

# Detrital zircon U-Pb data reveal a Mississippian sediment dispersal network originating in the Appalachian orogen, traversing North America along its southern shelf, and reaching as far as the southwest United States

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## ABSTRACT

Recent detrital zircon U-Pb geochronology reveals an increasing proportion of Grenville-age (ca. 0.95–1.3 Ga) and ca. 300–480 Ma grains in late Paleozoic strata of the SW United States. These grain populations are interpreted to have been sourced from the Appalachian orogen, though the precise timing, transport mechanisms, and pathway(s) of sediment dispersal remain unclear. We combine 35,796 published detrital zircon U-Pb ages from Ordovician to Pennsylvanian strata of southern Canada, northern Mexico, and the U.S. with new data (1,628 ages) from Kansas, Missouri, Montana, and South Dakota. These data are integrated with sedimentary structural data and paleogeographic reconstructions to reveal temporal and spatial patterns of the sediment routing system at continent scale. In Ordovician time, North America was partitioned into western, central, and eastern domains in which strata were derived primarily from the Peace River Arch, the Superior Craton, and the Appalachians, respectively. Silurian–Devonian time saw limited integration of these domains, corresponding with the delivery of Appalachian-derived detritus to the Midcontinent via prograding deltas and westward-flowing rivers. Appalachian detritus flowed westward in Mississippian time, accumulating in the Appalachian foreland and continuing westward through Mississippi, Arkansas, Missouri, Oklahoma, Kansas, Colorado, Arizona, and California along the continental shelf. Given that North America was at equatorial latitudes and was inundated by the Kaskaskia sea at this time, westward dispersal likely occurred by trade wind-driven longshore drift, waves, tides, and marine currents, with the possible added contribution of hurricanes. Modern analogs for the southern margin of North America during Mississippian time (e.g., the Great Barrier Reef and the east coast of South America) indicate that long-distance (>1000 km) shelf-parallel sediment transport is readily accomplished through fair-weather processes and extreme events. Finally, Appalachian-derived detritus became widespread throughout North America following regression of the Kaskaskia sea in Pennsylvanian time, likely via fluvial, deltaic, and aeolian processes.

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## INTRODUCTION

The presence of Grenville-age (i.e., 0.95–1.3 Ga) and ca. 300–480 Ma detrital zircon grains in Upper Mississippian and younger strata of the Grand Canyon (Arizona) and Inyo Mountains (California), and the absence of these populations in older strata, mark the arrival of Appalachian orogen-derived detritus in the western United States (Gehrels et al., 2011; Gehrels and Pecha, 2014; Attia et al., 2018). Indeed, detrital zircon ages from Appalachian foreland basin and Grand Canyon strata of equivalent age show considerable overlap, leading Gehrels et al. (2011) to infer that Appalachian-derived material was transported westward via large rivers, coastal currents, and trade winds. While it is not difficult to envision delivery of Appalachian detritus hundreds of km to the west via clastic wedges and documented paleoriver systems (Blake and Beuthin, 2008), numerous intervening basins (e.g., Illinois and Michigan), paleotopographic highs (e.g.,

Cincinnati and Transcontinental arches), and inland seas (e.g., the Appalachian sea) would have presented significant obstacles to westward sediment transport. Hence, tracing the specific Appalachian-to-Grand-Canyon sediment dispersal path is a necessary step in evaluating the transcontinental transport hypothesis and ruling out alternate sources (Thomas, 2011).

This research tests possible transcontinental sediment pathways using existing detrital zircon U-Pb data from Ordovician to Pennsylvanian clastic strata exposed across North America (170 samples) and filling gaps in coverage with new data (see GSA Data Repository Item<sup>1</sup>) from the Black Hills (South Dakota); the Ozark Dome and Illinois Basin (Missouri); the Madison, Bridger, and Big Snowy ranges (Montana); and drill core from Kansas. Below we discuss spatial patterns in detrital zircon U-Pb ages,

<sup>1</sup>GSA Data Repository Item 2019260, Sample descriptions, analytical techniques, data reduction methods, NMF details and results, ICP-MS zircon U-Pb datasets, and enlarged versions of Figure 3 panels, is available at <http://www.geosociety.org/database/2019>, or on request from [editing@geosociety.org](mailto:editing@geosociety.org).

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recognized and interpreted via non-negative matrix factorization (NMF) and multidimensional scaling (MDS) techniques, from Ordovician to Pennsylvanian time to constrain the location and timing of continent-scale sediment dispersal.

**METHODS**

Detrital zircon U-Pb data from published papers plus unpublished M.S. theses and Ph.D. dissertations are compiled in Table DR1. For grains younger and older than 900 Ma, <sup>206</sup>Pb/<sup>238</sup>U and <sup>207</sup>Pb/<sup>206</sup>Pb ages were tabulated, respectively. Analyses with greater than 10% uncertainty, 20% discordance, and/or 5% reverse discordance were excluded, when this information was made available by authors. Each published sample is assigned a sample identifier in Table DR1 and plotted using this identifier on Plates 1–4 in the Data Repository.

New sampling efforts focused on the Midcontinent region, where existing data was sparse or lacking. Detailed sample location information, including field sample identifiers, abbreviated sample identifiers for plotted locations on Plates 1–4, sample coordinates (WGS 84 datum), unit names, sample descriptions, detrital zircon age distributions, and inferred sources are provided below. New detrital zircon U-Pb data is presented in Table DR2.

Detrital zircon U-Pb geochronology was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center (ALC) following the methods outlined in Gehrels et al. (2006). Zircon grains were extracted from samples using standard mineral separation techniques of crushing, sieving, magnetic separation, processing through heavy liquids, and hand picking at the Missouri University of Science and Technology and Macalester College. Separates were then mounted in epoxy, polished, and imaged on a JEOL 6610LV Scanning Electron Microscope at Macalester College, or a Hitachi 3400N SEM at University of Arizona prior to analysis. Zircon grains were ablated using a 193 nm ArF laser with a pit depth of ~12 μm and spot diameters of 25–30 μm in Faraday collection mode and with a spot diameter of

10 μm for sample 18BH2A in ion counting mode. Unless otherwise noted (see Data Repository), most analyzed grains were subhedral to subrounded, ~50–350 μm in length, inclusion-poor, and exhibit simple oscillatory zoning patterns in cathodoluminescence images that we interpret as magmatic features. Data reduction was done using in-house ALC Microsoft Excel programs and IsoplotR (Vermeesch, 2018). New data reported in Table DR2 are filtered in the same manner as described above for compiled data.

Multidimensional scaling (MDS) is useful for visual exploration of large arrays of detrital zircon ages on a “map” (e.g., Vermeesch, 2013). We use detritalPy (Sharman et al., 2018) to generate MDS maps comparing detrital zircon age distributions across Laurentia from Ordovician to Pennsylvanian time (see Data Repository). The degree of similarity in detrital zircon U-Pb age spectra on an MDS map is higher for samples that plot close to each other than for samples that are positioned farther apart.

Non-negative matrix factorization (NMF), a tool widely used in signal and image processing and recently applied to detrital zircon geochronology (Sharman and Johnstone, 2017), was employed here to unmix ages of new and existing samples (“sink” samples) in an attempt to characterize “source” samples without a priori assumptions. We use the algorithm of Saylor et al. (2019); additional details on NMF and the approach used here are in the Data Repository.

**DETRITAL ZIRCON DATA AND SOURCE CHARACTERIZATION**

Figure 1 displays the distribution and ages of geologic provinces in North America. Non-negative matrix factorization was applied to the 186-sample, 37,424-age data set in order to reconstruct the potential sources for these samples. A two-source solution (see Data Repository), shown as kernel density estimates in Figure 2, yields the most realistic representation of known sources in North America (Fig. 1). The first source contains, in order of decreasing abundance, 1.8–2.0, 1.6–1.8, 2.5–2.8, ca. 2.1, 1.3–1.5, and 0.53–0.53 Ga detrital zircon grains. Referencing these ages with the paleogeographic framework of Figure 1 points to a distinctly

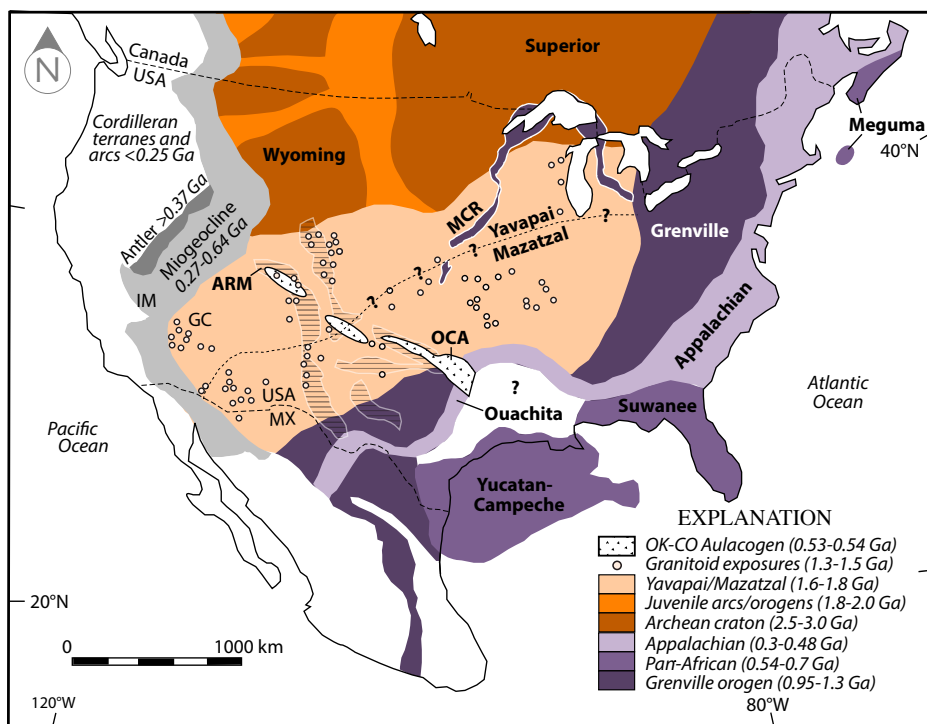
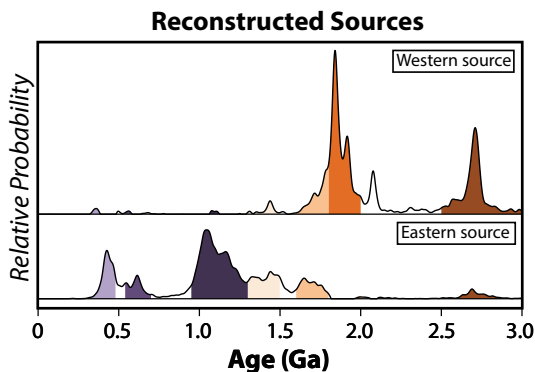


Figure 1. Basement map of major North American geologic provinces. Map modified after Gehrels and Pecha (2014). ARM—Ancestral Rockies Mountains, CO—Colorado, GC—Grand Canyon, IM—Inyo Mountains, MCR—Midcontinent Rift, MX—Mexico, OCA—Oklahoma-Colorado Aulacogen, OK—Oklahoma.



**Figure 2. Non-normalized kernel density estimates with 10 Myr bandwidth comparing NMF “sources.” Colors beneath each curve correspond to those of Figure 1 basement domains.**

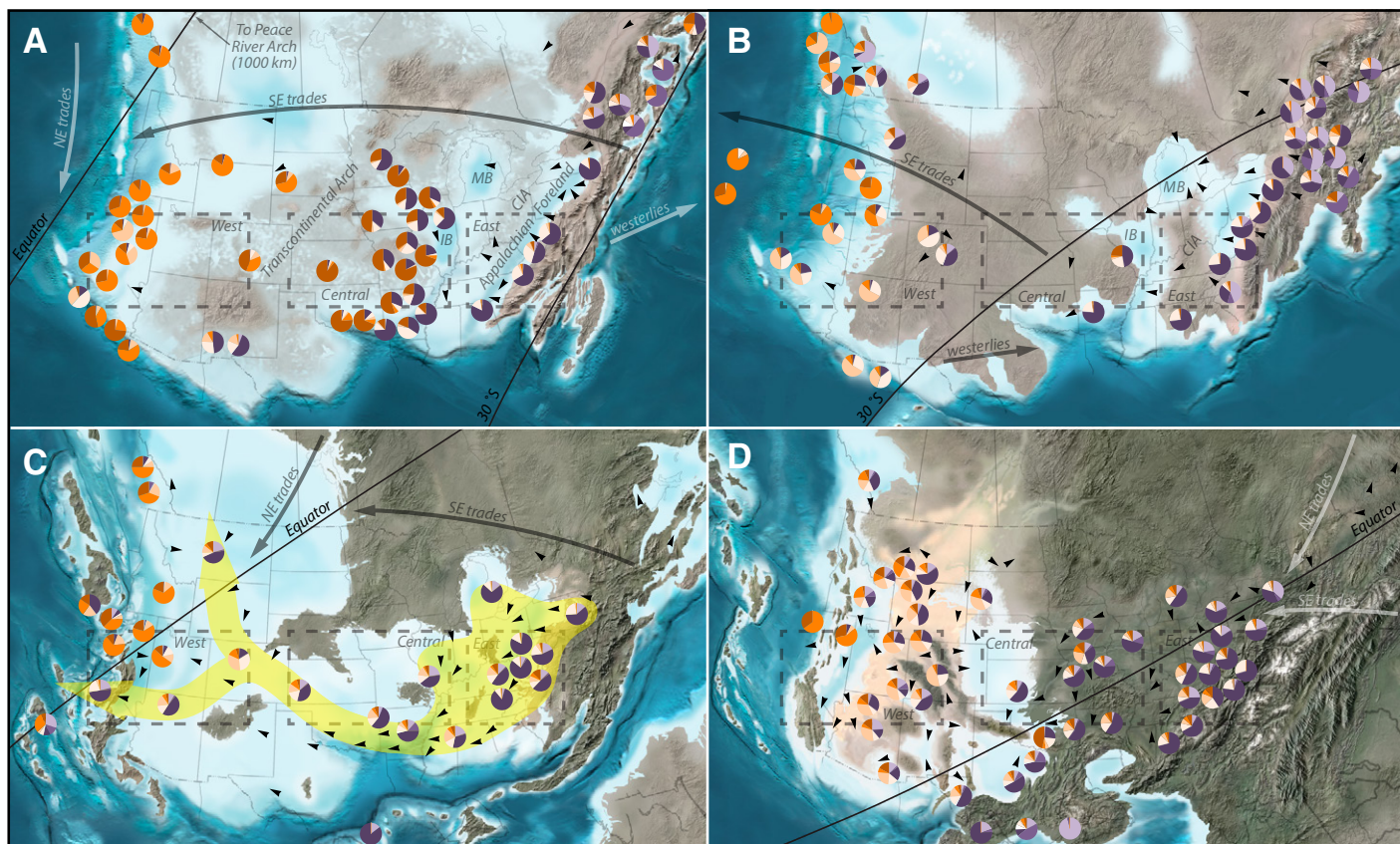
“western” Laurentian source containing, with respect to ages reported in the previous sentence, Juvenile arcs and orogens of NW Canada; Yavapai/Mazatzal orogens; Neoproterozoic cratonic material; recycled Belt supergroup and/or the Eburnian orogen of Gondwana; granitoid belts (including Granite/Rhyolite and anorogenic belts); and the Oklahoma–Colorado Aulacogen

(Thiéblemont et al., 2004; Whitmeyer and Karlstrom, 2007; Hanson et al., 2013). In contrast, the second source is of “eastern” Laurentian character containing detrital zircon ages of, in diminishing quantities, 0.95–1.30, 0.3–0.48, 1.3–1.5, 1.6–1.7, 0.54–0.7, and 2.5–2.8 Ga. These age ranges point to probable sources in the Grenville orogen (with possible additional input of ca. 1.1 Ga detrital zircon grains originating from the Midcontinent Rift; Vervoort et al., 2007); the Appalachian orogen; granitoid belts; Yavapai/Mazatzal orogens; Pan-African crust; and Neoproterozoic craton (Whitmeyer and Karlstrom, 2007; Park et al., 2010; Hanson et al., 2013).

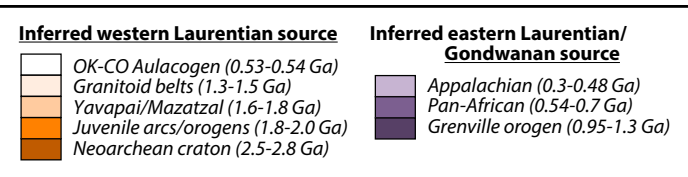
With the exception of ca. 2.1 Ga grains of unknown origin, we use the above age ranges as pie slices for diagrams plotted on paleogeographic base maps relevant to the depositional ages of analyzed strata (Fig. 3). Ages outside of the above listed ranges are not depicted on pie diagrams due to their rarity (averaging  $10.2 \pm 7.9\%$  [ $1\sigma$ ] per sample).

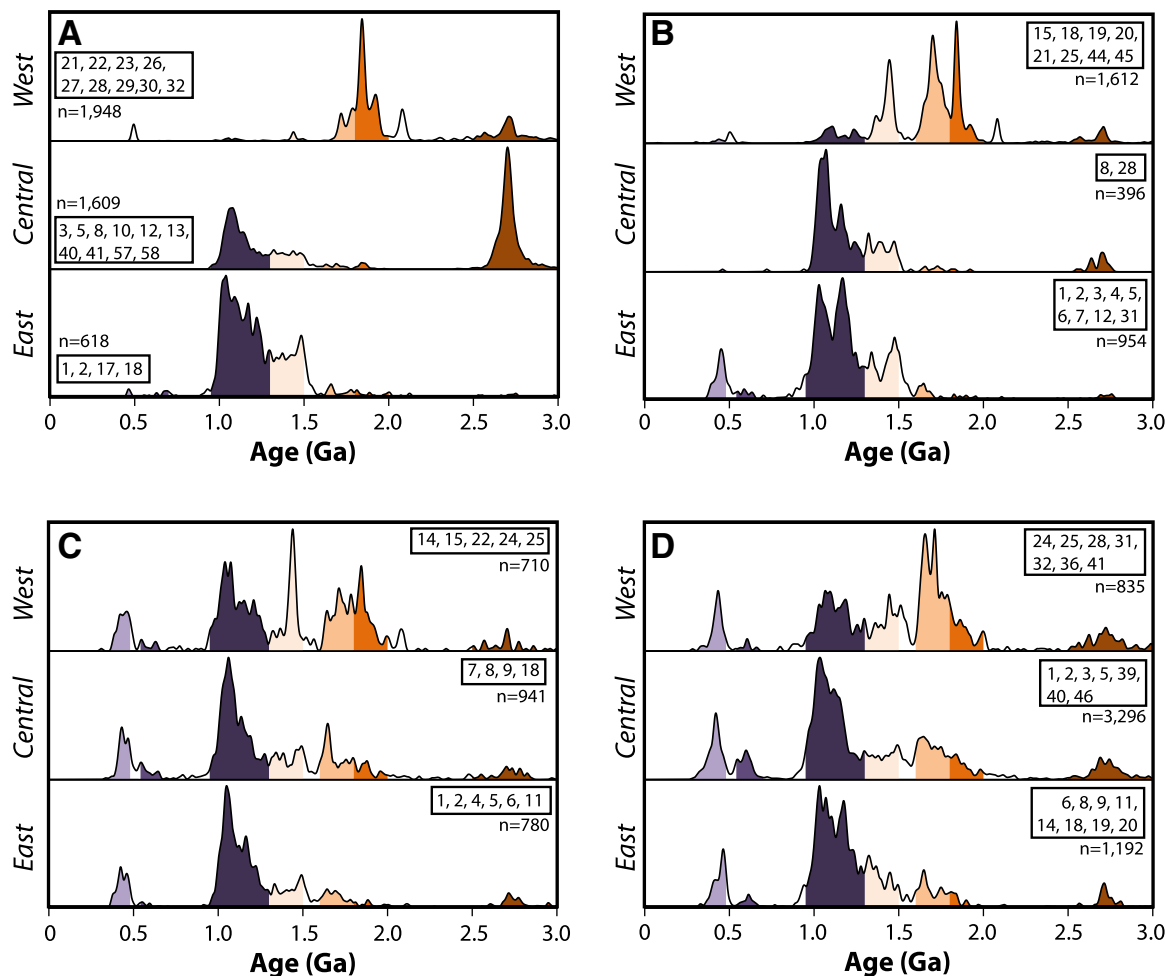
**Ordovician**

In Ordovician time, sediment dispersal patterns were influenced by the onset of Appalachian mountain building, the Tappanocoe marine transgressive-regressive cycle, and existing paleogeographic highs (e.g., the Transcontinental and Peace River arches) and lows (e.g., Illinois and Michigan basins and the Appalachian foreland; Sloss, 1963; Carlson, 1999; Figs. 3A and 4A). These paleogeographic features appear to have



**Figure 3. New and compiled detrital zircon age distributions plotted as pie diagrams on (A) Late Ordovician, (B) Middle Devonian, (C) Early Mississippian, and (D) Late Pennsylvanian paleogeographic maps (from North American Key Time Slices ©2013 Colorado Plateau Geosystems Inc.). Paleocurrent trends (black arrows) from Brand et al. (2015). Inferred Mississippian sediment dispersal pathway shown in yellow on panel C. CIA—Cincinnati Arch, IB—Illinois basin, MB—Michigan Basin.**





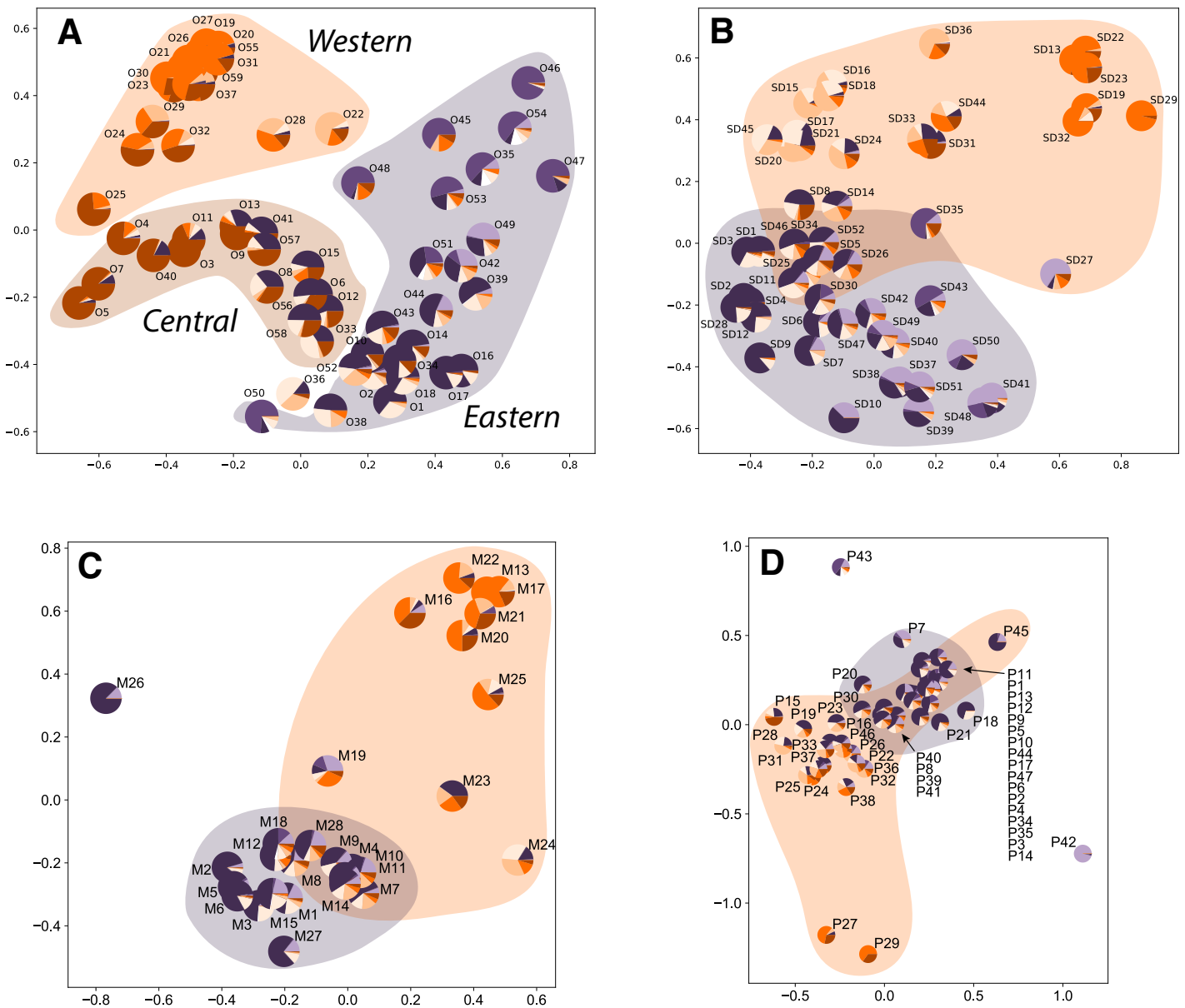
**Figure 4.** Non-normalized kernel density estimates with 10 Myr bandwidth comparing detrital zircon ages from samples collected from western, central, and eastern domains of North America (shown in Fig. 3) for (A) Ordovician, (B) Silurian and Devonian, (C) Mississippian, and (D) Pennsylvanian strata. Sample names from Table DR1. For example, sample 21 in panel A refers to Ordovician sample 21. Colors beneath each curve correspond to those of Figure 1 basement domains.

compartmentalized North America into three clear domains in terms of detrital zircon age spectra, as shown by the spatial variations in detrital zircon relative abundance (Figs. 3 and 4) and by clusters on the MDS map (Fig. 5). An eastern group of samples, collected from the Appalachians, contains abundant Grenville-aged detrital zircon grains, with diminishing proportions of Granite/Rhyolite, Yavapai/Mazatzal, and cratonic material; rare Paleozoic grains; and local additions of Neoproterozoic and Paleoproterozoic grains, presumably derived from Pan-African crust (e.g., Kuiper et al., 2017). A central group, located west of the Illinois and Michigan basins and east of the Transcontinental arch, is dominated by Archean and Grenville-aged grains, with minor (<10%) contributions of Granite/Rhyolite-aged material. Grains possibly derived from the Midcontinent Rift (i.e., grains overlapping 1085–1115 Ma at the  $1\sigma$  level, the timing of rift magmatism; Vervoort et al., 2007) comprise ~29% of Grenville-aged grains in the central group. Hence, the majority of Grenville-aged grains within the Midcontinent were likely ultimately derived from the Grenville orogen. It should be noted, however, that a significant proportion of Grenville-aged detrital zircon grains in Ordovician strata of the Midcontinent were likely recycled from eroded Proterozoic basins (Konstantinou et al., 2014). A western group, west of the Transcontinental Arch,

contains abundant (generally >50%) ca. 1.8–2.0 Ga grains, with smaller amounts of Archean and Yavapai/Mazatzal material. The clear separation of eastern, central, and western groups (Figs. 3, 4, and 5) indicates that these domains were not yet connected by Ordovician time.

### Silurian–Devonian

Silurian and Devonian deposits of the Appalachians and adjacent basins yield detrital zircon spectra with higher proportions of Paleozoic and Neoproterozoic grains, especially in the northern Appalachians, but are otherwise similar to those of Ordovician strata (e.g., Park et al., 2010; Figs. 3B and 4B). These observations likely record ongoing orogenic activity in eastern Laurentia, involving recycling of older sedimentary rocks and first-cycle dispersal of detritus from exhumed Grenville and Pan-African crust plus Taconic-aged (ca. 420–480 Ma; Thomas et al., 2017) magmatic rocks. The proportion of Grenville- and Taconic-aged zircon observed in the Midcontinent region (Siddoway and Gehrels, 2014; McGuire, 2017), and to a lesser extent in the North American Cordillera, increased from Ordovician time (Figs. 3B and 4B). These observations suggest that detritus from the growing Appalachian Mountains encroached



**Figure 5. Multidimensional scaling (MDS) maps showing dimensionless Kolmogorov-Smirnov (K-S) distances between arrays of detrital zircon age data from (A) Ordovician, (B) Silurian and Devonian, (C) Mississippian, and (D) Pennsylvanian strata. Sample names from Table DR1. For example, sample SD15 refers to Silurian and Devonian sample 15. Colored fields correspond to samples collected from eastern, central (A only), and western domains of North America.**

westward in Devonian time, largely via fluvio-deltaic systems (Ettensohn, 1985; Park et al., 2010), but the Transcontinental Arch continued to serve as a topographic barrier. It should be noted that recycling of Precambrian strata of the Grenville clastic wedge may have contributed Grenville-aged grains to Devonian passive margin strata (e.g., Rainbird et al., 1992). Paleozoic grains in Devonian strata of the North American Cordillera were most likely derived from the Arctic and/or SE Alaska (Cecil et al., 2011; Anfinson et al., 2012; Gehrels and Pecha, 2014).

### Mississippian

Mississippian strata record significant provenance changes across North America. The most striking difference between Devonian and

Mississippian zircon age distributions lies in the abundance of Grenville-age and Paleozoic grains from the Appalachian foreland, across the Mid-continent, and as far west as Arizona and California (Figs. 3C and 4C; note overlap in eastern and western populations in Fig. 5C). The fact that an integrated swath of Mississippian samples shows similar detrital zircon age spectra from the eastern seaboard to the SW U.S. strongly suggest a common provenance in the Appalachian orogen. In contrast, western Laurentian contributions were likely minor, as little overlap in detrital zircon age spectra between the SW U.S. and Franklinian and Antler orogens is observed (Gehrels et al., 2011; Beranek et al., 2016).

Given that the timing of sediment dispersal corresponded with the peak of the Kaskaskia marine transgression (e.g., Sloss, 1963), during which most of the continent was covered by the Kaskaskia sea, it is unlikely

that large river systems (e.g., Gehrels et al., 2011) played a significant role in transporting Appalachian detritus across the continent in Mississippian time. Instead, Mississippian paleocurrent and detrital zircon age patterns strongly suggest that sediment dispersal from the Appalachian Mountains to the western Laurentian margin included: 1) transport of eroded Appalachian hinterland materials westward into the foreland basin plus Illinois and Michigan basins via fluvio-deltaic processes; 2) flow ~1000 km to the SW along the axis of the submarine foreland basin; and 3) ~3000 km of coast-parallel marine transport from Mississippi and Arkansas to Oklahoma, trade wind-facilitated transport through a sag in the Transcontinental Arch in Kansas and Colorado (e.g., Carlson, 1999) and/or through the Texas panhandle and New Mexico, and westward into Arizona and California (Fig. 3C). High relative abundance of Appalachian and Grenville grains in central Montana might evidence branching of the swath conduit after traversing the Transcontinental Arch, or alternatively continued derivation from the Arctic and/or SE Alaska. Sedimentary petrology is consistent with the predominantly shallow marine sediment dispersal network outlined above, as samples from segments 2 and 3 are generally carbonates with significant clastic components (e.g., the Aux Vases and Ste. Genevieve units of Missouri and Kansas).

Shelf-parallel westward delivery of Appalachian-derived sediment was likely accomplished, in part, by longshore drift, local waves, tides, and marine currents driven by southeasterly trade winds (e.g., Orpin et al., 1999). The ability of these fair-weather processes to transport sediments great distances is well-documented along modern continental shelves, such as the redistribution of Amazon River sediment >1500 km along the east coast of South America (e.g., Nittrouer et al., 1986).

Given that North America was at tropical latitudes adjacent to the ocean in Mississippian time, hurricanes may also have played a key role in westward dispersal of Appalachian detritus. Studies of sediment transport along the Great Barrier Reef shelf system, an excellent modern analog for the Mississippian southern margin of North America, have shown that hurricanes are efficient at eroding seabeds and transporting sediment parallel to the shelf, particularly during sea-level highstands (Larcombe and Carter, 2004). Furthermore, the presence of island arcs along with the impinging African continent may have constricted cyclonic activity along the sediment dispersal pathway, thereby accelerating sediment flow during extreme weather events.

Detrital zircon age distributions in Mississippian strata of the NW U.S. and western Canada contrast sharply with those of the Appalachian-to-SW-U.S. swath, exhibiting spectra similar to those of older units. This observation suggests that Mississippian clastic material deposited NW of the Transcontinental Arch likely represents a combination of recycled Devonian and older strata from the growing Antler orogen and first-cycle detritus from the north (Gehrels and Pecha, 2014; Beranek et al., 2016).

## Pennsylvanian

Orogenic activity culminated in Pennsylvanian time along the margins of Laurentia plus the craton interior. In the east, collision of the NW shoulder of Africa with eastern North America (i.e., the Alleghenian event) led to continued growth of the Appalachians and the delivery of a new pulse of detritus, including disaggregated Acadian- and Alleghenian-aged material (ca. 350–420 Ma and ca. 300–350 Ma, respectively; Thomas et al., 2017), to the foreland and beyond. Inmixing of Appalachian-derived detritus with sediment in western North America is apparent in Figures 4D and 5D, which show that detrital zircon age spectra from the west are pulled toward a clustered, Appalachian-derived end-member.

In the south, mountain building in the Ouachita-Marathon belt occurred due to the impingement of northern South America with southern North

America. In contrast to the Appalachians, the Ouachita-Marathon belt lacks significant proportions of Taconic-aged intrusives and spatially overlaps the Early Cambrian Oklahoma-Colorado Aulacogen. Hence, it is unlikely that the Ouachita-Marathon belt contributed significant detritus to the SW U.S. at this time, based on the abundance of Taconic-aged detrital zircons and the scarcity of ca. 530 Ma grains in Arizona and California. Collision of South America also drove uplift of the Ancestral Rocky Mountains, which likely contributed significant proportions of Yavapai-Mazatzal and ca. 1.3–1.5 Ga granitoid-derived detritus to the western states.

Pennsylvanian time was also marked by a changing climate, which facilitated the dispersal of Appalachian-derived detritus across North America, including NW of the Transcontinental Arch. Glaciation and resulting recession of the Kaskaskia sea shut down the Mississippian shallow marine sediment dispersal pathway described above. Instead, the westward transport of sediment must have occurred by a variety of mechanisms, including a network of westward prograding deltas, large river systems with outflows in the Great Plains, and SW-migrating dune fields (Parrish and Peterson, 1988; Soreghan et al., 2002; Gehrels et al., 2011; Thomas et al., 2017).

## CONCLUSIONS

This research documents a previously unrecognized Mississippian transcontinental sediment dispersal network that began in the growing Appalachian Mountains, traversed the southern margin of North America, and is recognized as far as the SW U.S. Fluvio-deltaic processes played a minor role in the transport of Appalachian-derived material westward. Instead, shallow marine processes (e.g., tides, currents, and possibly hurricanes) likely transported sediment westward and parallel to the shelf, as is currently observed along the eastern margins of Australia and South America. Detrital zircon age distributions in Ordovician to Devonian strata indicate that North America was partitioned into three first-order domains prior to establishment of the Mississippian sediment dispersal pathway. Appalachian-derived detritus became more widespread in Pennsylvanian time as sea-level dropped and deltaic, fluvial, and aeolian processes continued to disperse these materials.

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