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ARTICLE

Detrital zircon provenance evidence for an early Permian longitudinal river flowing into the Midland Basin of west Texas

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ABSTRACT

Collision of Gondwana and Laurentia in the late Palaeozoic created new topography, drainages, and foreland basin systems that controlled sediment dispersal patterns on southern Laurentia. We utilize sedimentological and detrital zircon data from early Permian (Cisuralian/Leonardian) submarine-fan deposits in the Midland Basin of west Texas to reconstruct sediment dispersal pathways and palaeogeography. New sedimentological data and wire-line log correlation suggest a portion of the early Permian deposits have a southern entry point. A total of 3259 detrital zircon U-Pb and 357 εHf data from 12 samples show prominent groups of zircon grains derived from the Appalachian (500–270 Ma) and Grenville (1250–950 Ma) provinces in eastern Laurentia and the peri-Gondwana terranes (800–500 Ma) incorporated in the Alleghanian-Ouachita-Marathon orogen. Other common zircon groups of Mesoproterozoic-Archaean age are also present in the samples. The detrital zircon data suggest throughout the early Permian, Appalachia and Gondwana detritus was delivered by a longitudinal river system that flowed along the Appalachian-Ouachita-Marathon foreland into the Midland Basin. Tributary channels draining the uplifted Ouachita-Marathon hinterland brought Gondwana detritus into the longitudinal river with headwaters in the Appalachians or farther northeast. This drainage extended downstream westward and delivered sediments into the Permian Basin near the west terminus of the Laurentia-Gondwana suture. Estimated rates of deposition and proportions of zircons from more local (Grenville) versus more distal (Pan-African) sources indicate that river strength decreased throughout early Permian time. Primary sediment delivery pathway was augmented by minor input from the Ancestral Rocky Mountains and wind deflation of fluvial sediments north and east of the basin. Slope failure associated with early Permian deposition in the southeastern margin of the Midland Basin triggered gravity flows leading to submarine fan deposition.

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1. Introduction

The collision between Laurentia and Gondwana is likely to have formed a large orogenic plateau on the overriding northern Gondwanan plate during the late Palaeozoic, analogous to the Tibetan Plateau on the overriding Eurasia plate (Figure 1). Cenozoic uplift of the Himalaya and Tibetan Plateau shed large volumes of clastic sediments into the Himalayan foreland and the detritus was mainly transported by the Indus and Ganges-Brahmaputra rivers and accumulated in the submarine Indus and Bengal fans. Other examples of the continental collision resulted in similar systems of organized sediment transport along the axis of a peripheral foreland basin on the subducting continental plate (DeCelles and Giles 1996), including the Tigris-Euphrates rivers associated with the Tauride-Zagros highland and the Po River associated with the Alps. By analogy with these collisional systems, the Palaeozoic continental collision that formed Pangea should have reorganized regional drainage systems to deliver clastic sediments from the orogen into the remnant ocean on the Ouachita foreland on the Laurentian margin (Graham *et al*. 1975) (Figure 1(b)). The Permian Basin in west Texas and southeastern New Mexico, covered by an extension of the Panthalassa Ocean during the late Palaeozoic, was near the western terminus of the Laurentia-Gondwana suture zone and the associated river system (Figure 1(a)). Sedimentary rocks in the basin should archive information about the drainage system formed in response to Laurentia-Gondwana collision. Therefore, studies of depositional environments and sedimentary provenance of the basin-fills in the Permian Basin hold a key to reconstruct the palaeodrainage system and palaeogeography formed by Laurentia-Gondwana collision.

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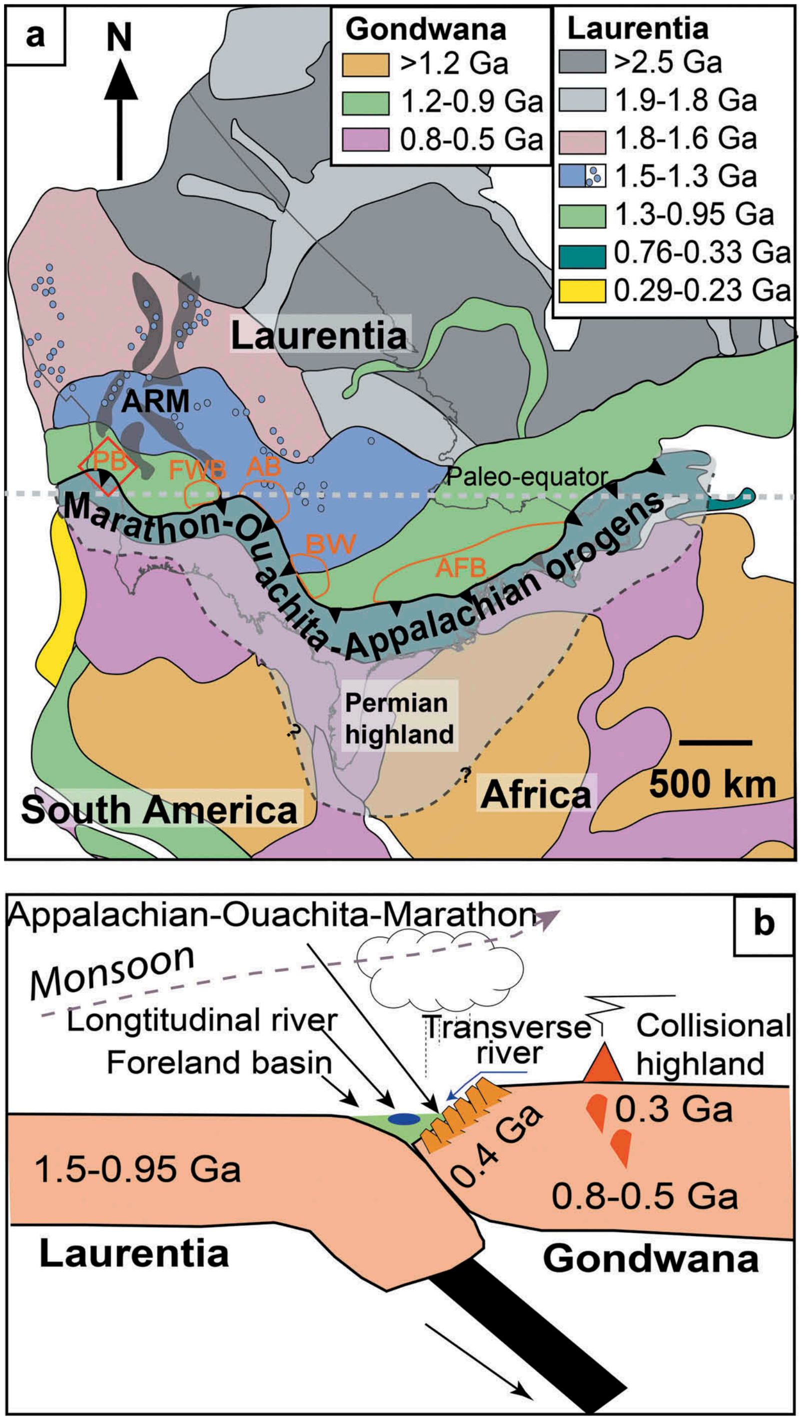

Figure 1. (a). Map showing main basement provinces in Pangea, locations of the Alleghanian-Ouachita-Marathon orogenic belt, Permian Basin, and other foreland basins. Basement maps are modified from Veevers (2017) and Dickinson and Gehrels (2009). Irregular dark grey polygons in western Laurentia represent Ancestral Rocky Mountain (ARM) uplifts. AB–Arkoma Basin, BW–Black Warrior Basin, FB–Fort Worth Basin, PB–Permian Basin, AFB–Appalachian foreland basin. (b). Simplified tectonic cross-section showing Pennsylvanian-Permian collision between Gondwana and Laurentia created orogenic highland, foreland basin, and monsoonal circulation.

The provenance and sediment dispersal pathways of clastic sediments into the Permian Basin remain poorly constrained. Earlier interpretations of sediment provenance are based largely on isopach and net-sand maps derived from subsurface well-log correlations (Handford 1981; Guevara 1988; Tyler *et al.* 1997; Hamlin and Baumgardner 2012). Deposition of the early Permian Spraberry Formation in the Midland Basin, the eastern portion of the greater Permian Basin (Figure 2(a)), is often described as the product of multiple submarine fans emanating from the northwest, with transport pathways that were redirected towards the southwest in the mid-fan region by a prominent shelf-slope promontory along the eastern margin of the basin (Tyler *et al*. 1997). Sediments from a southeastern source also contributed to submarine fan deposition (Handford 1981). Recent detrital zircon provenance studies, focusing on middle Permian strata in the Delaware Basin in the western Permian Basin (Figure 2(a)) challenge these interpretations (Soreghan and Soreghan 2013; Xie *et al*. 2018). These studies agree that middle Permian detritus were ultimately derived from the Ouachita-Marathon and Appalachian orogenic belts and from peri-Gondwana terranes accreted during the late Palaeozoic Laurentia-Gondwana collision, but disagree on the sediment delivery pathways. Soreghan and Soreghan (2013) suggest that the sediments were transported mainly by a regional fluvial system draining the piedmont of the Ouachita orogenic belt in which abundant Appalachian sediments were stored in the Palaeozoic strata and Peri-Gondwana terranes were incorporated during the collision, and the transport was augmented by aeolian deflation of fluvial sediments by seasonal wind. Xie *et al*. (2018) argue for direct sediment transport from the Appalachian orogenic belt by a transcontinental fluvial system in addition to the regional and local fluvial systems draining the Ouachita orogen and peri-Gondwana terranes. The transcontinental fluvial system drained westward through the midcontinent region of Laurentia (Xie *et al*. 2018) and was likely the one that dispersed sediments into the Grand Canyon region to the northwest of the Permian Basin during the Mississippian-Permian (Gehrels *et al*. 2011; Chapman and Laskowski 2019). This transcontinental fluvial system is different from the one that dispersed Pennsylvanian synorogenic sediments into the Ouachita foreland to the east of the Permian Basin (Alsalem *et al*., 2018; Graham *et al*. 1975) and the Marathon foreland to the southeast of the Permian Basin (Gleason *et al*. 2007; Gao *et al*. 2020). Based on detrital zircon U-Pb signature, it is suggested that the transcontinental river that delivered Appalachian detritus into the Fort Worth Basin and

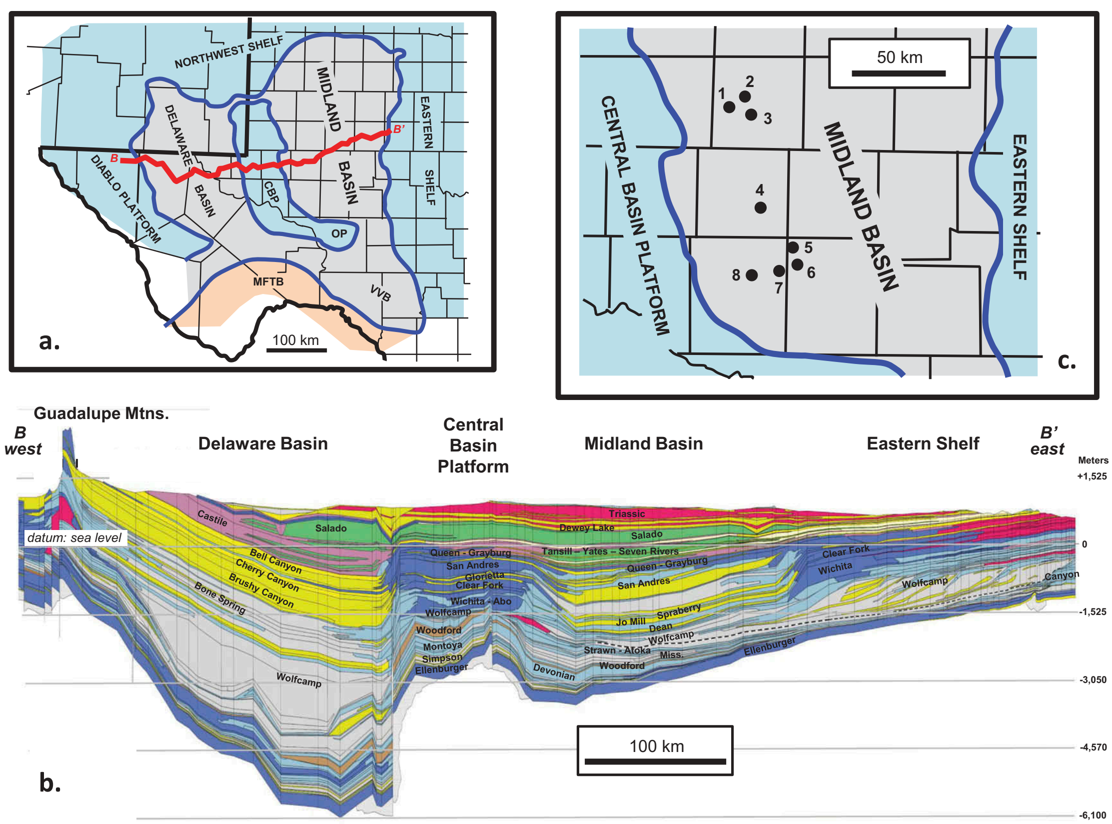

Figure 2. Permian Basin of the west Texas and southeast New Mexico. (a). Index map showing main physiographic features of the region; light blue–shallow shelves, grey–deeper basins. MFTB–Marathon fold and thrust belt, CBP–Central Basin Platform, OP–Ozona Platform/Uplift, VVB–Val Verde Basin. Location of cross-section B-B′ (Figure 2B) is indicated. (b). West – east geologic cross-section across the Permian Basin showing distribution and thickness of major stratigraphic units (modified from Matchus and Jones 1984). Vertical lines indicate the location of wells used for stratigraphic control. (c). Close-up of the central and southern portion of the Midland. Black dots represent the location of cores sampled for zircons in the Midland Basin (12 samples from eight wells). Stratigraphic position of samples shown in Figure 3.

Marathon foreland during the Pennsylvanian was a longitudinal river in the Appalachian-Ouachita-Marathon foreland (Alsalem *et al*., 2018; Gleason *et al*. 2007; Gao *et al*. 2020).

These conclusions are expanded on by Liu and Stockli (2020), who studied detrital zircon provenance of the lower Permian Wolfcampian and lowermost Leonardian (Cisuralian) sedimentary rocks from the Permian Basin. They concluded that the sandstones in their data set (Figure 3) reflect significant contributions from Gondwanan and peri-Gondwanan sources of Mexico and Central America. Typical Laurentian basement signatures such as from the Grenville province (950–-1300 Ma) are mostly absent from their early Leonardian samples, suggesting a drainage reorganization and major sediment provenance shift to peri-Gondwanan terranes in modern Mexico and Central America during Cisuralian (Wolfcampian – Leonardian) time.

Here, we study the depositional environment and sediment provenance of lower Permian (Cisuralian/Leonardian) sedimentary rocks in the Midland Basin in order to test the early Permian major reorganization (Liu and Stockli 2020), and infer the palaeodrainage that shed sediments into the western terminus of the Laurentia-Gondwana suture. This study integrates core and logs analyses and detrital zircon U-Pb and Hf-Lu data from the subsurface. Our results suggest a northward transport of the submarine fans and mixing

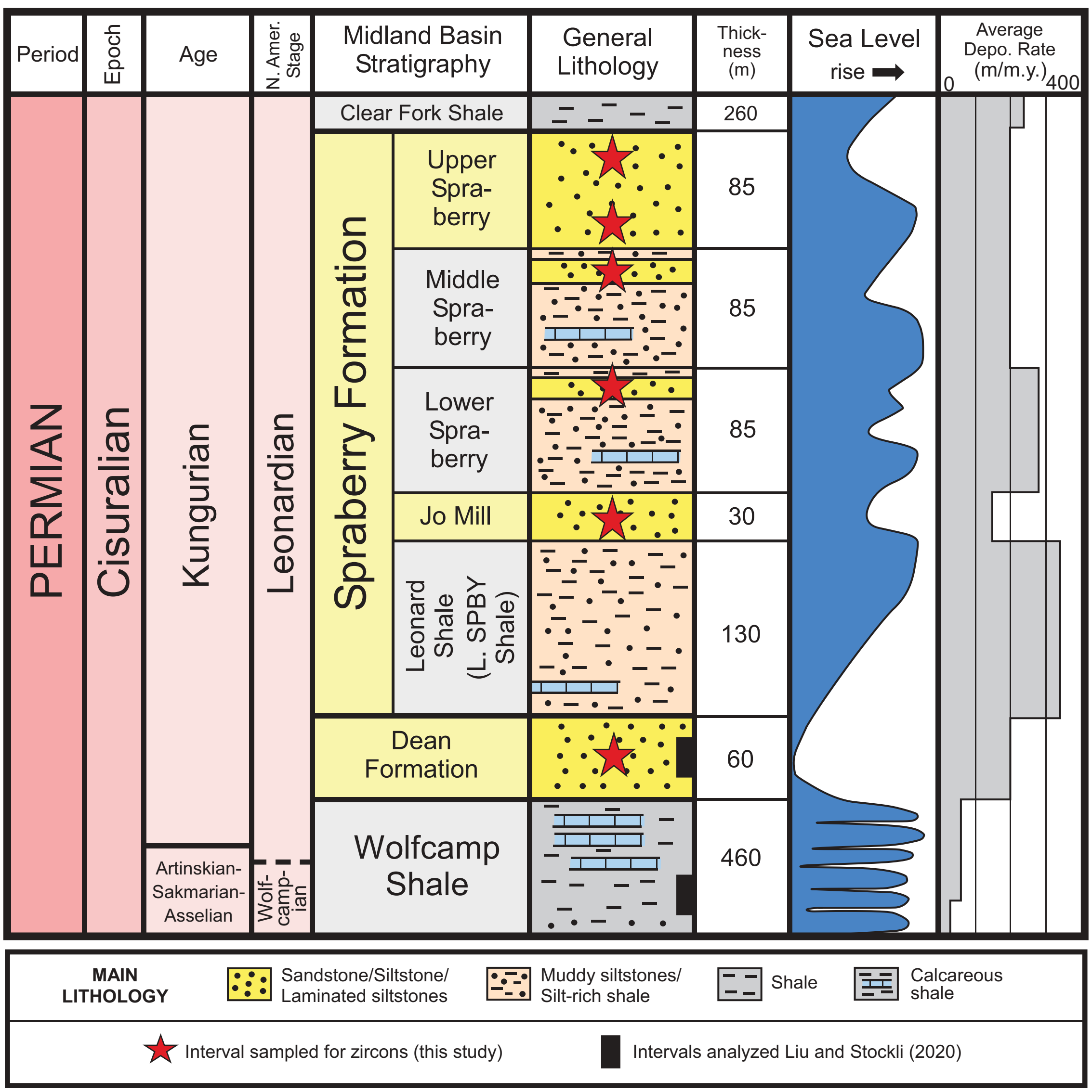

Figure 3. Simplified stratigraphy of lower Permian strata, Midland Basin. Red stars indicate stratigraphic intervals of samples used for detrital zircon study; black bars indicate intervals studied by Liu and Stockli (2020). General lithology and thickness data are taken from wells in central Midland County, TX. Sea-level curve from Ross and Ross (2009). Depositional rate calculations represent minimal estimates, uncorrected for compaction.

of Appalachian and Gondwana detritus in the Midland Basin throughout early Permian time. We use these data to suggest that far-travelled detritus from Gondwana as well as Grenvillian terranes in Laurentia fed into the southeastern part of the Permian Basin by one or more large rivers draining the Appalachian-Ouachita foreland.

2. Significance and geologic setting of the Permian Basin

The Permian Basin is a world-class oil and gas province, having produced more than 30 billion barrels of oil from reservoirs of Palaeozoic age (Dutton *et al*. 2005). Recently, the Delaware and Midland basins have emerged as the U.S. A's richest cache of unconventional shale reserves, primarily in Permian mudstones (Gaswirth *et al*. 2016). The early Permian Spraberry Formation in the Midland Basin hosts the giant Spraberry Trend oil accumulation, a 120 km-long, 16–56 km-wide, deep-water clastic reservoir (Handford 1981; Galloway *et al*. 1983; Montgomery *et al*. 2000; Dutton *et al*. 2005; Hamlin and Baumgardner 2012). Given the economic significance of the basin fill, previous studies of the Permian Basin have focused mainly on petroleum resource investigations. Nevertheless, sediment provenance is also important for predictions of reservoir extent and quality but has not been extensively studied in the Midland Basin.

The Permian Basin began its evolution on the Laurentia passive margin as an early Palaeozoic continental sag known as the Tobosa Basin (Galley 1958). During latest Mississippian through early Permian time, subduction and collision along the southern and southeastern margins of Laurentia beneath the northern margin of Gondwana caused the Alleghany-Ouachita-Marathon orogenies during the assembly of the supercontinent Pangea (e.g. Thomas 2006) (Figure 1(b)). The resulting transcontinental orogenic belt stretched for at least 5000 km across Pangea. At the same time, the Ancestral Rocky Mountains (ARM) Orogeny occurred mainly in Colorado, New Mexico, Oklahoma in western Laurentia as an intracontinental response to subduction and collision at Laurentia margins (Ye *et al*. 1996; Dickinson and Lawton, 2003; Leary *et al*. 2017). The basement-involved Central Basin and Ozona uplifts of the southernmost ARM partitioned the Permian Basin into the Midland and Delaware basins (Figure 2(a,b)). The Midland Basin is bounded to the north and east by the Northwest and Eastern shelves, which are Late Carboniferous to Permian shallow marine platforms. Loading of the Alleghany-Ouachita-Marathon orogens on the southern margin of Laurentia caused flexural subsidence to form an assemblage of foreland basins (Hills 1984; Yang and Dorobek 1992; Ewing 1993), including, from east-to-west, the Black Warrior, Arkoma, Fort Worth, and Val Verde basins (Figure 1(a)). The foreland basin system was likely connected along strike except where it was affected by the ARM. The ARM orogenesis waned during the early Permian, and erosion of several uplifts has removed the lower and middle Palaeozoic sediments to expose Proterozoic basement rock (e.g. Kluth 1986)

During early Permian time, the Permian Basin and the Ouachita-Marathon orogenic front were located slightly north of the palaeoequator (Figure 1(a)) (Ziegler *et al*. 1997). Western and central equatorial Pangaea experienced gradual drying while northwestern equatorial Pangaea was persistently dry during the Late Pennsylvanian-early Permian (Tabor and Montañez 2002). In the Permian Basin region, the palaeoclimate was humid based on abundant coals and palaeosol geochemistry results (Tabor *et al*. 2008) and palaeoclimate simulation of flanking regions (Tabor and Poulsen 2008). The juxtaposition of highlands to the south and remnant ocean to the west near the equator is likely to have caused a strong monsoon system (Figure 1(b)) (Tabor and Poulsen 2008), similar to the present-day South Asia Monsoon caused by seasonal heating and cooling of the Tibetan Plateau. If such monsoonal circulation in early Permian time existed, the summer (rainy) surface winds were generally eastward, opposite to the Permian northeast trade winds (Tabor and Poulsen 2008).

Transgression of the Laurentian craton by an arm of the Panthalassic Ocean during Pennsylvanian and early Permian time periodically submerged the U.S. midcontinent region. Approximately one kilometre or more of lower Permian deep-water clastic sediment accumulated in the Midland Basin (Figure 3). The lower Permian strata in the Midland Basin include, from oldest to youngest, the Wolfcamp Shale, Dean Formation, and Spraberry Formation. The Dean and Spraberry formations are not exposed. The Spraberry Formation is divided by oil industry geologists into several informal units including the Leonard shale, Jo Mill sand, and lower, middle, and upper Spraberry units. The Dean and Spraberry formations were deposited during the Leonardian North America Stage. The Dean and Spraberry formations consist primarily of very fine-grained sandstones, siltstones, previously interpreted as deposits of submarine fan complexes (Handford 1981; Guevara 1988; Tyler *et al*. 1997; Hamlin and Baumgardner 2012). These submarine fan complexes generally correlate with the early Permian marine lowstands (Ross and Ross 2009). Estimated sedimentation rates of the Dean and Spraberry formations calculated for this study are generally greater than that of the underlying Wolfcamp Shale by a factor of 4 or more (Figure 3).

3. Sedimentology and Northward Progradation of early Permian submarine fans

3.1 Materials and sedimentologic observations

We studied the sedimentology of the Spraberry Formation by examining and describing five slabbed cores and correlating wireline logs along an N-S cross-section in the basin. The depth intervals of interest belong to the Jo Mill unit (Figure 3). Detailed core descriptions allow interpretation of depositional facies, ichnological fabric, and correlation of core facies to gamma-ray response in wire-line logs along an N-S cross-section. This allowed the facies progression within this unit to be assessed. Dense coverage (up to 40-acre spacing) of gamma-ray well logs within the Jo Mill unit unambiguously fill correlation gaps between cores.

Clastic rocks in the Jo Mill unit in the central and southern portion of the Midland Basin consist of repetitive, thinly bedded cycles, typically 1–3 m thick, including massive, horizontally- or cross-bedded very fine-grained sandstone, laminated siltstone, clay-rich laminated siltstone, bioturbated siltstone and mudstone, and organic-rich mudstone (Figure 4(a)). The sandstones have sharp, erosive bases (Figure 4(b)) and commonly contain fluid-escape structures (Figure 4(c)). The tops of the massive sandstones commonly contain redeposited argillaceous rip-up clasts (Figure 4(d)). Burrows within bioturbated siltstones and mudstones observed in core belong to deep-water ichnofacies of Cruziana, Zoophycos, and Nereites. Towards the centre of the basin, the Jo Mill cycles become slightly thinner (0.3–1.3 thick) and contain a higher percentage of shale. Massive Jo Mill sandstones are more amalgamated in the southern part of the basin and become increasingly more interbedded with shale to the north. Scoured contacts (Figure 4(e)) observed at the base of major sandy units in the southernmost vertical and horizontal cores were not observed in the northernmost core utilized in this study.

3.2 Sedimentological interpretation

The sedimentological observations of the Jo Mill unit in the central and southern portions of the Midland Basin suggest deposition within submarine fan complexes. This is consistent with previous interpretations of the Spraberry Formation and Dean Sandstone as submarine fans (Handford 1981; Guevara 1988; Hamlin and Baumgardner 2012). The deep-water ichnofacies and bedding pattern of massive sandstones grading upwards into laminated and/or bioturbated siltstones and/or organic-rich mudstones suggest stacked or recurring submarine sediment gravity flows (e.g. Lowe 1982). The sharp bases and fluid-escape structures of the massive sandstones indicate rapid deposition and erosion by episodic turbidity flows which scoured the basin floor substrate.

Vertical stacking patterns of flow units as seen in core and logs transition smoothly from amalgamated sandstone to fully preserved turbidite cycles from south to north and allow identification of proximal, middle, and outer fan sub-environments (Figure 5). Proximal facies consist primarily of amalgamated 1–3 m-thick, massive sandstones and siltstones with relatively few breaks in a sandy deposition. The middle fan contains full cycles of massive sandstones to interbedded siltstones and mudstones. The distal outer fan facies towards the basin centre is more thinly bedded (0.3–1.3 m) with individual sandy flow units grading into mudstones. The overall frontal and lateral facies progression and stacking pattern are similar to those described by Spychala *et al.* (2017). The gross thickness of the proximal facies in the Jo Mill is less than the thickness of the distal facies. Distal thickening is hypothesized to be due to successive remobilization of proximal unconsolidated seafloor from subsequent turbidity-flows in the Jo Mill system (Paull *et al.* 2018). A proximal (south) to distal (north) relationship for the Jo Mill submarine fan complex is supported by the relative proportion of facies A–E, as described in available core samples (Figure 5).

The vertical and lateral facies successions based on sedimentological core descriptions and correlation of wire-line logs suggest that the Jo Mill submarine fan complex in the southern portion of the Midland Basin has a southern entry point. A northward-directed dispersal of Jo Mill sediments is consistent with a previously published isopach map of the Spraberry by Handford (1981) (Figure 6). Spraberry fan systems were likely fed by turbidity and saline density currents sources from the surrounding depositional shelves (Fischer and Sarnthein 1988; Montgomery *et al.* 2000). Likely triggering mechanisms of turbidity flows in the southern Midland Basin included slope failure caused by the instability due to rapid deposition, storm events, sinking of hyperpycnal river floodwater, typhoons, or earthquakes (e.g. Talling *et al.* 2013).

4. Detrital zircon analysis and provenance interpretation

4.1 Methods

In concert with the sedimentological study, we selected 12 fine-grained sandstone and siltstone samples from eight conventional cores from the Spraberry and Dean formations in the central Midland Basin for detrital zircon

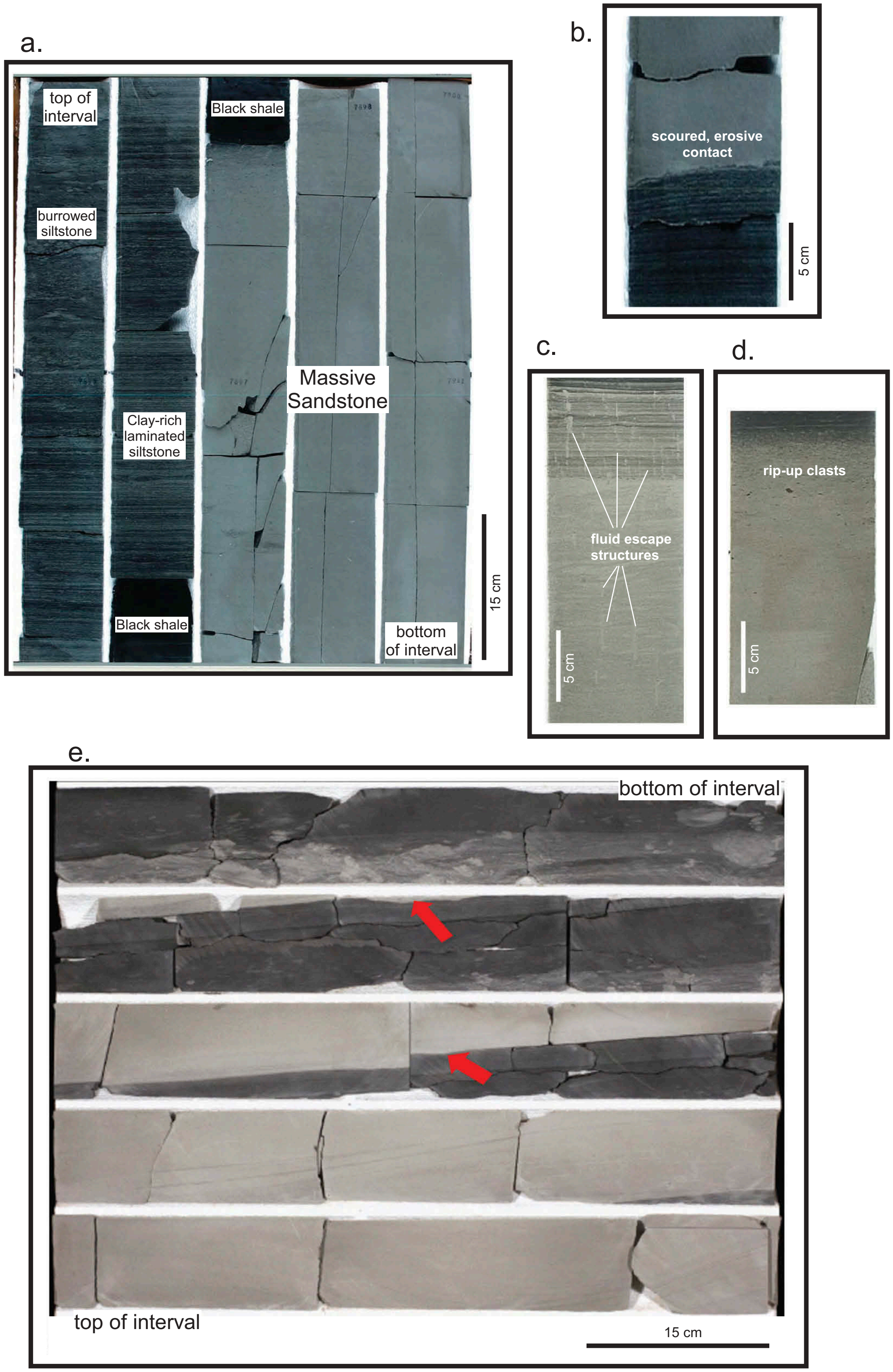

Figure 4. Representative Jo Mill lithofacies of the Midland Basin. (a). Core box photo of a vertical core succession illustrating massive, very fine-grained sandstones capped by a thin, organic-rich mudstone, grading upwards into laminated and burrowed siltstones. (b). Close-up of core piece showing a scoured, erosive contact at the base of a massive sandstone. (c). Close-up of core piece showing numerous fluid-escape structures. (d). Close up of core showing abundant small rip-up clasts at the top of a massive sandstone. (e). Core box photo of a sharp, scoured contact between massive light-coloured sandstone and dark shale facies within a horizontal core.

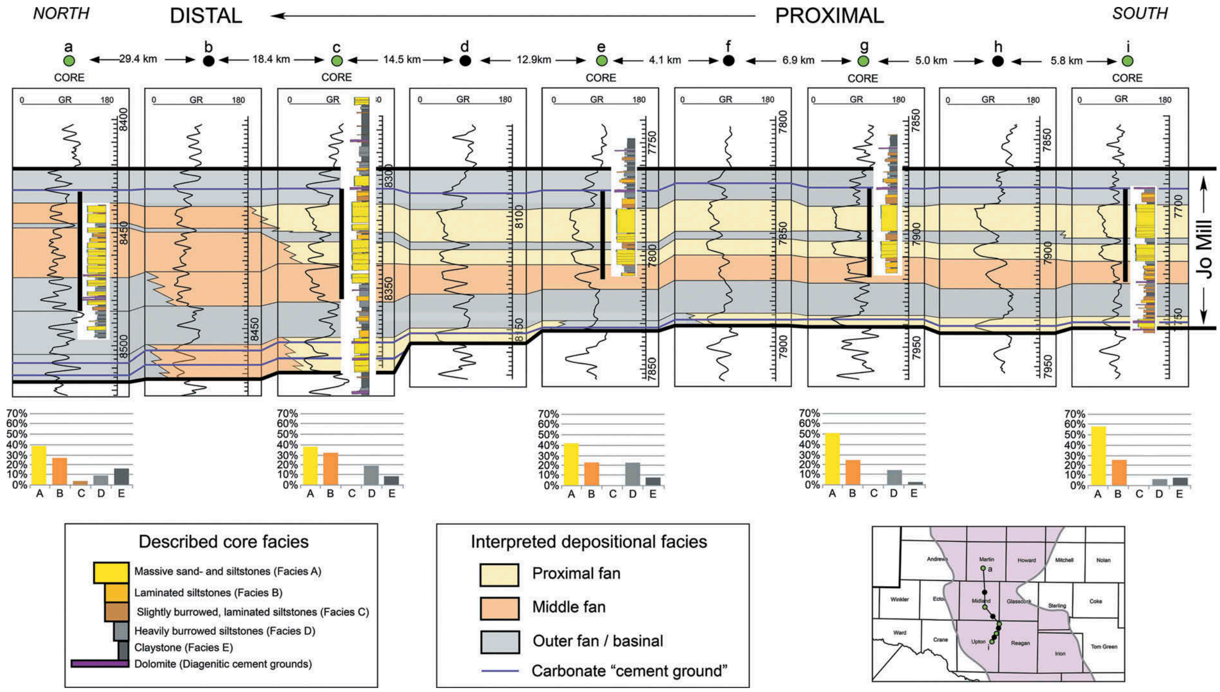

Figure 5. Regional core and log cross-section of the Jo Mill showing vertical stacking patterns and proximal (south) to distal (north) dispersal. Histograms display the relative proportion of Bouma A – E units as measured in core. Thick black vertical bars indicate core intervals displayed in histograms.

study (Figure 2(c); Table 1). Ten samples are from the Spraberry Formation, stratigraphically younger than the Dean Formation studied by Liu and Stockli (2020). Four of the Spraberry samples are from the Jo Mill unit. Zircon separation included crushing followed by separation with a Wilfley table, Frantz magnetic separator, and heavy liquids (MI). Grains were mounted in a 1″ epoxy mount alongside U-Pb and Hf primary standards. Mounts were polished to a 1 µm finish, imaged using cathodoluminescence (CL) and backscatter electron (BSE) methods, and cleaned with a 2% HNO_3 and 1% HCl solution prior to isotopic analysis. CL and BSE images were utilized to select analytical points, avoiding complex internal structures and fractures.

U-Pb and Hf isotopic analyses were conducted at the Arizona LaserChron Centre utilizing methods described by Gehrels *et al*. (2008), Gehrels and Pecha (2014), and Pullen et al. (2018). U-Pb analyses of zircon grains were conducted with an Element2 ICPMS connected to a Photon Machines G2 laser, whereas Hf isotope analyses were conducted with a Nu Instruments multicollector ICPMS connected to a second G2 laser. Calibration standards included SL-M, FC-1, and R33 for U-Th-Pb and 91,500, FC-1, Mud Tank, Plesovice, R33, and Temora for Lu-Hf. Laser beam diameters were 30 microns for U-Th-Pb and 40 microns for Lu-Hf, with Hf analysis pits located on top of U-Pb pits. For U-Th-Pb, 315 unknowns were selected for analysis from each sample. Following filtering for 10% discordance, 5% reverse discordance, and 10% uncertainty in age, between 207 and 306 analyses were retained from each sample (Table DR2). Kernel-density estimate plots were used to display detrital zircon U-Pb age spectra following Vermeesch *et al*. (2016) (Figures 3 and 4). All <800 Ma grains from each sample were selected for Lu-Hf analysis, yielding between 8 and 51 Lu-Hf analyses from each sample (Table DR3).

4.2 Zircon U-Pb ages and Hf isotopic compositions

A total of 3259 detrital zircon U-Pb ages show prominent age groups of Grenville (1250–950 Ma, 32%), Gondwana (800–500 Ma, 17%), and Appalachian (500–270 Ma, 21%) affinities (Figure 3). The Appalachian grains are mostly between 500 and 350 Ma. The Grenville group has two major subgroups of 1190–1120 Ma and 1090–980 Ma. Small age groups of zircons with Laurentian affinities, including the granite-rhyolite province (1500–1300 Ma, 8%), Yavapai-Mazatzal province (1800–1600 Ma, 7%), and Archaean craton and shield (>2500 Ma, 3%), are present (Figure 7, 8). The rest of the zircons are scattered between these age groups. A majority of the detrital zircon data do not show any obvious spatial and temporal patterns. Zircons derived from a Grenville source, however, display a marked increase in percentage through time (Table 2; Figure 9). In contrast, zircons

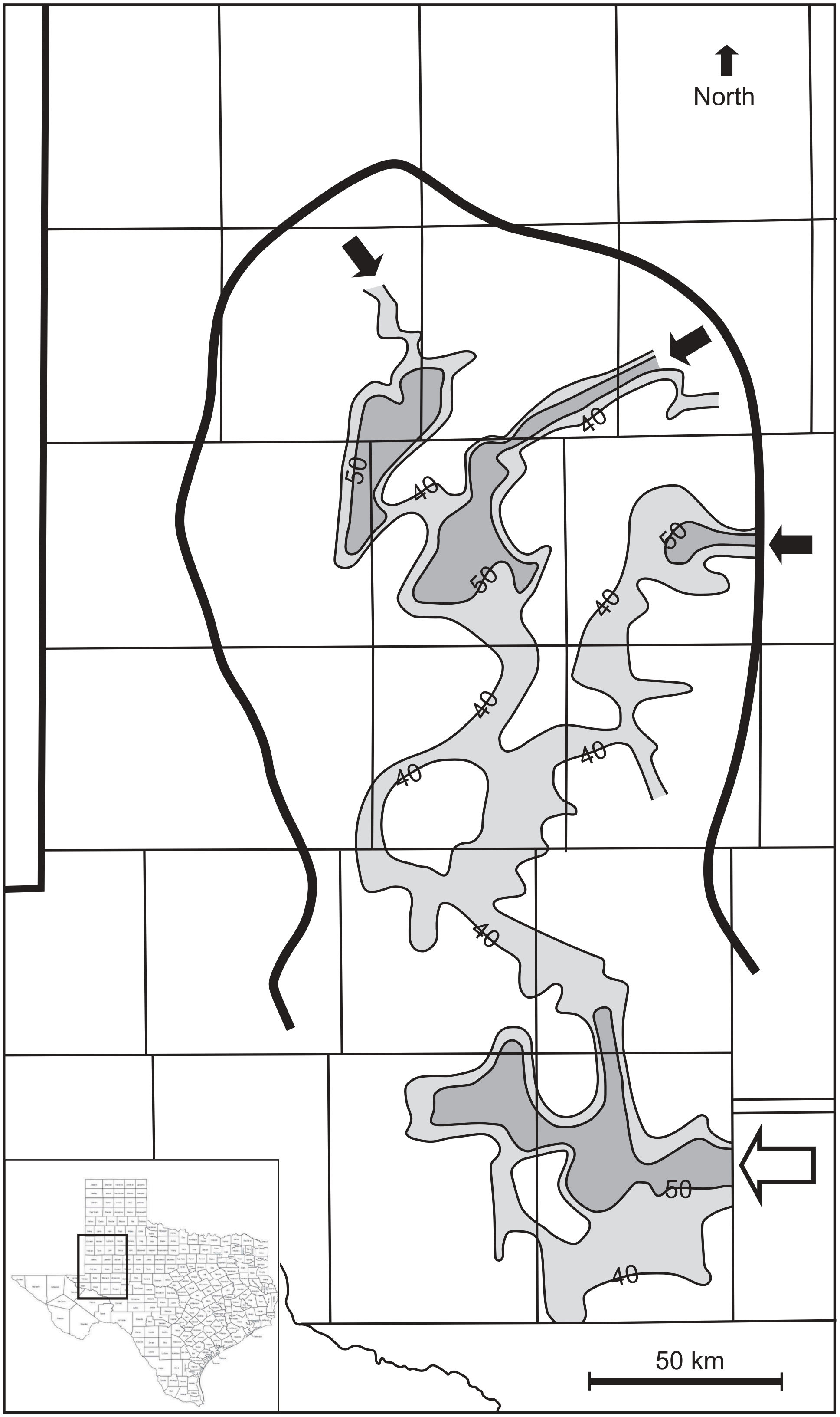

Figure 6. Previously published isopach of an upper Spraberry unit in the Midland Basin showing a possible southern input point (large arrow). Displayed thickness is in feet. Redrawn from Handford (1981).

Table 1. Sample identification, well number, sample depth, and sample location for present Midland Basin zircon and hafnium isotope study.

Sample ID	well #	Formation	Measured depth (m)	Latitute (ºN)	Longitude (ºW)
Pioneer 7	3	Upper Spraberry	2326.5	32.2317777	−101.9851949
Pioneer 3	7	Upper Spraberry	2133.9	31.5123600	−101.7951100
Pioneer 5	2	Middle Spraberry	2495.4	32.3300245	−102.0162145
Pioneer 2	1	Middle Spraberry	2595.4	32.2800773	−102.1278066
Pioneer 1	1	Lower Spraberry	2655.7	32.2800773	−102.1278066
Pioneer 4	4	Lower Spraberry	2448.8	31.8008508	−101.9540853
Spraberry 2	3	Jo Mill	2576.5	32.2317777	−101.9851949
Spraberry 3	3	Jo Mill	2581.0	32.2317777	−101.9851949
Spraberry 4	5	Jo Mill	2376.4	31.6033500	−101.7761300
Spraberry 1	8	Jo Mill	2715.2	31.5033547	−101.9841956
Pioneer 8	3	Dean	2783.1	32.2317777	−101.9851949
Pioneer 6	6	Dean	2507.9	31.5218341	−101.7366076

derived from a Pan-African source indicate a significant decrease in abundance with decreasing age.

A total of 357 detrital zircon εHf analyses range from −22 to +15 (Figure 10). The $εH_f$ values of zircons >800 Ma are generally juvenile (>-5), and the values of zircons between 800 and 270 Ma are evolved and juvenile (−22 to +15).

4.3 Ultimate sources of major zircon age groups

Zircons with affinities to the 500–270 Ma Appalachian province and perhaps western Europe were produced during igneous activity associated with the Taconic (490–-440 Ma), Acadian (390–350 Ma), and Alleghanian (330–270 Ma) orogenies (see summary in Thomas *et al.* 2017). Palaeozoic sedimentary rocks in the Appalachian foreland basin have prominent Taconic and Acadian zircon age groups, but less abundant Acadian grains (Thomas *et al.* 2017). This group of zircons has εHf values between −12 and +6 (Thomas *et al.* 2017). The East Mexico arc was active between 284 and 232 Ma (McKee *et al.* 1988; Torres *et al.* 1999) and may have provided some of the young grains in the group. The crust of 500–270 Ma is also known from the western margin of Gondwana, and the group lacks grains equivalent to the Acadian event but contains abundant grains equivalent to the Alleghanian event (Figure 8; Bahlburg *et al.* 2009). Our samples have zircons mainly between 500 and 330 Ma, suggesting that the Appalachians or once-contiguous regions to the east were the ultimate sources of this group of zircons.

Zircons of 800–500 Ma were formed mainly by the Pan-African-Brasiliano orogeny that assembled Gondwana (Unrug 1997). Peri-Gondwana terranes, including the Avalonian-Carolinian-Uchee, Suwannee, Sabine, Yucatan-Maya, Coahuila, and Oaxaquia terranes, contain Pan-African-Brasiliano igneous rocks and were accreted to Laurentia during the Palaeozoic (e.g. Rankin *et al.* 1989; Mueller *et al.* 1994; Ortega-Gutierez *et al.* 1995; Dickinson and Lawton 2001; Murphy *et al.* 2004; Thomas 2004, 2013; Poole *et al.* 2005; Gleason *et al.* 2007; Martens *et al.* 2010). The late Neoproterozoic-Early Cambrian break-up of Rodinia produced synrift volcanic and plutonic rocks of 760–530 Ma along the Iapetan rifted margin of Laurentia (e.g. Hatcher *et al.* 1989; Aleinikoff *et al.* 1995; Thomas 2014). The closest magmatic provinces related to the break-up include the ~535 Ma igneous rocks of the Southern Oklahoma Aulacogen (e.g. Thomas *et al.* 2016), which was uplifted during the ARM Orogeny (Walper 1977), and the ~550 Ma crystalline rocks in New Mexico and Colorado, which were exhumed by the ARM Orogeny during the Pennsylvanian-early Permian (Bickford *et al.* 1989; McMillan and McLemore 2004). This group of zircons has εHf values between −12 and +10. Despite that the grains from the Southern Oklahoma Aulacogen have positive εHf (Thomas *et al.* 2016), it is difficult to distinguish those from the grains derived from the crystalline rocks in New Mexico and Colorado. Because the Iapetan rift-related rocks have very limited distribution, they are most likely a minor source of the Neoproterozoic zircon grains. The inference of peri-Gondwanan terranes is supported by the observation that this zircon group is not abundant in the Permian strata in the Grand Canyon region of Arizona (Gehrels *et al.* 2011) or the northwestern Delaware Basin (Soreghan and Soreghan 2013; Xie *et al.* 2018; Figure 8(a)) even though these areas are adjacent to the ARM. The conclusion that Peri-Gondwana terranes served as the major source of this group of zircons is also supported by the observation that Palaeozoic strata in the western and northern margins of Gondwana (Bahlburg *et al.* 2009; Diez-Fernandez *et al.* 2010; Pastor-Galán *et al.* 2013) have prominent 800–500 Ma zircon groups (>40%, Figure 8; Bahlburg *et al.* 2009; Pastor-Galán *et al.* 2013; Shaw *et al.* 2014). Peri-Gondwana terranes in southern Mexico (Weber *et al.* 2006, 2009) also have prominent 800–500 Ma zircon groups (>40%; Figure 8(b)).

Grenville-age zircons (1250–950 Ma) may be sourced mainly from the Grenville basement in the eastern margin of Laurentia, which was exhumed during the

Table 2. Zircon percentage of lower Permian stratigraphic units by source provenance.

Stratigraphic unit	N	Alleghanian 270–330 Ma %	Acadian 350–390 Ma %	Taconic 440–490 Ma %	Pan African 500–800 Ma %	Grenville 900–1200 Ma %	Granite – Rhyolite 1300–1500 Ma %	Yavapai – Mazatzal 1600–1800 Ma %	Pre Yavapai – Mazatzal > 1800 Ma %	Total % of samples in study
Upper Spraberry	606	2.2	2.0	4.0	11.4	37.0	12.2	7.3	6.3	82.2
Middle Spraberry	533	2.1	6.6	4.5	13.3	32.1	11.6	4.7	4.3	79.2
Lower Spraberry	573	1.9	2.1	6.1	23.4	22.3	9.1	6.6	9.4	81.0
Jo Mill	1036	1.7	3.3	2.4	15.7	29.3	11.0	8.0	10.0	81.6
Dean	511	1.4	2.9	4.1	20.7	25.6	9.2	5.5	11.0	80.4

Alleghanian Orogeny. This group of zircons has εHf values varying between −5 and +10 in the Appalachian foreland (Thomas *et al*. 2017). Grenville basement was also distributed along the southern margin of Laurentia (Figure 1(a)) but was mostly buried during the late Palaeozoic. The Llano uplift in central Texas was exhumed during the late Palaeozoic (Erlich and Coleman 2005) and contains Grenville basement of 1360–1232 Ma and Mesoproterozoic plutons of 1288–1070 Ma (Mosher 1998). In the Appalachians, the Grenville basement preserves evidence of two major orogenies, including the 1090–980 Ma Ottawan orogeny (Heumann *et al*. 2006) and the 1190–1160 Ma Shawinigan orogeny in Canada (McLelland *et al*. 2010). These two subgroups are characteristic of U-Pb zircon ages of Appalachian foreland basin clastic rocks (Thomas *et al*. 2017). Our samples also have the two age groups, with age peaks at 1042 and 1158 Ma (Figure 8), suggesting that the Grenvillian zircons in the Midland Basin were ultimately from the Appalachians. Despite the evidence that Grenvillian zircons are present in some upper Palaeozoic clastic rocks from the northern and western margins of Gondwana, they are characterized by the broad distribution of grains of 900–1100 Ma (Figure 8(b)), which is different from the distribution of Grenvillian zircons observed in the Midland Basin.

The granite-rhyolite province (1500–1300 Ma) and the Yavapai-Mazatzal province (1800–1600 Ma) dominate the crust in southwestern and midcontinent regions of Laurentia (Figure 1(a)). The late Palaeoproterozoic-early Mesoproterozoic basement was exhumed by the Transcontinental Arch during the early Palaeozoic and by the ARM orogeny during the late Palaeozoic in Colorado, Arizona, New Mexico, Oklahoma, and Texas (e.g. Kluth 1986). Archaean craton and shield (>2500 Ma) includes mainly the Wyoming-Heame-Rae and Superior provinces, which were covered in northern Laurentia during the late Palaeozoic (McKee and Oreil 1967). Zircons likely derived from the Yavapai-Mazatzal province are a minor component of the zircons we analysed, suggesting that this region was mostly not uplifted and eroded during the early Permian, or that sediment transport from this region was directed away from the Permian Basin.

5. Discussion

5.1 Early Permian sediment dispersal pathways

The Taconic-Acadian plutons and Grenville magmatic province in the Appalachians were exhumed by the late Palaeozoic Alleghanian orogeny and shed zircons into the Appalachian foreland basin along the eastern Laurentia margin (Thomas *et al*. 2017). This transcontinental river must have connected the Appalachian foreland region with the Midland Basin. Several peri-Gondwana terranes accreted to eastern and southern Laurentia along the Appalachian-Ouachita-Marathon orogen before and during the Laurentia-Gondwana collision. Zircon grains from these terranes may have been delivered directly into the Midland Basin through a transcontinental or regional river that drained northward and westward. The match of εHf data between our samples and the source terranes (Figure 10) also supports the interpretation of mixing sediments from the Appalachians and Gondwana in the Midland Basin. This interpretation is consistent with that for the underlying earliest Leonardian Wolfcamp C shale (Liu and Stockli 2020; Figure 8). Based on the difference of detrital zircon signatures between the Wolfcamp shale and overlying early Leonardian Dean Formation, however, Liu and Stockli (2020) suggest the transcontinental river drainage changed to regional rivers from the accreted peri-Gondwana terranes during the Leonardian. Our zircon data from the Dean and Spraberry formations show similarity to those of the Wolfcamp C shale of Liu and Stockli (2020). We observe an increasing proportion of Grenville zircons and decreasing proportion of Pan-African zircons through early Permian time (Table 2), suggesting the large-scale drainage pattern of the river system remained consistent during contraction of the drainage basin. An independent assessment of river strength through time may be derived from our estimates of average depositional rate (Figure 3), indicating rates were highest during deposition of the Lower Spraberry. These estimates of sedimentation

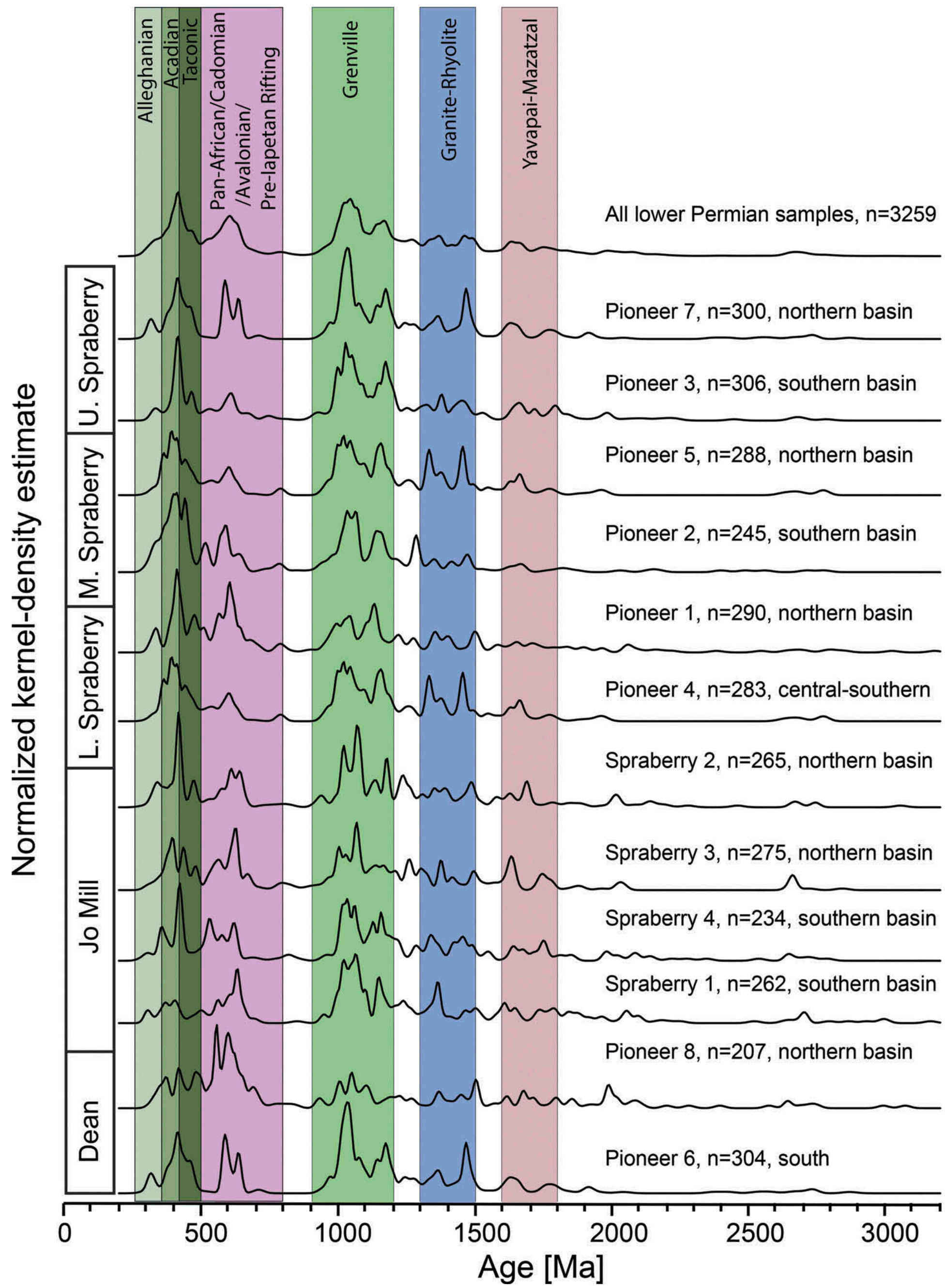

Figure 7. Normalized kernel-density estimate plots (bandwidths of 8) of detrital zircon populations for the 12 studied lower Permian samples in the subsurface of Midland Basin. n – number of grains.

rate, however, are approximate and need further refinement.

Local rivers originated from the ARM region to the north and east of the Permian Basin may also have provided the late Palaeoproterozoic-early Mesoproterozoic zircon grains directly to the basin. The ARM orogeny peaked in Pennsylvanian time and Proterozoic basement was exposed after the denudation of most of the lower-middle Palaeozoic sedimentary cover (Kluth 1986). Because our samples have a minor amount of zircon grains from the granite-rhyolite and Yavapai-Mazatzal provinces, the ARM was likely not a primary sediment source. Proterozoic zircon grains in our dataset do not increase to the north (Figure 7), indicating minimal sediment input from the ARM.

In addition to the direct input of zircons from the source terranes, recycling of Palaeozoic strata surrounding the basin may have also contributed zircon grains. Early Pennsylvanian-Permian aeolian deposits have been documented on the western margin of Pangea (e.g. Blakey 2003; Link *et al.* 2014; Lawton *et al.* 2015), and the sediments were transported by northeasterly trade wind

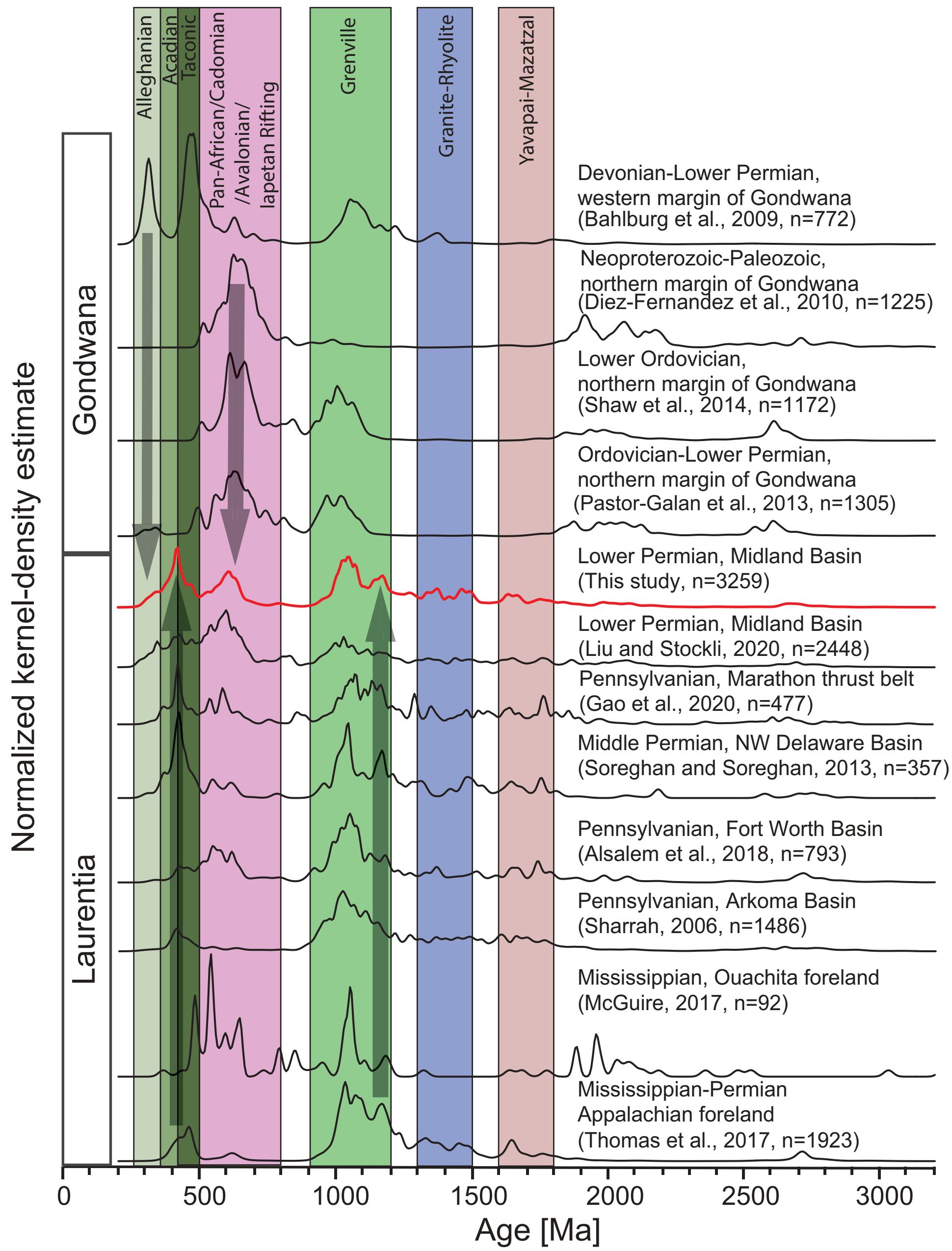

Figure 8. Normalized kernel-density estimate plots (bandwidths of 8) of (a). Detrital zircon populations for lower Permian in the Midland Basin and middle Permian in the Delaware Basin, and (b). Palaeozoic strata in western and northern margins of Gondwana, and Palaeozoic strata in other basins in southern and eastern Laurentia. n – number of grains. Gray arrows highlight the age groups of the same ultimate sources.

(Peterson 1988). Westerly seasonal monsoon may have also redistributed aeolian sediments during the period (Parrish and Peterson 1988; Parrish 1993). Aeolian input into the Midland Basin during the early Permian may also have contributed some grains into the basin, and longshore drift in the marine basin may have promoted mixing of these grains with the fluvial input (e.g. Lawton *et al.* 2015). The aeolian deposits on the western margin of Pangea have nearly equal amounts of zircons from the Grenville and Yavapai-Mazatzal provinces and subordinate number of zircons of the Appalachian province (e.g. Dickinson and Gehrels 2003; Gehrels *et al.* 2011; Link *et al.* 2014; Lawton *et al.* 2015). Our samples have a low abundance of Yavapai-Mazatzal grains suggesting that aeolian input was not a major sediment source of early Permian sediment in the Midland Basin.

5.2 Sediment dispersal by an orogen-parallel longitudinal river

The transcontinental river that delivered Appalachian detritus to the Midland Basin was most likely

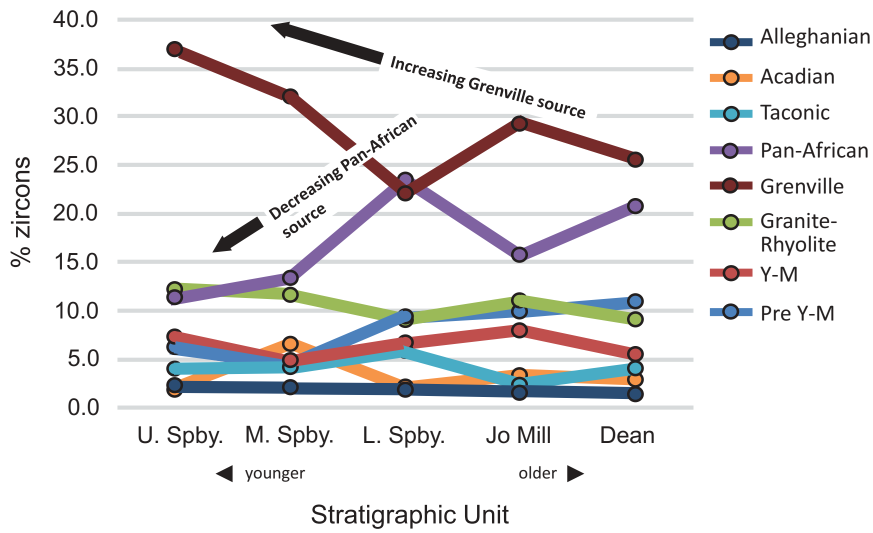

Figure 9. Percentage of zircons in each sedimentary unit by sediment provenance. Zircons sourced from Grenville terranes in the Midland Basin increase in amount throughout lower Permian time, while zircons from Pan-African terranes display an opposite trend. U. Spby = Upper Spraberry; M. Spby = Middle Spraberry; L. Spby = Lower Spraberry; Y-M = Yavapai-Mazatzal.

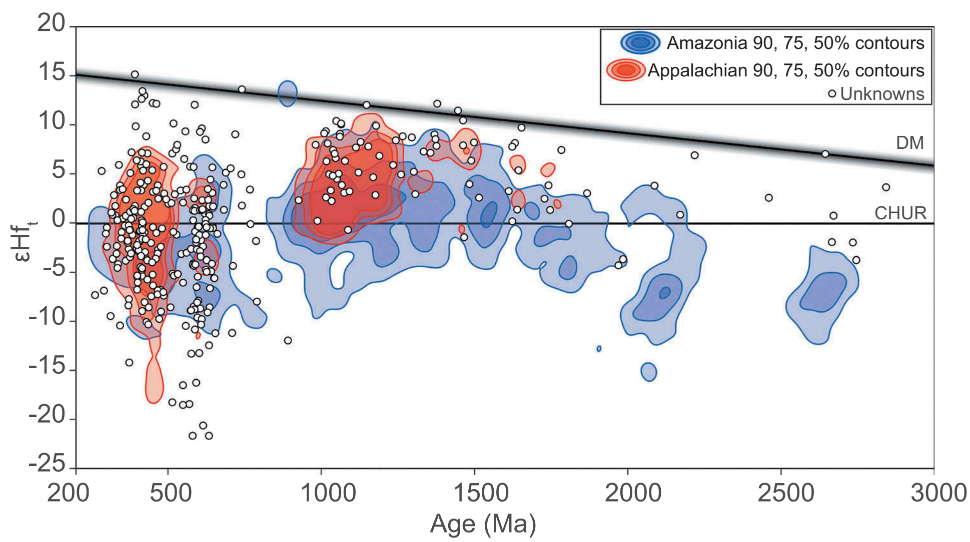

Figure 10. Detrital zircon ε(Hf) values are compared with those of potential sources. Unknown grains from the Midland Basin.

a longitudinal river system given that a major sediment entrant for Spraberry submarine fans is located in the southeast portion of the basin. The late Palaeozoic plate tectonic setting also favours such a river in the Appalachian-Ouachita-Marathon foreland. Continental collisions build orogenic highlands on the overriding plates (such as Gondwana) and deep, asymmetric foreland basins on the lower plates (such as Laurentia; Figure 1(b)). A good example of such a system is the Himalaya–Tibet highlands and the Ganges River in the Himalaya foreland basin (Graham *et al*. 1975). Rivers in such systems are characterized by multiple feeder channels sourced in the highlands that merge in the foreland as an axial river flowing along the length of the foreland basin (Figure 11). The upper reaches of the longitudinal river system are known from deposits in the central Appalachian foreland in Ohio (Thomas *et al*. 2017), but tributaries may have extended northeastward into the northern Appalachian foreland to the limits of Pennsylvanian clastic sediments and farther northeast into uplifts now occupied by New England and western Europe, which was affected by the Variscan orogeny (Matte 2003). The trunk stream was likely fed by many transverse rivers draining the Ouachita-Marathon hinterland, flowing westward, entering Panthalassa in the eastern Midland Basin (Figure 11). An increasing proportion of Grenville zircons and a decreasing proportion of Pan-African zircons through time (Figure 10) suggest the

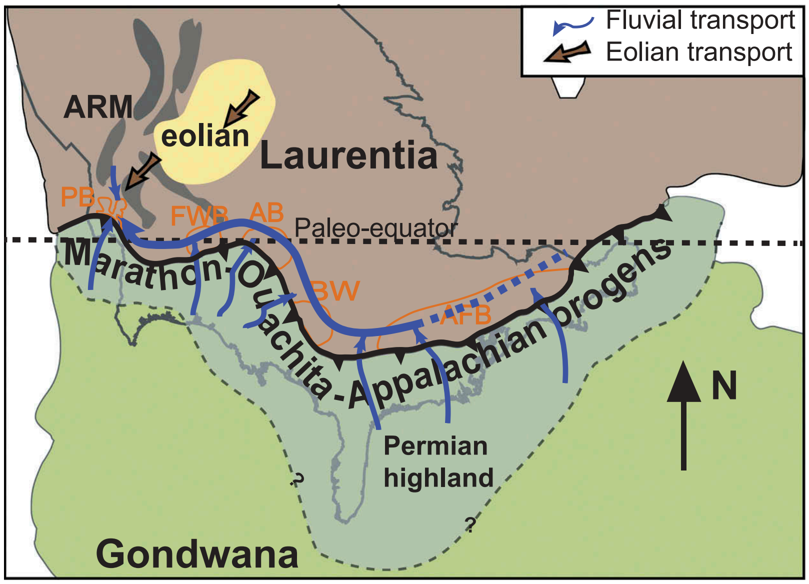

Figure 11. Map showing interpreted sediment dispersal pathways. See text for further explanation.

drainage basin of the river system contracted through early Permian time. This is consistent with a major reduction of detrital sediments in the Midland Basin during the middle Permian (Guadalupian). An independent assessment of river strength through time can be derived from our estimates of average depositional rate (Figure 3), indicating depositional rates were highest during deposition of the Lower Spraberry. These estimates of sedimentation rate, as mentioned, are approximate and need further refinement.

Physical evidence of this transcontinental river, however, is missing from the sedimentological record. The path of the river may have been disrupted by the Muenster Uplift, an intersecting uplift to the ARM in north Texas. Documentation of specific entry points into the Midland Basin awaits further assessment via detailed subsurface mapping.

How did the fluvial sediments feed into the early Permian submarine fans? We postulate that the tremendous amount of sediments transported by a transcontinental river system flowing westward down the foreland basin on the north side of the Laurentia-Gondwana collision zone may have generated fast-moving channelized flows that travelled for several hundred kilometres in the deep basin (Talling *et al*. 2013). As an example, the modern Congo River in Africa is linked with the Zaire submarine channel. In January 2004, a fast-flowing gravity flow with a frontal speed of 3.5 m/s was generated on a gradient of 0.23° and travelled 240 km in water depths of 3420–4070 m; the flow then moved at a reduced frontal speed of 0.7 m/s for a further 380 km to the termination at a much shallower gradient (Vangriesheim *et al*. 2009). Similar processes are envisioned for sediment transport associated with a large river flowing into the southeast Midland Basin in early Permian time. Examples of large rivers that feed submarine fans include the Mississippi River and fan (Fildani *et al*. 2016); the Ganges-Brahmaputra river system and Bengal Fan (Blum *et al*. 2018); and the Amazon River and Amazon fan (Mason *et al*. 2019). These studies suggest that the detrital zircon U-Pb provenance data in deep submarine fans record the same provenance information as the fluvial sediments in the lower reaches of the rivers. Such an observation is also made in the early Permian river-Permian Basin submarine fan system. Our Permian detrital zircon age distribution of the submarine fan deposits in the Midland Basin is most similar to that of the Pennsylvanian deltaic deposits in the Fort Worth Basin (Alsalem *et al*., 2018, Figure 8). The Midland Basin contains about the same amount of peri-Gondwana grains (17%) as the Fort Worth Basin (15%), suggesting the connection of depositional environments of the two basins during the late Palaeozoic.

Previous studies have suggested another transcontinental river connecting the Appalachians with western Pangea through the midcontinent during the early Permian (Dickinson and Gehrels 2003; Gehrels *et al*. 2011; Xie *et al*. 2018). The fluvial sediments of this transcontinental river were deflated by wind under arid climate and contributed to aeolian deposits in central Pangea based on the similarity of detrital zircon U-Pb signatures of fluvial and aeolian sedimentary rocks (Gehrels *et al*. 2011). The detrital zircon signature of this transcontinental river is different from the longitudinal river we propose here. The central Laurentia transcontinental river has abundant (~39%) grains from the Yavapai-Mazatzal province because it drained along northern portions of the ARM (Gehrels *et al*. 2011). This transcontinental river also lacks grains from the peri-Gondwana terranes because it is far from the terranes incorporated in the Ouachita-Marathon orogen. Middle Permian detritus in the Delaware Basin, interpreted to have been primarily delivered by the central Laurentia transcontinental river (Xie *et al*. 2018), contain ~10% of peri-Gondwana grains, less than the 17% of peri-Gondwana grains in our Midland Basin samples (Figure 7), suggesting that a different drainage system may have been involved.

The presence of zircons from the Appalachian and peri-Gondwana provinces in the Mississippian strata in the Ouachita foreland (McGuire 2017; Figure 8) suggests that the large-scale river system may have existed as early as the Mississippian time. Because collision of Laurentia and Gondwana began in the east and progressed westward (Dickinson and Lawton 2003), the longitudinal river system would have formed first along the northeastern margins of Laurentia, extending southwest into the westward-retreating remnant ocean (Graham *et al*. 1975; Gleason *et al*. 2007; Thomas *et al*. 2017; Gao *et al*. 2020). The river system formed deep, N-S striking palaeovalleys in the central Appalachian foreland basin during early Pennsylvanian time (Archer and Greb 1995), but left little direct evidence elsewhere. The precise drainage linkage between the two basins may have been disrupted by the Muenster Uplift, an intersecting uplift to the ARM in north Texas. Sea-level changes during Pennsylvanian-early Permian time (Figure 3) suggest the river system may have emerged during marine regressions and waned during transgressions.

5.3 Variation of detrital zircon signature of the longitudinal river

Comparison of detrital zircon data in the Midland Basin with data for late Palaeozoic clastic rocks in the Appalachian and Ouachita-Marathon forelands and Arkoma and Fort Worth basins shows varying sediment sources along the orogen (Figure 8). Sediments in the Appalachian foreland only have a small 800–500 Ma age group, but very abundant Appalachian and Grenvillian grains, indicating that Appalachian terranes were a predominant sediment source (Thomas *et al*. 2017). Mississippian clastic rocks in the Ouachita foreland show a major age group of 800–500 Ma (35%) and a major peak at ~550 Ma (McGuire 2017). The ~550 Ma peak is also present in the lower Palaeozoic strata in the Yucatan-Maya terrane (Weber *et al*. 2006, 2009; Figure 8), reflecting input from local peri-Gondwana terranes, including the Sabine and Yucatan/Maya terranes. This difference suggests more input of local detritus than distal detritus downstream the large river-submarine fan system, similar to what is observed in Quaternary Amazon River and fan system (Mason *et al*. 2019). However, the Pennsylvanian rocks in the Arkoma Basin contain minor 800–500 Ma grains (3%), suggesting a lack of detritus from peri-Gondwana terranes (Sharrah 2006). Its difference to the Mississippian sediment provenance in the same region (McGuire 2017) may suggest dilution of the longitudinal river signature by the entrant of a distributary river draining through the Laurentia interior.

The detrital zircon signature of the lower Permian strata in the Midland Basin is different from that of the middle Permian strata in the northwestern (Soreghan and Soreghan 2013) and central and southern Delaware Basin (Xie *et al*. 2018). The middle Permian strata in the Delaware Basin have fewer peri-Gondwana grains (800–-500 Ma) than the early Permian strata in the Midland Basin (Figure 8). While Soreghan and Soreghan (2013) suggest that the middle Permian sediments were likely dispersed by the combination of a fluvial system draining the piedmont region of the Ouachita orogen and aeolian deflation of the fluvial sediments, Xie *et al*. (2018) suggested that a transcontinental river originated in the central Appalachians and passed through the Illinois Basin and regional rivers draining the Ouachita-Marathon orogen. Our interpreted longitudinal river does not preclude the coexistence of a central Laurentia transcontinental river, and it is likely Permian detritus in the Permian Basin were delivered by more than one fluvial system, particularly given that the early Permian sediments in the Midland Basin have additional entrants in the north and northeast sides of the basin (Handford 1981; Guevara 1988; Hamlin and Baumgardner 2012).

6. Conclusions

The lower Permian Dean and Spraberry clastic rocks in the Midland Basin contain deep-water submarine-fan deposits. Our new sedimentologic observations suggest that the submarine fan deposits have an entry point to the south of the basin and propagated northward into the southern portion of the basin. These rocks have detrital zircon groups of the Taconic and Acadian magmatic events and Grenville basement in the Appalachians, and grains from the peri-Gondwana terranes incorporated in the Appalachian-Ouachita-Marathon orogenic belt during the late Palaeozoic Laurentia-Gondwana collision. The εHf data of these detrital zircons also overlap with the data of Appalachian and Gondwana sources. We suggest that the early Permian detritus was transported to the southeastern margin of the Midland Basin by a longitudinal river in the Appalachian-Ouachita foreland. This longitudinal river had headwaters in the Appalachians and was fed by multiple transverse rivers draining the Appalachian-Ouachita-Marathon highland. Slope failure triggered by sedimentation at the mouth of this river system may have formed fast-flowing gravity flows and reworked fluvial-deltaic sediments into submarine fans in the deep water. The detrital zircon signature of early Permian deposits in the Midland Basin differs from that of the middle Permian deposits in the Delaware Basin, and the latter was interpreted to be transported by a transcontinental river system across central Laurentia and/or by regional river recycling sediments from the Ouachita highland. Therefore, sand and silt detritus in the Permian Basin region was likely delivered by more than one river system. Local sediment input from the Ancestral Rocky Mountains and wind deflation of fluvial sediments had limited contribution to the detritus. The nutrients needed to produce the rich oil deposits of the Permian Basin are likely to have been supplied in part by the distal component of these early Permian river systems.

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