axis of a Morrowan (Bashkirian) incised valley fill system, from which two samples of medium-grained sandstone were collected and are distinct from the Chesterian (Serpukhovian) in terms of grain size, angularity, age distributions (Figs. 1 and 2). The Morrow 1 sample yields four major age clusters at 368–503 Ma, 908–1288 Ma, 1306–1543 Ma and 1614–1804 Ma. The Morrow 2 sample is similar (p = 0.406) with four major modes at 324–500 Ma, 904–1271 Ma, 1320–1494 Ma and 1602–1800 Ma.

Morrowan (Bashkirian) strata are well correlated from the Cutter to the Lahey oil fields (Fig. 2). Two samples of coarse-grained sandstone were collected from the Hanke A4 borehole in the Lahey field (Fig. 2). The Hanke 1 sample shows three major age groups of 922–1186 Ma, 1332–1478 Ma and 1638–1790 Ma. The Hanke 2 sample shows similar age distribution (p = 0.631) yielding three dominant age clusters of 949–1259 Ma, 1310–1548 Ma and 1616–1794 Ma.

Table 1
U—Pb ages.

	SampleName	Concordantages	500–350 Ma	900–500 Ma	1300–900 Ma	1550–1300 Ma	1800–1600 Ma	>1800 Ma	Other
Southwestern Kansas	CHS 1	122	23%	5%	44%	8%	6%	12%	2%
	CHS 2	104	34%	6%	42%	10%	4%	5%	0%
	MOR 1	87	14%	2%	35%	26%	16%	6%	1%
	MOR 1	85	18%	2%	42%	21%	15%	1%	0%
	HAN 1	59	12%	2%	15%	37%	24%	9%	2%
	HAN 2	126	10%	3%	30%	25%	21%	10%	1%
Northwestern Arkansas	17CH01	123	20%	2%	44%	11%	17%	4%	2%
	17PG01	95	15%	5%	42%	12%	15%	12%	0%
	17PG02	112	13%	6%	47%	10%	9%	12%	3%
	17BF01	115	18%	4%	46%	10%	6%	12%	4%
	17BF02	88	34%	10%	39%	8%	6%	3%	0%
	17AF01	89	17%	6%	26%	16%	18%	15%	3%
	17AF02	116	17%	6%	35%	13%	16%	12%	2%
	17AF03	102	21%	4%	35%	12%	21%	7%	1%
	17HF01	122	12%	3%	53%	12%	10%	12%	0%

4.2.2. Northwestern Arkansas outcrop samples

4.2.2.1. Lower Pennsylvanian sandstones. Five samples of Lower Pennsylvanian (Morrowan; Bashkirian) sandstones were analyzed (Fig. 3). A sample of fine-grained sandstone from the Lower Pennsylvanian Cane Hill Member of the Hale Formation (17CH01) yields ages ranging from 403 to 2698 Ma, with two major age clusters of 403–500 Ma and 905–1327 Ma, and other minor age groups. Two samples of the Prairie Grove Member of the Hale Formation, a hybrid sandstone with approximately equal amounts of quartz sand and carbonate grains, also has similar age distributions. The 17PG01 sample yielded ages ranging from 411 to 3200 Ma and 17PG02 ranged from 400 to 2831 Ma, with 900–1300 Ma and 400–500 Ma age accounting for 57% and 60% of the ages, respectively. Two samples of the Brentwood Member of the Boyd Formation, also a hybrid sandstone, were also analyzed (17BF01 and 17BF02), yielding ages ranging from 381 to 2790 Ma and 352–2868 Ma, respectiviely, and dominated by 900–1300 Ma and 350–500 Ma ages.

4.2.2.2. Middle Pennsylvanian (lower Atokan) sandstones. Two samples of fine-grained sandstone were collected from shoreface exposures of the Cecil Spiro Member of the lower Atoka Formation (Fig. 3). Sample 17AF01 ranges from 302 to 2770 Ma and is similar ($p = 0.679$) to sample 17AF02, which ranges from 400 to 2968 Ma. Both samples have major 900–1300 Ma and 300–500 Ma age groups that account for 43% and 52% of the ages, respectively.

4.2.2.3. Middle Pennsylvanian (upper Atokan and Desmoinesian) sandstones. Two samples were collected from the Middle Pennsylvanian foreland basin fill succession for comparison (Fig. 3). The 17AF03 sample was collected from the lower Alma-Carpenter sandstones, interpreted as an east-west strike-fed marginal marine system that was much larger scale than in the lower Atokan (McGilvery et al., 2016). The sample is similar ($p = 0.826$ and 0.971) to the lower Atokan samples, with age clusters of 420–487 Ma and 919–1298 Ma accounting for more than half the data. Sample 17HF01, collected from deltaic sandstones of the Desmoinesian Hartshorne Formation, contains zircons ranging from 401 to 2720 Ma and contained similar age groups, but with a larger proportion of 900–1300 Ma ages (53% of total).

5. Discussion

5.1. Sandstone provenance

The detrital zircon geochronology data indicate that Chesterian (Serpukhovian) incised valley fill sandstones in southwestern Kansas are distinct from their Morrowan (Bashkirian) counterparts (Fig. 5). The two Chesterian (Serpukhovian) samples are characterized by dominant clusters of Taconic-Acadian (500–350 Ma) and Grenville (1300–900 Ma) grains, accounting for 66%–77% of the analyzed grains, and smaller proportions of Granite-Rhyolite (1550–1300 Ma; 9%) and Yavapai-Mazatzal (1800–1600 Ma; 4%–6%) grains. These results are similar to published data from elsewhere along the incised valley fill system (Wang and Bidgoli, 2019) and suggest distant and possibly recycled sediment sources (Fig. 6B). Both the Grenville and Taconic-Acadian orogenies are represented in the Appalachian region,

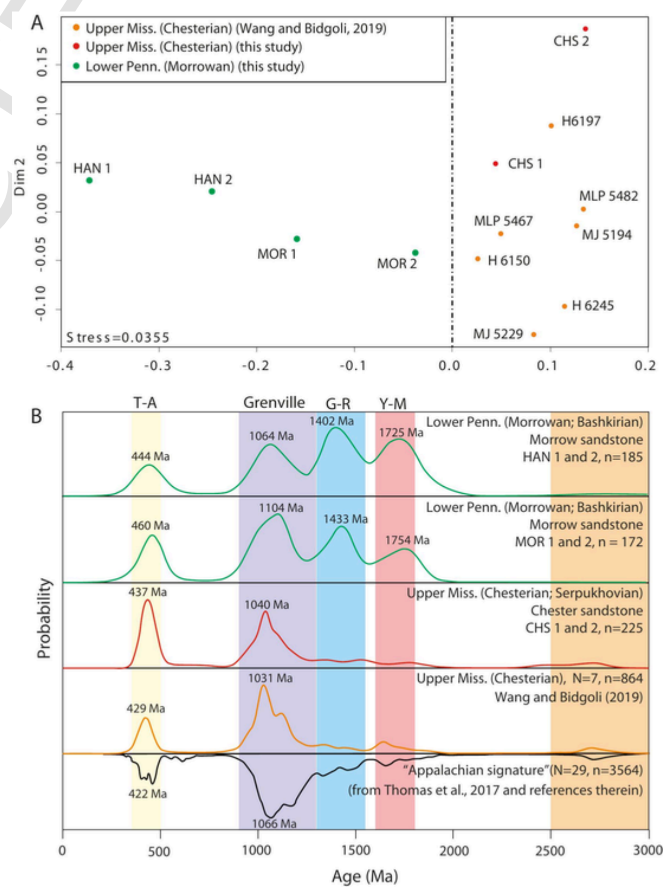


Fig. 6. (A) Multidimensional scaling (Vermeesch, 2013) relationships of detrital zircon U—Pb ages from Chesterian (Serpukhovian) and Morrowan (Bashkirian) incised valley fill sandstones in southwestern Kansas. (B) Kernel density estimation plots (Vermeesch, 2012; Vermeesch et al., 2016) of detrital zircon U—Pb ages of these same samples and the composite signature of late Paleozoic Appalachian Appalachian foreland basin (from Thomas et al., 2017 and references therein). Data are discretized at a fixed interval (50 Ma).

and comparison of the Chesterian incised valley fill samples with published data from synorogenic clastic wedge sediments of the Appalachian foreland basin suggest a high degree of similarity (Fig. 6; Thomas et al., 2017 and references therein). In contrast, samples from the Morrowan (Bashkirian) incised valley fill system are characterized by significantly larger proportions of Granite-Rhyolite (21%–37%) and Yavapai-Mazatzal (15%–22%) grains, components of the local basement. This change in the age distributions is also reflected in the multidimenionsional scaling plot (Fig. 6A), which shows that Chesterian (Serpukhovian) and Morrowan (Bashkirian) samples form separate and distinct groups. Petrographic data from the southwestern Kansas samples also show distinct differences, with Morrowan (Bashkirian) samples having an increase in volcanic lithic, total lithic, and plagioclase grain concentrations, suggesting additional igneous sources (Fig. 4). Together, these observations suggest an important change in provenance in the Early Pennsylvanian, from a major extraregional Appalachian source to more influence of local sediment sources.

A strong Appalachian signature is also recognized for Lower to Middle Pennsylvanian samples from the Arkoma Shelf in northwestern Arkansas (Fig. 7). These units record a transition from a carbonate-dominated passive continental margin to thick clastic deposits tied to

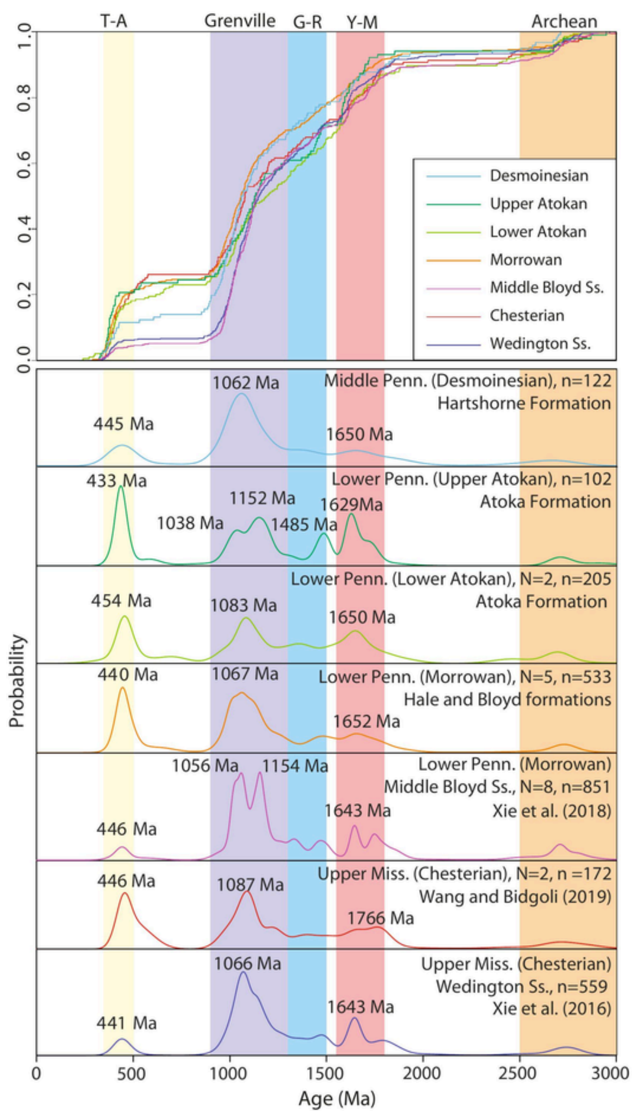


Fig. 7. Cumulative probability and kernel density estimation plots for new and published (Xie et al., 2016, 2018; Wang and Bidgoli, 2019) detrital zircon U—Pb ages from outcrops samples in northwestern Arkansas. Data are discretized at a fixed interval (50 Ma).

the subsidence of the Arkoma foreland basin (Sutherland, 1988; McGilvery et al., 2016). Detrital zircon data from the Morrowan (Bashkirian) Hale and Bloyd formations, which record mixed clastic-carbonate deposition, are dominated by Grenville (1300–900 Ma; 41–47%) and prominent clusters of Taconic-Acadian (500–350 Ma; 13–20%) ages (Fig. 5). In addition, these samples contain variable proportions of Yavapai-Mazatzal grains (6%–16%) that may reflect the influence of local uplifts (Xie et al., 2016, 2018) or recycling from Iapetan *syn*-rift or passive margin successions of Appalachian region (Thomas et al., 2017). The Lower Atokan shoreface sandstones of the Cecil Spiro Member also have similar age distributions but with slightly larger Yavapai-Mazatzal grain fractions (16–18%) (Fig. 5). The Upper Atokan Alma-Carpenter sandstones, a succession of foreland basin fill, contains even larger numbers of Yavapai-Mazatzal zircons (21%), while these ages only account for 10% of the ages in the Desmoinesian Hartshorne Formation (Sample 17HF01) (Fig. 5).

Published age distributions for the Upper Mississippian Batesville and Wedington sandstones in northwestern Arkansas are similar to U—Pb age distributions of our Lower to Middle Pennsylvanian shelf and foreland basin samples, with a dominant Appalachian signature and subordinate contributions from Yavapai-Mazatzal and Archean age provinces (Xie et al., 2016; Wang and Bidgoli, 2019; Fig. 7). The similarity in the age distributions of Upper Mississippian through Middle Pennsylvanian units makes it difficult to differentiate the samples through multidimensional scaling analysis and suggests a continuous Appalachian provenance for much of the Carboniferous. This similarity carries over to the petrographic data, which are relatively consistent for all of the Arkoma Shelf samples (Fig. 4). It is also worth noting that the study by Xie et al. (2016), conducted on the Wedington sandstone, as well as another on the Morrowan (Bashkirian) Middle Bloyd sandstone (Xie et al., 2018), sampled a more extensive area and reported smaller percentages of Taconic-Acadian grains (Figs. 3 and 7). The larger percentages of Taconic-Acadian grains observed in our samples may reflect the limited sampling of these units in this study. However, large numbers of Taconic-Acadian grains are also recognized in both the Lower Pennsylvanian Mauch Chunk-Pottsville clastic wedge and longitudinal drainage system of Appalachian foreland basin (Becker et al., 2005; Thomas et al., 2017) and the Illinois Basin (Kissock et al., 2018). Thus, the large concentration of the Taconic-Acadian grains in our samples may be hinting at recycling of the Appalachian foreland basin sediments and/or contributions from the longitudinal system (Becker et al., 2005; Thomas et al., 2017; Kissock et al., 2018).

5.2. Provenance evolution from late Mississippian to early Pennsylvanian

Gehrels et al. (2011) suggested that beginning in the Late Mississippian, sediments from the Appalachian region propagated to the Laurentian interior, as far west as the Grand Canyon in Arizona, via a transcontinental sediment dispersal system. This model is corroborated by detrital zircon ages from Upper Mississippian through Middle Pennsylvanian sandstones in northwestern Arkansas and the Upper Mississippian incised valley fill system in the southwestern Kansas, which are located along the proposed transport path and have age signatures that mirror those of the Appalachian foreland basin (Wang and Bidgoli, 2019; Figs. 6 and 7). However, by the Early Pennsylvanian, a significant change in provenance occurs in samples from the Hugoton Embayment, with large numbers of Granite-Rhyloite and Yavapai-Mazatzal grains replacing Appalachian sourced grains (Figs. 3, 6 and 7). The petrographic data are broadly complementary with the detrital zircon data. They display similar mineralogical assemblages in the samples from Arkansas and the Upper Mississippian samples from Kansas. However, the Lower Pennsylvanian samples from Kansas show a clear influx of igneous detritus that is not observed elsewhere.

The change in provenance observed in our Hugoton Embayment samples is even more pronounced farther west (Figs. 8 and 9). In northern Colorado, alluvial fan and fluvial deposits of the Lower Pennsylvanian Fountain Formation, deposited on the flanks of the ancestral Front Range, are characterized by a prominent Yavapai-Mazatzal peak and a major Granite-Rhyolite age group, accounting for 71% of the concordant ages; whereas the Grenville (1026–1293 Ma) only makes up 21% of the ages and Taconic-Acadian ages are absent (Siddoway and Gehrels, 2014). The age distribution suggests any influence from Appalachian sediment sources was greatly diminished in the Pennsylvanian. However, the age distribution of the Upper Pennsylvanian Ingleside Formation is more complicated, with larger numbers of Grenville (33%) and Taconic-Acadian grains (8%) in addition to Yavapai-Mazatzal (24%) and Granite-Rhyolite (9%) grains (Nair et al., 2018), and may reflect complications in sediment routing, decreasing influence of proximal uplifts as sediment sources, and/or increasing influence of west-directed aeolian transport (e.g., Soreghan et al., 2008; Sur et al., 2010; Lawton et al., 2021; Figs. 8 and 9). In southwestern Colorado, in the Paradox Basin on the western margin of Uncompahgre uplift, the Lower Pennsylvanian Molas Formation contains silt-sized aeolian sediments dominated by an Appalachian age signature (Evans and Soreghan, 2015; Nair et al., 2018); whereas, the age pattern of the overlying Lower Pennsylvanian Hermosa Formation is dominated by Yavapai-Mazatzal and Granite-Rhyolite ages that account for 58% of the grains (Figs. 8 and 9, Nair et al., 2018).

Similar changes are also documented in the Grand Canyon, where the Grenville and Taconic-Acadian grains make up more than 50% of the ages in Upper Mississippian samples, whereas Granite-Rhyolite and Yavapai-Mazatzal grains account for 30%. In contrast, the Appalachian signature is greatly reduced in Lower Pennsylvanian samples (27% Grenville and 4% Taconic-Acadian grains) and replaced with Yavapai-Mazatzal (31%) and Archean (25%) grains (Figs. 8 and 9).

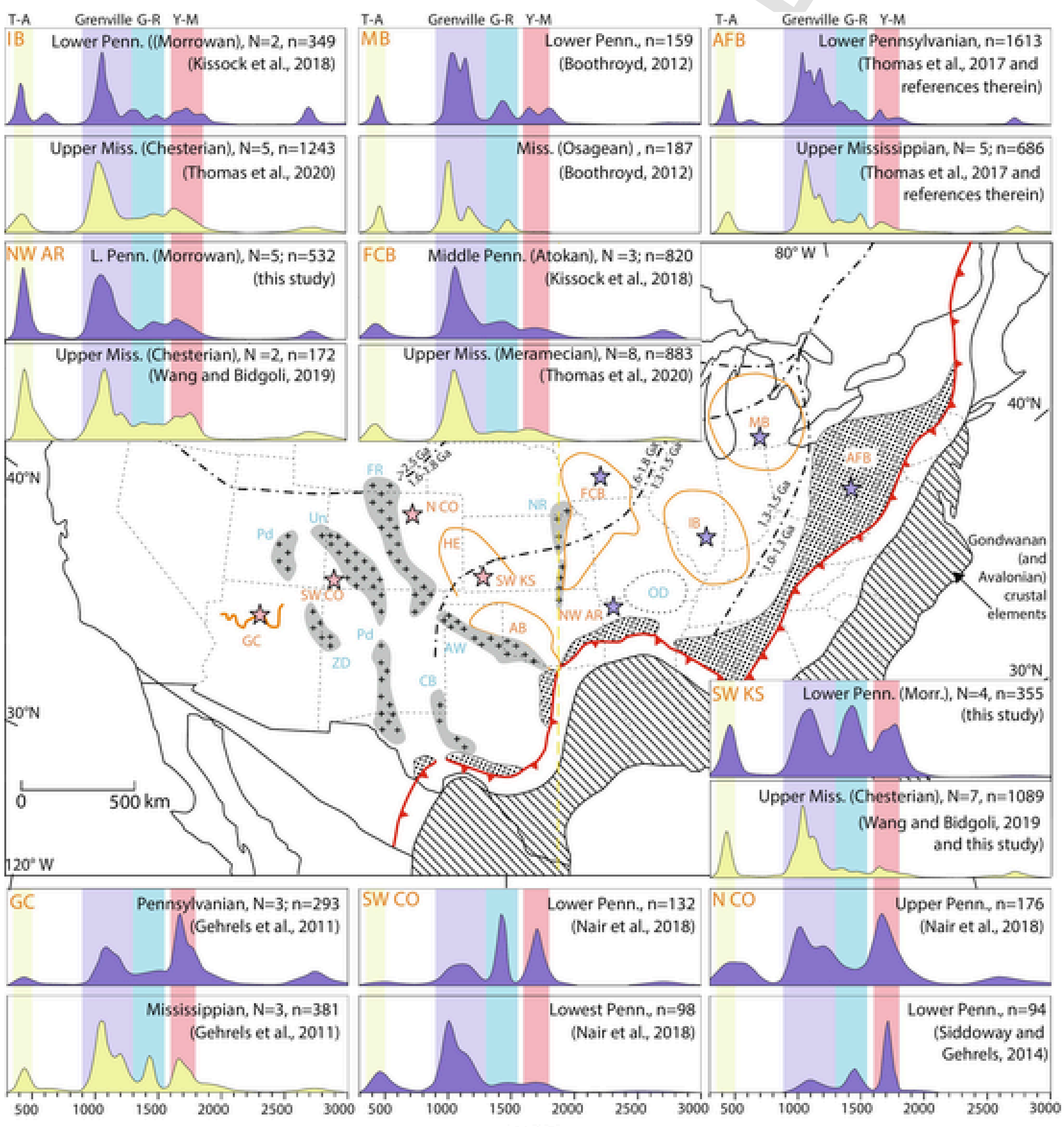


Fig. 8. Comparison of detrital zircon U—Pb age spectra of samples from the Appalachian Foreland basin (AFB), Michigan Basin (MB), Illinois Basin (IB), Forest City Basin (FCB), Akoma Shelf in northwestern Arkansas (NW AR), Hugoton Embayment (HE) in southwestern Kansas (SW KS), northern (N CO) and southwestern Colorado (SW CO), and Grand Canyon (GC). Data are discretized at a fixed interval (50 Ma). Other abbreviations: ARM = Ancestral Rocky Mountains; NR = Nemaha Ridge; OD = Ozark Dome; FR = Front Range; AW = Amarillo-Wichita Uplift; Un = Uncompahgre Uplift; CB = Central Basin platform; Pd = Pedernal; Pi = Piute; ZD = Zuni Defiance. The red dotted line represents the Appalachian-Ouachita-Marathon orogenic belt. Base map is modified from Dickinson and Lawton (2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

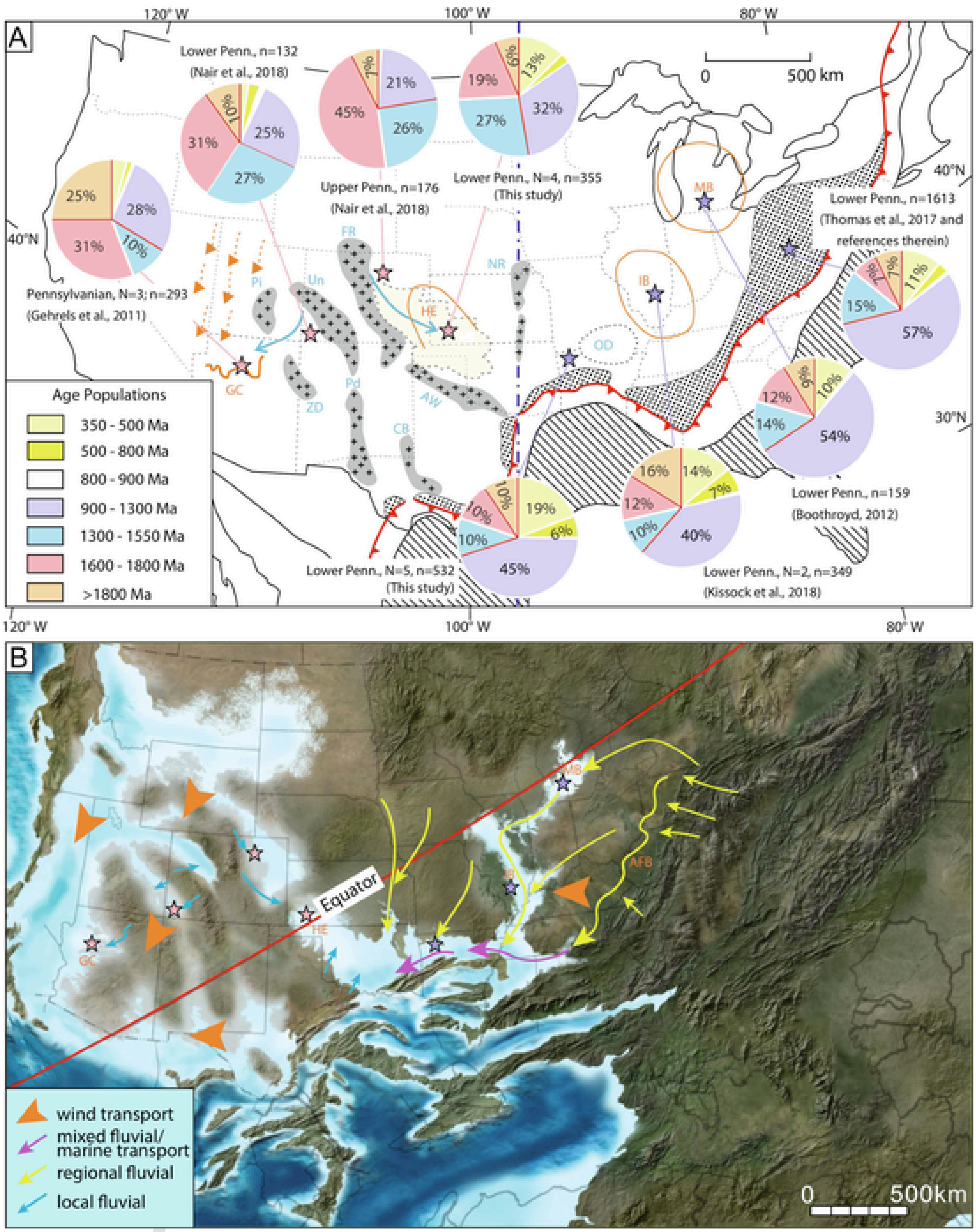


Fig. 9. (A) Relative abundances of detrital zircon age populations. The blue arrows represent general sediment dispersal directions from the ARM uplifts and the orange arrows represent possible aeolian transport paths. The yellow shaded region represents the approximate distribution of the Morrow incised valley fill system in Kansas and Colorado. Abbreviations follow Fig. 8. (B) Pennsylvanian (~315 Ma) paleogeography (from North American Key Time Slices ©2013 Colorado Plateau Geosystems, Inc.) and possible configuration for sediment dispersal in the Morrowan (Bashkirian). Exact routes are difficult to determine due to Pennsylvanian through Permian erosion and later burial, which affected much of the region. Abbreviations follow Fig. 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The data from this and other studies (e.g., Gehrels et al., 2011; Siddoway and Gehrels, 2014; Nair et al., 2018; Leary et al., 2020) suggest that the introduction of Granite-Rhyolite and Yavapai-Mazatzal age components, as recorded in age distributions of sandstones across western Laurentia, likely signals the onset of the Ancestral Rocky Mountains orogeny in the Early Pennsylvanian. An Early Pennsylvanian onset is also corroborated by recent investigations by Sweet and others (2021), who explored the subsidence history of eight ARM basins, including major basins such as Anadarko, Denver, Midland, and Paradox basins, among others. These authors found that all of these ARM basins have a consistent and relatively narrow timing of initiation in late Morrowan to early Atokan (Bashkirian). The timing implies a lag of approximately 5 Myr between the signal of collision on the margin and that of ARM-related deformation in the interior.

In contrast, the Arkoma Shelf and foreland basin maintain a fairly consistent Appalachian age signature from the Late Mississippian through Middle Pennsylvanian, a pattern that is similar to that of the Appalachian foreland basin and other basins in eastern Laurentia (Figs.

7 and 8). The Appalachian foreland basin, which is made of up two regional transverse clastic wedges (the Mauch Chunk-Pottsville in the north and Pennington-Lee in the south) and a major longitudinal system, has a fairly consistent age signature from the Late Mississippian to Pennsylvanian (Park et al., 2010; Grimm et al., 2013; Thomas et al., 2017; Kissock et al., 2018). These transverse and longtidunal systems are characterized by a dominance of Grenville-ages and strong Taconic-Acadian age components. The minor spatial and temporal differences in age signatures that do exist are mainly reflected in the relative proportions of Taconic-Acadian, Yavapai-Mazatzal, and Archean age populations (Fig. 8; Park et al., 2010; Thomas et al., 2017).

Likewise, late Paleozoic sandstones from the Michigan and Illinois basins also suggest a persistent Appalachian signature (Rothschild et al., 2016; Kissock et al., 2018; Thomas et al., 2020). Mississippian to Lower Pennsylvanian strata from the Michigan Basin, west of the Appalachian foreland, are dominated by Grenville and Taconic-Acadian zircons. Subtle shifts in provenance are expressed as minor variations in the Yavapai-Mazatzal and Archean age components and may reflect the relative influences of local erosion and recycling of zircons versus regional sediments from the Appalachian orogen that periodically overfilled the foreland to reach the basin (Figs. 8 and 9). Upper Mississippian to Upper Pennsylvanian strata from the Illinois Basin also preserve dominantly Grenville and Taconic-Acadian age components, and like the Michigan Basin, samples contain small variations in the minor age groups. The variations are interpreted to be a consequence of recycling of underlying Mississippian strata that contain a larger Midcontinent age population (1750–1300 Ma) and sediments derived from exhumed sources in the New England region that are characterized by prominent Neoproterozoic age clusters (750–530 Ma) (Fig. 8; Rothschild et al., 2016; Kissock et al., 2018; Thomas et al., 2018).

5.3. Tectonic configuration and influence on sediment dispersal

The Appalachian orogenic series that culminated in the Alleghanian orogeny in the Late Mississippian, continued into the Pennsylvanian and was followed by the formation of the Pangean supercontinent (Hatcher Jr et al., 1989). The collision exposed basement and earlier orogenic foreland basin strata, with zircons dominated by Grenville and Taconic-Acadian ages (Thomas et al., 2017). Detrital zircon data from Mississippian (Chesterian; Serpukhovian) units in this study and age equivalent sandstones (e.g., from the Michigan and Illinois basins) suggest that the transition to this Appalachian signature was roughly synchronous across much of Laurentia and tied this orogenesis along the eastern margin of the continent (Fig. 8; Thomas et al., 2017; Wang and Bidgoli, 2019; Chapman and Laskowski, 2019). Although the relative roles of rivers, wind, and ocean currents in the transport of these sediments are debated (e.g., Chapman and Laskowski, 2019, Lawton et al., 2021), the consistency in age signatures across Laurentia in Chesterian (Serpukhovian) time suggests that away from the plate margin, relative steady conditions, inherited from the Early-Middle Mississippian, prevailed. Though deformation was occuring within orogenic belts along the margin, elsewhere in Laurentia, this tectonic quiescence meant there were few topographic barriers to overall east-west-transport of Appalanchian sourced sediments.

However, by the Early Pennsylvanian, the Hugoton Embayment and regions farther west experienced an important change in provenance that is likely related to the development of the ARM (Figs. 8 and 9). Although a clear record of ARM deformation is documented by Pennsylvanian to lower Permian strata on the margins of major uplifts in Colorado (ancestral Front Range and Uncompaghre) and Oklahoma (Wichita uplift) and the role of the ARM on midcontinental sedimentation patterns and provenance is well explored (e.g., Sweet and Soreghan, 2010; Leary et al., 2020; Sweet et al., 2021), the eastern limit of ARM influence and its relation with the transcontinental sediment dispersal pattern is poorly defined. The obvious increasing percentages of Yavapai-Mazatzal and Granite-Rhyolite grains from Chesterian (Serpukhovian) to Morrowan (Bashkirian) in the Hugoton Embayment suggest exhumation of relevant basement in Early Pennsylvanian time and is consistent with early onset of the ARM orogeny (e.g. Sweet et al., 2021). The new data from this study also suggests that the development of these topographic highs (and basins) within the Laurentian interior altered the provenance of sediments 100 s of kilometers from these uplifts, with ARM-derived detritus reaching as far east as southwestern Kansas.

While the Hugoton Embayment dataset shows that ARM-derived detritus could reach as far east as southwestern Kansas, it has been difficult to establish the eastern terminus of ARM sedimentary influence. Part of the challenge is that most of the late Paleozoic strata in the midcontinent, in states like Kansas and Oklahoma, is not exposed at the surface and only a limited number of detrital zircon studies have included subsurface core samples from this region (e.g., Kissock et al., 2018; Thomas et al., 2020). The role of the temporally related, but buried ARM structures is also not clear. For example, the Nemaha Ridge (also called the Nemaha uplift), the easternmost expression of ARM deformation, has been suggested as a possible source of first-cycle and recycled zircons in midcontinent sandstones (Kissock et al., 2018; Xie et al., 2018; Thomas et al., 2020). The Nemaha Ridge extends ~650 km across the midcontinent, from northeastern Nebraska to central Oklahoma (Merriam, 1963; Dolton and Finn, 1989; Gay Jr, 2003a; Burberry et al., 2015). Subsurface investigations indicate erosion of Precambrian through Mississippian strata in the Early Pennsylvanian and subsequent burial of the high by the Middle to Late Pennsylvanian (Dolton and Finn, 1989; Steeples 1989; Woelk and Hinze 1995). Xie and other (2018) have suggested the ridge as a probable source of sediments for the Lower Pennsylvanian Middle Bloyd sandstone of the Arkoma Basin based on enrichment of Yavapai-Mazatzal age components. While it is possible that erosion of this structural high served as a source of sediments, the uniformity in Yavapai-Mazatzal (and Granite-Rhyolite) age components in the Upper Mississippian through Middle Pennsylvanian samples from the Arkoma Shelf casts doubt on this hypothesis. Likewise, the relative uniformity of age signatures from this region and the similiarity in proportions of these age groups with samples of the Appalachian foreland and other nearby basins, suggests a dominantly Appalachian source for the the zircons. Thus, the data from this study suggest that, at least for the Arkoma Shelf and basins in eastern Laurentia, the Nemaha Ridge likely exterted limited influence (at least in any substantial volume) on provenace and routing of Carboniferous sediments in midcontinent.

6. Conclusions

In this study, we report 1544 new concordant detrital zircon U—Pb ages from Upper Mississippian through Middle Pennsylvanian sandstones collected from cores in southwestern Kansas and from outcrops in northwestern Arkansas. Based on the new data and comparisons with published detrital zircon data from age-equivalent Paleozoic sandstones across Laurentia, we draw several key conclusions:

(1) Detrital zircons from Upper Mississippian samples in the Hugoton Embayment in southwestern Kansas contain two distinct Middle to Late Paleoproterozoic (1300–900 Ma) and Paleozoic (500–350 Ma) age clusters that correspond to a dominant source in the Appalachian region. However, Yavapai-Mazatzal (1600–1800 Ma) and Granite-Rhyolite (1300–1550 Ma) grains, major components of the local basement, partially replace this sediment source in the Lower Pennsylvanian (Morrow (Bashkirian) samples.

(2) Detrital zircons from Upper Mississippian to Middle Pennsylvanian sandstones from the Arkoma Shelf in northwestern Arkansas also show distinct Middle to Late

Paleoproterozoic (1300–900 Ma) and Paleozoic (500–350 Ma) age clusters, consistent with a persistent major source in the Appalachians for much of the Carboniferous.

(3) The new and published data from across Laurentia confirm that in the Late Mississippian, deformation along the eastern margin of Laurentia tied to the Alleghanian orogeny established continental-scale sediment dispersal systems, delivering sediments with a relatively uniform and strong Appalachian signature as far west as the Grand Canyon in Arizona. However, by the Early Pennsylvanian, long-distance sediment dispersal was disrupted by the ARM uplifts. Although the Arkoma Shelf continued to receive Appalachian sourced sediments, transcontinental sediment distributions systems farther west were more complicated and were dominated by erosion and recycling of these basement uplifts.

Uncited references

Boothroyd, 2012
Gay Jr, 2003b
Gerhard, 2004
Konstantinou et al., 2014
Krystinik and Beverly, 1990
Maughan, 1990
McLean et al., 2016
Sloss, 1963
Wallenberg et al., 2016

Declaration of Competing Interest

None.

Acknowledgements

This study was jointly supported by the National Natural Science Foundation of China (No. 42002131), the Fundamental Research Funds for the Central Universities, and the China University of Geosciences (Wuhan). We thank Andreas Möller and Joseph Andrew with the Isotope Geochemistry Lab at the University of Kansas for assistance with sample processing and U—Pb analysis and data reduction. This research benefited from thoughtful discussions with Lynn Watney, Marty Dubois, Mike Blum, and Isaac Allred. We thank the Kansas Geological Survey and in particular, Nicki Potter, for assistance with core sample collection. This manuscript benefited from detailed reviews by Dustin Sweet (guest editor), Ryan Leary, and an anonymous reviewer.

Appendix A. Supplementray data

References

Barbeau, D.L., 2003. A flexural model for the Paradox Basin: implications for the tectonics of the Ancestral Rocky Mountains. Basin Res. 15, 97–115.
Becker, T.P., Thomas, W.A., Samson, S.D., Gehrels, G.E., 2005. Detrital zircon evidence of Laurentian crustal dominance in the lower Pennsylvanian deposits of the Alleghanian clastic wedge in eastern North America. Sediment. Geol. 182 (1), 59–86.
Boothroyd, J., 2012. Carboniferous Provenance Trends from Clastic Strata of the Michigan Basin Master Thesis. Michigan State University.
Bowen, D.W., Weimer, P., 2003. Regional sequence stratigraphic setting and reservoir geology of Morrow incised-valley sandstones (lower Pennsylvanian), eastern Colorado and western Kansas. AAPG Bull. 87 (5), 781–815.
Burberry, C.M., Joeckel, R.M., Korus, J.T., 2015. Post-Mississippian tectonic evolution of the Nemaha Tectonic Zone and Midcontinent Rift System, SE Nebraska and N Kansas. Mountain Geol. 52 (4), 47–67.
Cirilo, L.L., 2002. Transgressive Estuarine Fill of an Incised Paleovalley, Upper Mississippian Chesterian Series, Shuck field area, Seward County. Kansas, Houston, TX.
Coleman, J.L., 2000. Carboniferous submarine basin development of the Ouachita Mountains of Arkansas and Oklahoma. In: Bouma, A.H., Stone, C.G. (Eds.), AAPG Memoir 72 / SEPM Special Publication No. 68: Fine-Grained Turbidite Systems. The American Association of Petroleum Geologists and SEPM (Society for Sedimentary Geology), pp. 21–32.
Curtis, B.F., 1958. Pennsylvanian paleotectonics of Colorado and adjacent areas: Symposium on Pennsylvanian rocks of Colorado and adjacent areas. Rocky Mountain Association of Geologists, Denver, Colorado, pp. 9–12.
Dickinson, W.R., Lawton, T.F., 2003. Sequential intercontinental suturing as the ultimate control for Pennsylvanian Ancestral Rocky Mountains deformation. Geology 31 (7), 609–612.
Dickinson, W.R., Suczek, C.A., 1979. Plate tectonics and sandstone compositions. Am. Assoc. Pet. Geol. Bull. 63, 2164–2182.
Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geol. Soc. Am. Bull. 94, 222–235.
Dolton, G.L., Finn, T.M., 1989. Petroleum geology of the Nemaha uplift, central Mid-continent. (No. 88-450-D). In: US Geological Survey.
Drake, A.A.J., Sinha, A., Laird, J., Guy, R., 1989. The taconic orogen. In: Hatcher, R.D.J., Thomas, W.A., Viele, G.W. (Eds.), The Appalachian-Ouachita Orogen in the United States: Boulder, Co.
Eardley, A.J., 1951. Tectonic divisions of North America. Am. Assoc. Pet. Geol. Bull. 35 (10), 2229–2237.
Evans, J.E., Soreghan, M., 2015. Long-distance sediment transport and episodic resedimentation of Pennsylvanian dust (eolian silt) in cave passages of the Mississippian Leadville Limestone, southwestern Colorado, USA. Caves and Karst Across Time 516, 1–22.
Garzanti, E., 2016. From static to dynamic provenance analysis-Sedimentary petrology upgraded. Sediment. Geol. 336, 3–13. https://doi.org/10.1016/j.sedgeo.2015.07.010.
Gay, Jr., S.P., 2003a. The Nemaha Trend—A system of compressional thrust-fold, strike-slip structural features in Kansas and Oklahoma, Part 1. Shale Shaker 9–17.
Gay, Jr., S.P., 2003b. The Nemaha Trend—A system of compressional thrust-fold, strike-slip structural features in Kansas and Oklahoma, (Part 2, conclusion). Shale Shaker 39–49.
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.
Gerhard, L.C., 2004. Review of the Nemaha Ridge: a new look at an old structure. Kansas Geological Survey, Kansas Geological Survey. Curr. Res. Earth Sci. Bull. 250 (part 1). http://www.kgs.ku.edu/Current/2004/Gerhard/07_nemaha.html.
Graham, S.A., Dickinson, W.R., Ingersoll, R.V., 1975. Himalayan–Bengal model for flysch dispersal in the Appalachian–Ouachita System. Geol. Soc. Am. Bull. 86, 273–286. https://doi.org/10.1130/0016-7606(1975)86<273:HMFFDI>2.0.CO;2.
Granath, J.W., 1989. Structural evolution of the Ardmore basin, Oklahoma: progressive deformation in the foreland of the Ouachita collision. Tectonics 8 (5), 1015–1036. https://doi.org/10.1029/TC008i005p01015.
Grimm, R.P., Eriksson, K., Carbaugh, J., 2013. Tectono-sedimentary evolution of Early Pennsylvanian alluvial systems at the onset of the Alleghanian orogeny, Pocahontas Basin, Virginia. Basin Res. 25, 450–470.
Gutschick, R.C., Sandberg, C.A., 1983. Mississippian continental margins of the conterminous United States. SEPM Spec. Publ. 33, 79–96.
Guynn, J., Gehrels, G., 2006. Comparison of detrital zircon age distribution using the K-S test. In: K-S Test Instruction of the Arizona LaserChron Center Retrieved from. https://drive.google.com/file/d/0B9ezu34P5h8eZWZmOWUzOTItZDgy.
Hatcher, R.D., 2002. Alleghenian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins. In: Mattinez Catalan, J.R., et al. (Ed.), Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement: Geological Society of America Special Paper, 364. pp. 199–208.
Hatcher, Jr., R.D., Thomas, W.A., Geiser, P.A., Hatcher, Jr., R.D., Thomas, W.A., 1989. Alleghanian Orogen. In: Viele, G.W. (Ed.), The Appalachian-Ouachita orogen in the United States, vol. F- 2. Geological Society of America, Boulder, CO, pp. 233–318.
Henbesi, L.G., 1953. Morrow group and lower Atoka formation of Arkansas. Am. Assoc. Pet. Geol. Bull. 37, 1935–1953.
Hoffman, P.F., 1989. Precambrian geology and tectonic history of North America. In: Bally, A.W. (Ed.), The Geology of North America - An Overview. Geological Society of America, Boulder, CO, pp. 447–512.
Houseknecht, D.W., 1986. Evolution from passive margin to foreland basin: The Atoka Formation of the Arkoma basin, south-central U.S.A. In: Allen, P.A., Homewood, P. (Eds.), Foreland Basins: International Association of Sedimentologists Special Publication, 8. pp. 327–345.
Houseknecht, D.W., Kacena, J.A., 1983. Tectonic and sedimentary evolution of the Arkoma foreland basin. In: Houseknecht, D.W. (Ed.), Tectonic-sedimentary evolution of the Arkoma basin: Society of Economic Paleontologists and Mineralogists, Midcontinent Section, Guidebook, 1. pp. 3–33.
Houseknecht, D.W., Rouse, W.A., Paxton, S., Mars, J.C., Fulk, B., 2014. Upper Devonian–Mississippian stratigraphic framework of the Arkoma Basin and distribution of potential source-rock facies in the Woodford–Chattanooga and Fayetteville–Caney shale-gas systems Arkoma Basin Shale-Gas Systems. AAPG Bull. 98 (9), 1739–1759.
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. Chem. Geol. 211, 47–69.
Kissock, J.K., Finzel, E.S., Malone, D.H., Craddock, J.P., 2018. Lower–Middle Pennsylvanian 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.
Kluth, C.F., 1986. Plate tectonics of the Ancestral Rocky Mountains. In: Peterson, J.A. (Ed.), Paleotectonics and Sedimentation in the Rocky Mountain Region, United States, 41. American Association of Petroleum Geologists Memoir, pp. 353–369.
Kluth, C.F., 1998. Late Paleozoic deformation of interior North America: the greater Ancestral Rocky Mountains: Discussion. AAPG Bull. 82, 2272–2276.
Kluth, C.F., Coney, P.J., 1981. Plate tectonics of the Ancestral Rocky Mountains. Geology

9, 10–15.
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. J. Geol. 122 (2), 201–216.
Krystinik, L.F., Beverly, B.A., 1990. Sedimentology of the upper Morrow Formation in eastern Colorado and western Kansas. In: Sonnenberg, S.A., Shannon, L.T., Rader, K., Von Drehle, W.F., Martin, G.W. (Eds.), Morrow Sandstones of Southeast Colorado and Adjacent Areas. Rocky Mountain Association of Geologists, pp. 37–50.
Lane, H.R., De Keyser, T.L., 1980. Paleogeography of the late Early Mississippian (Tournaisian 3) in the central and southwestern United States. In: Rocky Mountain Symposium.
Lawton, T.F., Cashman, P.H., Trexler, Jr., J.H., Taylor, W.J., 2017. The late Paleozoic southwestern Laurentian borderland. Geology 45, 675–678. https://doi.org/10.1130/G39071.1.
Lawton, T.F., Blakey, R.C., Stockli, D.F., Liu, L., 2021. Late Paleozoic (Late Mississippian-Middle Permian) sediment provenance and dispersal in western equitorial Pangea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 572, 110386 35 pp https://doi.org/10.1016/j.palaeo.2021.110386.
Leary, R.J., Umhoefer, P., Smith, M.E., Riggs, N., 2017. A three-sided orogen: a new tectonic model for Ancestral Rocky Mountain uplift and basin development. Geology. 45 (8), 735–738.
Liner, R.T., 1979. Lithostratigraphy and Biostratigraphy of the Cane Hill Member of the Hale Formation, Northern Arkansas [M.S. thesis]. University of Arkansas 140 p.
Ludwig, K.R., 2008. Isoplot 3.60. Berkeley Geochronology Center, Special Publication. 4. p. 77.
Mallory, W.W., 1958. Pennsylvanian coarse arkosic redbeds and associated mountains in Colorado. In: Symposium on Pennsylvanian Rocks of Colorado and Adjacent Areas. Rocky Mountain Association of Geologists, Denver, CO, pp. 17–20.
Manger, W.L., 2014. An Introduction to the Lower Mississippian (Kinderhookian-Osagean) Geology of the Southern Ozarks, Guidebook. University of Arkansas, Fayetteville, AR.
Maughan, E.K., 1990. Summary of the Ancestral Rocky Mountains epeirogeny in Wyoming and adjacent Areas (No. 90-447). US Geological Survey.
McGilvery, T.A., Manger, W.L., Zachry, D.L., 2016. Summary and Guidebook to the depositional and tectonic history of the Carboniferous succession Northwest Arkansas. In: 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. Geochem. Geophys. Geosyst. 17, 2480–2496.
Merriam, D.F., 1963. The Geologic history of Kansas. Kansas Geol. Surv. Bull. 162, 317.
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 Bull. 83 (3), 393–409.
Mueller, P.A., Heatherington, A.L., Foster, D.A., Thomas, W.A., Wooden, J.L., 2014. The Suwannee suture: significance for Gondwana-Laurentia terrane transfer and formation of Pangaea. Gondwana Res. 26, 365–373.
Nair, K., Holm-Denoma, C., Singleton, J., Egenhoff, S., 2018. Detrital zircon geochronology of Pennsylvanian-Permian Strata in Colorado: evidence for Appalachian-Derived Sediment and Implications for the Timing of Ancestral Rocky Mountains Uplift. Mountain Geol. 55 (3), 119–140.
Nilsen, T.H., Stewart, J.H., 1980. The Antler Orogeny – Mid-Paleozoic tectonism in western North America. Geology 8, 298–302.
Park, H., Barbeau, Jr., D.L., 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. J. Geol. 118 (1), 23–44.
Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1986. Numerical Recipes; The Art of Scientific Computing. Cambridge University Press, Cambridge, UK.
Rader, K., 1990. Petrography of Morrow sandstones in southeast Colorado, southwest Kansas and northwest Oklahoma. In: Sonnenberg, S.A., Shannon, L.T., Rader, K., Von Drehle, W.F., Martin, G.W. (Eds.), Morrow Sandstones of Southeast Colorado and Adjacent Areas. Rocky Mountain Association of Geologists, pp. 51–58.
Rascoe, B.J., Adler, F.J., 1983. Permo-carboniferous hydrocarbon accumulations, Midcontinent, USA. AAPG Bull. 67 (6), 979–1001.
Ross, C.A., Ross, J.R., 1988. Late Paleozoic transgressive deposition. In: Wilgus, D.K. (Ed.), Sea Level Changes: An Integrated Approach: SEPM Special Publication, 42. pp. 227–247.
Rothschild, T.J., Malone, D.H., Craddock, J.P., Devera, J., 2016. Detrital zircon geochronology of Chesterian sandstones in the Illinois Basin, USA. In: Paper Presented at the Conference on Geological Society of America. Denver, CO.
Senior, P.J., 2012. Depositional Environment, Reservoir Properties, and EOR Potential of an Incised-Valley-Fill Sandstone, Pleasant Prairie Oilfield, Haskell County, Kansas: Unpublished M.S. thesis. University of Kansas, Lawrence, KS.
Siddoway, C.S., Gehrels, G.E., 2014. Basement-hosted sandstone injectites of Colorado: a vestige of the Neoproterozoic revealed through detrital zircon provenance analysis. Lithosphere 6 (6), 403–408.
Sims, P.K., 1996. Early Proterozoic Penokean orogen. In: Sim, P.K., Carter, L.M.H. (Eds.), Archean and Proterozoic geology of the Lake Superior region, USA. U.S. Geological Survey Professional Paper, pp. 28–30.
Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon—a new natural reference material for U–Pb and Hf isotopic microanalysis. Chem. Geol. 249, 1–35.
Sloss, L.L., 1963. Sequences in the cratonic interior of North America. GSA Bull. 74 (2), 93–114.
Sonnenberg, S.A., Shannon, L.T., Rader, K., von Drehle, W.F., 1990. Regional structure and stratigraphy of the Morrowan Series, southeast Colorado and adjacent areas. In: Sonnenberg, S.A., Shannon, L.T., Rader, K., Von Drehle, W.F., Martin, G.W. (Eds.), Morrow Sandstones of Southeast Colorado and Adjacent Areas. Rocky Mountain Association of Geologists, pp. 1–8.
Soreghan, G.S., Soreghan, M.J., Hamilton, M.A., 2008. Origin and paleoclimatic significance of tropical silt in the late Paleozoic icehouse. Palaeogeogr. Palaeoclimatol. Palaeoecol. 268, 234–259. https://doi.org/10.1016/j.palaeo.2008.03.050.
Speed, R.C., Sleep, N.H., 1982. Antler orogeny and foreland basin: a model. GSA Bull. 93, 815–828. https://doi.org/10.1130/0016-7606(1982)93<815:AOAFBA>2.0.CO;2.
Stampfli, G.M., Hochard, C., Verard, C., Wilhem, C., von Raumer, J., 2013. The formation of Pangea. Tectonophysics v. 593, 1–19. https://doi.org/10.1016/j.tecto.2013.02.037.
Sur, S., Soreghan, G.S., Soreghan, M.J., Yang, W., Saller, A.H., 2010. A record of glacial aridity and Milankovitch-scale fluctuations in atmospheric dust from the Pennsylvanian tropics. J. Sediment. Res. 80 (12), 1046–1067. https://doi.org/10.2110/jsr.2010.091.
Sutherland, P.K., 1988. Late Mississippian and Pennsylvanian depositional history in the Arkoma basin area, Oklahoma and Arkansas. GSA Bull. 100 (11), 1787–1802.
Sweet, D.E., Soreghan, G.S., 2010. Late Paleozoic tectonics and paleogeography of the ancestral Front Range: structural, stratigraphic, and sedimentologic evidence from the Fountain Formation (Manitou Springs, Colorado). GSA Bull. 122 (3–4), 575–594.
Sweet, D.E., Brotherton, J.L., Chowdhury, N., Ramsey, C.E., 2021. Tectonic subsidence analysis of the Ancestral Rocky Mountains from the interior to the southern margin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 576 (12), 110508.
Thomas, W.A., 2014. A mechanism for tectonic inheritance at transform faults of the Iapetan margin of Laurentia. Geosci. Can. 41 (3), 321–344.
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. Geosphere 13 (6), 2206–2230.
Thomas, W.A., Gehrels, G.E., Sundell, K.E., Greb, S.F., Finzel, E.S., Clark, R.J., Malone, D.H., Hampton, B.A., Romero, M.C., 2020. Detrital zircons and sediment dispersal in the eastern Midcontinent of North America. Geosphere 16 (3), 817–843. https://doi.org/10.1130/GES02152.1.
Trappe, J., 2000. Pangea: extravagant sedimentary resource formation during supercontinent configuration, an overview. Paleogeogr. Paleoclimatol. Paleoecol. 161 (1–2), 35–48. https://doi.org/10.1016/S0031-0182(00)00116-4.
Trexler, Jr., J.H., Cashman, P.H., Cole, J.C., Snyder, W.S., Tosdal, R.M., Davydov, V.I., 2003. Widespread effects of middle Mississippian deformation in the Great Basin of western North America. Geol. Soc. Am. Bull. 115, 1278–1288.
Trexler, Jr., J.H., Cashman, P.H., Snyder, W.S., Davydov, V.I., 2004. Late Paleozoic tectonism in Nevada: timing, kinematics, and tectonic significance. Geol. Soc. Am. Bull. 116, 525–538.
Van Schmus, W.R., Bickford, M.E., Anderson, J.L., 1993. Transcontinental Proterozoic provinces. In: Reed, J.C. Jr, Bickford, M.E., Houston, R.S. (Eds.), Precambrian: Conterminous U. S. Geology of North America, Boulder, CO, pp. 171–334.
Vermeesch, P., 2012. On the visualisation of detrital age distributions. Chem. Geol. 312, 190–194.
Vermeesch, P., 2013. Multi-sample comparison of detrital age distributions. Chem. Geol. 341, 140–146.
Vermeesch, P., Resentini, A., Garzanti, E., 2016. An R package for statistical provenance analysis. Sediment. Geol. 336, 14–25.
Waite, L., Fan, M., Collins, D., Gehrels, G., Stern, R.J., 2020. Detrital zircon provenance evidence for an early Permian longitudinal river flowing into the Midland Basin of west Texas. Int. Geol. Rev. 1–21.
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. In: Geological Society of America Abstracts with Programs. Vol. 48, No. 7 doi: 10.1130/abs/2016AM-284406. Abstract Presented at the GSA Annual Meeting in Denver, CO, September 2016.
Wang, W., Bidgoli, T.S., 2019. Detrital zircon geochronologic constraints on patterns and drivers of continental-scale sediment dispersal in the Late Mississippian. Geochem. Geophys. Geosyst. 20 (11), 5522–5543 doi:??.
Whitmeyer, S.J., Karlstrom, K.E., 2007. Tectonic model for the Proterozoic growth of North America. Geosphere 3 (4), 220–259.
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, 867–870.
Xie, X., Cains, W., Manger, W.L., 2016. U-Pb detrital zircon evidence of transcontinental sediment dispersal: provenance of Late Mississippian Wedington Sandstone member, NW Arkansas. Int. Geol. Rev. 58 (15), 1951–1966.
Xie, X., Buratowski, G., Manger, W.L., Zachry, 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. J. Sediment. Res. 88 (7), 795–810.
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 Planet. Sci. Lett. 475, 44–57.
Ye, H., Royden, L., Burchfiel, C., Schuepbach, M., 1996. Late Paleozoic deformation of interior North America: the greater ancestral Rocky Mountains. AAPG Bull. 80 (9), 1397–1432.
Ziegler, P.A., 1990. Geological Atlas of Western and Central Europe, 2nd ed. Shell Internationale Petroleum Maatschappij B.V, The Hague, Netherlands.