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Comparison of U-Pb detrital zircon signatures across sediment routing system segments: insights from the late Pleistocene Mississippi River and deep-sea fan

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Abstract:

The Pleistocene Mississippi sediment routing system has experienced significant drainage reorganizations in response to Northern Hemisphere glaciation. Geologically recent (<25 ka) and large (~90 km) river avulsions have occurred in the Mississippi's lower alluvial valley, yet whether these punctuated autogenic phenomena influenced down system records of sedimentary provenance is unknown. We present U–Pb detrital zircon (DZ) geochronology from near last glacial maximum (LGM; ~25 ka) and early deglacial (~14 ka) aged fluvial deposits of the Mississippi Valley, United States, integrated with published DZ samples from the Gulf of Mexico (Mississippi fan), to show a high similarity of DZs from late Pleistocene fluvial deposits and those from time correlative deep-marine deposits. These results imply the last glacial Mississippi River efficiently transferred DZs from river to deep-sea with little modification to the riverine DZ signature. Stratigraphically deeper DZ samples in the Mississippi fan contain distinct DZ age spectra, which likely represent the primary DZ signature of the Mississippi between isotope (MIS) stages 5 – 3. Mixture modeling of DZ samples recovered from late Pleistocene (MIS-2) deposits in the Western Lowlands and Eastern Lowlands of the Mississippi Valley suggests ~80% of the DZs in a LGM-to-deglacial Mississippi River were sourced from the glacial Missouri River, with lesser but appreciable contributions from the glacial Upper Mississippi River (13 – 20%). Only minute contributions of DZs are interpreted from the glacial Arkansas (1 – 5%) and Ohio Rivers (0 – 2%). Given the interpreted lack of Ohio river derived DZs in the Western Lowlands at ca. 25 ka, we suggest a glacial Ohio river did not join a combined Missouri-Mississippi River at the sampled location in the Western Lowlands at ~25, and may or may not have joined the Missouri-Mississippi in the Eastern Lowlands at ~15 ka. Our geochronological analyses included several grain size fractions for each sample location; a

lack of Gondwanan-Appalachian aged DZs in one sub sample grain size fraction illustrates the need for mineral separation methods and U-Pb age measurement methods that include all available size fractions, or risks serious error in provenance interpretations.

Introduction:

The manner in which climate change, tectonic perturbations, or autogenic sedimentary phenomena influence sediment supply magnitude, grain size, and sediment supply rate to basins is crucial knowledge when attempting to decode stratigraphic patterns (Dickinson, 1974; Jerolmack and Paola, 2010; Allen and Allen, 2013; Allen et al., 2016; Romans et al., 2016; Jonell et al., 2018; Straub et al., 2020). An equally important aspect of deciphering upstream environmental changes from stratigraphy is the potential for changes in sediment source areas as inferred from detrital minerals (Weislogel et al, 2006; Gehrels, 2014; Sharman et al., 2019). Indeed, constraining the sources of sediment preserved in basins using sedimentary provenance has become an integral component to studies which attempt to decode paleogeography or invert past external forcings from ancient sedimentary deposits (Thomas, 2011; Lawton, 2014; Caracciolo, 2020). Furthermore, studies of sedimentary provenance in modern- to sub-modern sedimentary systems — those systems much older than historical records, but for which past drainage basin configurations may be fairly well constrained (e.g. Sømme et al., 2009) — when combined with published tectonic and climatic records and direct observations, have allowed geoscientists to refine how deep-time boundary conditions may have influenced stratigraphic archives (Mason and Romans, 2018; Blowick et al., 2019; Malkowski et al., 2019; Blum et al., 2018; Capaldi et al., 2019; Sickman et al., 2016; 2019; Mason et al. 2019; Fildani et al., 2018; Hessler et al., 2018).

Sediment routing systems move sediment and solutes across Earth's surface, generally from upland regions of sediment production, to adjacent sedimentary basins (Allen, 2008; Sinha, 2011). Studies of sedimentary basins often rely on sedimentologic and stratigraphic data from only one system segment, leaving open the prospect for unrecognized effects of grain size fractionation or autogenic sediment recycling along depositional dip of the sediment routing system (Pettit et al., 2019). For example, differential preservation and/or lack of access to outcrops or cores in subsiding or ancient sedimentary basins often precludes direct comparisons of sedimentary provenance across time correlative system segments. The Mississippi River to deep-sea fan system (Fig. 1 A) is a globally significant sediment routing system, has been well-studied since the mid 1900s (Fisk, 1944; Saucier, 1986; Bentley et al., 2016; Fildani et al., 2016; Blum, 2019), and is composed of relatively well-dated and relatively accessible deposits in the fluvial (Rittenour et al., 2007) and marine environments (Bouma et al., 1986; Fildani et al., 2016). The Mississippi sediment routing system has revealed numerous insights about the manner in which climatic histories of North America have impacted the sedimentary record and preservation of its fluvial systems (Saucier, 1994; Blum, 2000; Counts et al., 2015), the architecture of deep-sea fans (Bouma, 1986; Bentley et al., 2016), and global climate through the flux of glacial meltwater to Earth's oceans (Licciardi et al., 1999; Aharon, 2003). One significant finding is that ice sheet growth and decay may have modified the sources of riverine sediment input to the Mississippi fan over the last glacial-interglacial period (Mason et al., 2017; Fildani et al., 2018). However, the nature of the apparent changes in sediment sources, as preserved in the deep-sea, are not well constrained and thus merit further investigation.

In this paper we present new detrital zircon U-Pb geochronology (N = 6 samples, n = 742 individual U-Pb ages), and integrate these new results with abundant existing DZ geochronology from the Modern Mississippi River and its tributaries (Blum and Pecha, 2014), and the Mississippi deep-sea fan (Fildani et al., 2016; Mason et al., 2017; Fildani et al., 2018). We interpret these DZ age spectra across the fluvial to marine zones in the context of potential allogenic forcings (e.g. ice sheet fluctuations) and autogenic forcings along depositional dip (*e.g.* large river avulsions, sediment recycling and or mixing in the coastal to marine zone).

Study Area and Methods

The Mississippi sediment routing system (Fig. 1 A) consists of an onshore, transcontinental fluvial network, a large subaerial delta positioned at the edge of the continental shelf in the Gulf of Mexico, a submarine canyon system active during glacioeustatic lowstands, and a deep-sea fan consisting of accumulations of mainly terrigenous sediment (Fig. 1 A-B). The onshore Mississippi fluvial system has experienced significant modifications since the onset of northern hemisphere glaciations (Carson et al., 2018). Between > 65 ka to 25 ka, the course of the Missouri – Upper Mississippi Rivers likely followed a path through the Western Lowlands, west of Crowley's Ridge (Fig. 1) in the Mississippi Valley (Rittenour et al., 2007; Blum 2019). After ~25 ka the Mississippi – Missouri River avulsed east into the Eastern Lowlands. The course of the glacial Ohio River may or may not have joined the main trunk Mississippi in the western lowlands, and similarly is unconstrained in space and time in the eastern Lowlands (Blum, 2019). Deep-sea sediment deposited between approximately 65 – 11 ka records large fluctuations in the relative proportions of DZs from the Ohio and Mississippi-Missouri Rivers (Fildani et al., 2018). Sediment aged ~25 to 15 ka in the Mississippi Valley may hold clues to the complex and most recent avulsion history.

The modern Missouri River supplies the majority (>40 – 50%) of suspended sediment to the main stem Mississippi River and delta (Heimann et al., 2011), and likely was more significant in terms of relative sediment loads in the pre-dam historical period. Past the limit of instrumental and historical records, U-Pb DZ provenance of sands from ancient deposits may be used to constrain sediment source areas (Blum and Pecha, 2014), as well as changing relative sediment loads through time (Mason et al., 2017). Specifically, Mason et al. (2017) identified a strong similarity between measured relative suspended sediment loads of tributaries to the Mississippi, and the results of quantitative DZ top-down mixing models (e.g. Sharman and Johnstone, 2017). Mason et al. (2017) concluded that a full glacial Missouri River supplied greater amounts of DZs (>70 – 90% of total) to the deep-sea fan than the river supplies to the modern fluvio-deltaic zone (~60 – 70% of total), which is consistent with historical accounts of sediment loads before anthropogenic modifications to the Missouri River.

Relatively high proportions of Western Cordillera aged DZs (0 – 280 Ma) in MIS-2 aged deep-sea deposits (Fig. 2) support an interpretation that the refractory detrital composition of the Mississippi fan is largely sourced from drainage basins in the western United States. The relative proportions of DZ age spectra change in a systematic way through stratigraphically older portions of the Mississippi fan, suggesting that sediment sources were more equally partitioned between eastern, northern, and western regions of the drainage basin—e.g. the Ohio River, Upper Mississippi River, and Missouri River, respectively, before the LGM (Fig. 2; Fildani et al., 2018). Taken together, DZs from the deep-sea fan and the modern fluvio-deltaic system segment fingerprint sediment sources, and tell a story of changing detrital mixtures, interpreted as changing source areas or relative sediment loads in the ancient Mississippi catchment through time. To summarize these observations, interglacial to early glacial climates appear to be associated with deposits containing higher proportions of eastern-derived DZs, whereas full glacial climates appear to be associated with deposits containing higher proportions of western- and northern-derived DZs. The record of detrital mixtures for the fluvial realm across the Late Pleistocene is largely unconstrained, but may yield insights into the functioning of the sedimentary system across glacial-interglacial cycles.

In order to interrogate DZ signatures of the ancient fluvial archive, we collected samples from the Western and Eastern Lowlands of the Central Mississippi Valley (Fig. 1 B). We used a sediment vibracore and a power auger to recover late Pleistocene river sands buried beneath several meters of late Pleistocene to Holocene soil and loess deposits (See Fig. 3 A – C for surface morphology at sample locations).

Sampling was guided by the published optically stimulated luminescence (OSL) chronology of Rittenour et al. (2007), and the published dissertation (2004) that contains detailed sedimentologic descriptions for each OSL sample location (noted below). The site of sample MV01 (this study) is located in the Western Lowlands, west of Crowley's Ridge, and was collected from the 24.6 ± 1.8 ka Ash Hill fluvial braid belt (Fig. 1 B for location). At this location, Rittenour described the Peoria loess from a depth of 0 – 220 cm, and fine to medium grained sand below 220 cm depth (sample 125). Sample MV01 was collected from below the Peoria loess at a depth of ~250 cm, and consisted of relatively clean, fine to medium grained sands (Fig. 3 D).

The site of sample MV03 (this study) is located south of- and east of Crowley's Ridge, in the Eastern Lowlands of the central Mississippi Valley, and was collected from the 14.7 ± 1.1 ka Kennett fluvial channel belt (Fig. 1 B). Rittenour (2004) described silty clay, interpreted as natural levee deposits, from 0 – 140 cm, underlain by oxidized to unoxidized medium to coarse sands from 140 – >240 cm depth (sample 122). Sample MV03 was collected beneath thicker loess and levee deposits at a depth of ~330 – 340 cm, and consisted of silty very fine to medium grained sand (Fig. 3 D).

Grain size is known to influence DZ age distributions in fluvial environments such as the Rio Orinoco (Ibañez-Mejia et al., 2018), and the Amazon River (Lawrence et al., 2011), yet the influence of grain size on DZ age distributions has not been investigated in the modern or ancient Mississippi River catchment System. We address this using a reconnaissance level sampling strategy. At each sample location we collected one bulk sample of unconsolidated sand from the subsurface. Each bulk sample was later dried, split and then sieved into grain size fractions of <63 μm, 63 – 125 μm, 125 – 250 μm, 250 – 500 μm, and >500 μm (see Table 1, Fig 2 D). A total of six sub samples were processed for extraction of DZs — the bulk sediment for each sample, the 63 – 125 μm, and the 125 – 250 μm fraction from samples MV01 and MV03.

We applied standard mineral separation techniques to samples of bulk sediment and grain size splits at the UTChron facility, University of Texas at Austin (USA), following the procedures of Thomson et al. (2017). After separation of zircons, U-Pb ages were measured using laser ablation–inductively coupled plasma–mass spectrometry. Of the subsample grain size fractions, insufficient amounts of DZs were recovered from the >250 μm size fractions to perform robust U-Pb geochronology. A data file of full isotopic measurements can be found in the supplementary data file (*this data file will not be available in the preprint version*).

In order to guide interpretations of U-Pb geochronologic results, we applied a statistical mixing model (after Fildani et al., 2018; Mason et al., 2019) to define the most likely sources of DZs to downstream sedimentary deposits in the Western and Eastern Lowlands between ~25 – 15 ka. In this method of unmixing DZ samples, DZs from Pleistocene fluvial samples represent a daughter composite mixture that we assume to be derived completely from several representative parent components—DZ samples collected from modern sands of the major tributaries to the Mississippi River (Blum and Pecha, 2014). We used a Monte Carlo approach to forward model 2e6 random combinations of parent components, and select the best fit model by minimizing the areal mismatch between observed daughter mixture and modeled daughter composite. The calculated relative mixing coefficients should give clues about the relative sediment supply across the LGM to early deglaciation in the Mississippi Valley, and ultimately clues into the ancient river configurations. The unmixing results also serve as a valuable comparisons to similar published quantifications of sediment sources for age correlative deep-sea fan DZ samples (Mason et al., 2017; Fildani et al. 2018).

Results

Individual DZ U-Pb age spectra for each bulk sample and each subsample are plotted as kernel density estimates (KDEs) and cumulative distribution functions in Figure 4 (using detritalPy; Sharman et al., 2018). These results show a subtle, systematic variation in DZ age spectra between bulk grain size, and subsamples of MV01 and MV03. In general, sample MV01 (Western Lowlands; 25 ka) is characterized by higher proportions of Trans-Hudson/Penokean and Wyoming/Superior aged DZs (>1800 Ma), and relatively low proportions of Appalachian-Gondwanan aged DZs (280 – 800 Ma). Sample MV01 contains a greater proportion of Jurassic aged DZs, as compared to MV03. Sample MV03 (Eastern Lowlands; 15 ka) is characterized by a greater proportion of Appalachian-Gondwanan aged DZs, and lower proportions of Trans-Hudson/Penokean and Wyoming/Superior aged DZs.

Overall, there appears to be no systematic variation in DZ age spectra with respect to grain size for each sub sample group, with the exception of subsample MV01 125 – 250 μm size fraction. Here we note the complete absence of Appalachian-Gondwanan aged DZs, and a relatively high proportion of Archean DZs as compared to other sub samples from the same deposit. We address this result further in the discussion section.

When U-Pb DZ age data for subsamples are amalgamated (Fig. 5), the product is a well-characterized DZ signature of the ancient Mississippi River as it flowed first through the Western Lowlands around 25 ka, and later through Eastern Lowlands around 15 ka. Unmixing the amalgamated DZ samples from the Western Lowlands results in mixing coefficients strongly partitioned between the Missouri River (79%), and the Upper Mississippi River (21%) (Fig. 6 C; Table 1). Unmixing DZ samples from the Eastern Lowlands results in mixing coefficients weighted toward the Missouri (80%), Upper Mississippi (13%), and lesser values for contributions from the Arkansas River (5%), and minimal values for contributions from the Ohio River (2%) (Fig. 6 D).

Discussion

New DZ age data from late Pleistocene deposits of the Mississippi fluvial system offer insights into sediment sources during the LGM through early deglacial conditions in the Mississippi fluvial system, a time of significant environmental change and major river avulsions in the Mississippi River Valley. Qualitatively, fluvial DZ samples resemble a mixture of the modern Missouri River, and the Upper Mississippi River, while also strongly resembling DZ samples from time correlative Mississippi deep-sea fan sediment (Fig. 5). These results suggest a robust link between river and deep-sea fan.

To better interpret the potential sediment sources, and to quantitatively visualize the similarity of each sample's age spectra, we plotted existing DZ age data for the largest modern tributaries to the Mississippi River (from Blum and Pecha, 2014; presented in Mason et al., 2017) and the new DZ age data on a multidimensional scaling map (MDS map; after Vermeesch, 2013) (Fig. 7). The resulting Euclidean distances between samples on the MDS map show the Ohio River is relatively dissimilar to MIS-2 Pleistocene fluvial samples and to the MIS-2 aged deep-sea samples. The MDS map indicates a close similarity of LGM fluvial samples to the modern Missouri River, and to a lesser degree the Upper Mississippi River. Mixing models agree with, and reinforce interpretations made from the MDS map. Given the strong similarity between previous mixing model results and measured relative sediment supply in the modern Mississippi system, it is likely these new model results offer a glimpse into the ice age relative sediment loads of the Mississippi River (Fig. 8). Mixing coefficients for sample MV01 suggest the Missouri River and Upper Mississippi supplied most or nearly all of the sediment to the Ash Hill braid belts in the Western Lowlands at ~25 ka, and neither the Arkansas nor the Ohio Rivers contributed quantifiable proportions of DZs to this location at that time.

After 25 ka, the Missouri – Mississippi River avulsed into the Eastern Lowlands through the Bell City Oran Gap (Fig. 8; Rittenour et al., 2017). It would seem plausible, or perhaps likely the DZ signature in the Eastern Lowlands would be influenced by the glacial Ohio River with its abundant Grenville and Appalachian-Gondwanan DZs. However, this prediction is not borne out by the DZ distributions from sample MV03. The samples from the eastern lowlands do not contain the strong Grenville DZ signature which could be related to the modern Ohio River, yet do contain abundant Western Cordillera aged DZs. Early deglacial aged Kennett channel belts (~14 ka) of the central/Eastern Lowlands contain less Archean and Jurassic DZs (northern and western signatures, respectively), and slightly more Appalachian-Gondwanan DZs (eastern signature). Bulk samples and subsamples of MV03 plot closest to the MIS-2 deep sea fan samples in MDS space (Fig. 7). Furthermore. These samples, like those of MV01, cluster nearest the modern Missouri River in MDS space. Mixing coefficients for sample MV03 suggest the Missouri River supplied about the same proportion of DZs to the Eastern Lowlands at 15 ka (80%), while the Upper Mississippi and Arkansas also contributed moderate amounts of DZs, and the Ohio River supplied scarcely quantifiable amounts of DZs to this location in the Eastern Lowlands at ~15 ka. Our results and interpretations suggest that sediment supply from the Missouri River was dominant in all segments of the Mississippi system between the fluvial valley and deep-sea fan during the immediate lead up to the LGM through early deglaciation (Fig. 8).

While mixing model results suggest that a glacial Ohio River may not have contributed DZs to the main trunk Mississippi at 15 ka, that scenario—where the hydrologically largest tributary was dammed by ice, or flowed parallel to, but apart from the Mississippi in the Eastern lowlands at 15 ka—may be overly simplistic. One plausible explanation for an apparent lack of glacial Ohio River derived DZs might be the relative erodibility of substrate in western vs. eastern drainage basins. For example sedimentary substrates in the Missouri River basin and the Great Plains could have supplied abundant Mesozoic through Cenozoic aged clastic sediment to the system, while eastern substrates, carved by the Ohio River, are composed of dominantly resistant Paleozoic strata, and simply eroded more slowly providing less clastic sediment to the Mississippi river system. The glacial till from northern and western basins could have enhanced the amount Western Cordillera DZs and account for relatively low proportions of eastern sourced DZs. However, Mason et al (2017) quantified ~14 – 17% contributions of Ohio derived DZs in modern lower Mississippi River sediment, which suggests relative erodibility alone may not explain the lack of apparent Ohio-derived DZs. Another plausible explanation is that geographically variable climatic conditions (temperature, hydroclimate) across the Mississippi catchment modulated erosion rates over late Pleistocene to Holocene timescales, as proposed for the Trinity, Brazos, and Colorado Rivers of Texas (Hidy et al., 2014), and the continent scale Amazon River catchment (Mason et al., 2019).

The potential for grain size to influence interpretations of sediment provenance is illustrated by the DZ age spectra of subsample MV01 (125 – 250 μm). If the fine sand sized subsample from MV01 were the only provenance data available for a given sedimentary basin, one would be forced to interpret a complete lack of Appalachian-Gondwanan sourcing in its upstream catchment — an unlikely phenomenon for large rivers of central or eastern North America (Dickinson, 2009; Blum and Pecha, 2014), nor deposits from ancient sedimentary basins of western North America, all of which which tend to incorporate recycled Grenville and older DZ populations (Schwartz et al., 2019). One logical explanation for a lack of Appalachian DZs in the 125 – 250 μm fraction of MV01, is that Appalachian and Gondwanan aged zircons tend to be smaller, and that Archean zircons found in abundance in other subsample size fractions tend to be larger. This result may merit further investigation but is out of the immediate scope of this work. However, given the initial result of analyses of grain size fractions in the Mississippi sediment routing system, we advocate for the inclusion of all grain size fractions when performing mineral separations for DZ provenance analysis.

The relatively high abundance of late Cretaceous DZs in all existing samples from the late Pleistocene Mississippi sediment routing system is an unexplained phenomenon. Fildani et al. (2016) proposed enhanced sediment supply from the Rocky Mountains of the American west (and perhaps the Canadian Rockies), driven by large glacial outburst floods, and an associated increase in the supply of glacial till rich in western derived detritus. The DZ distributions of newly sampled Pleistocene fluvial deposits contain an abundance of late Cretaceous DZs, which is consistent with the interpretation of Fildani et al. (2016). Similar high proportions of Western Cordillera DZs in fluvial sediments and age correlative deep-sea fan sediments argue against grain size fining as a primary control on this age populations.

Pleistocene fluvial deposits in the Western and Eastern Lowlands are dominated by supply from the ancestral Missouri River, and to a lesser degree the Upper Mississippi River, as are the deep-sea deposits of MIS-2 age in the Mississippi fan. The similarity of late Pleistocene fluvial DZ samples to time correlative DZ samples from the deep-sea fan supports the concept of rapid signal propagation through a glacial to early deglacial continent scale river to fan system, during glacioeustatic lowstand. Here, we have shown again that deep-sea fans are faithful recorders of continent scale catchments (Fildani and Hessler, 2019). The application of relatively high resolution sampling across sediment routing system segments in the Mississippi River and fan contributes to the growing body of work that posits sediment sources in the fluvial segment, and as recorded in deep-sea fans, are sensitive to climatic and ice sheet controlled forcings over Milankovitch timescales. A novel result of this work is that DZ provenance of deposits from the late Pleistocene river and fan appear less sensitive to the relatively large river avulsions documented between ~25 – 15 ka in the Mississippi Valley, than to overall system-wide external forcing of climate change and associated ice sheet growth and decay throughout the Pleistocene.

Conclusions

We applied U-Pb detrital zircon (DZ) geochronology to late Pleistocene fluvial deposits of the Mississippi Valley to investigate the sources of sediment in the Mississippi sediment routing system just prior (25 ka) to the last glacial maximum (LGM) and during early deglaciation (15 ka). We find the Missouri-Mississippi River dominated DZ supply at all observed periods of time, and found no evidence from the DZ record of the glacial Ohio River contributing significant quantities of sediment or DZs the Mississippi River or deep-sea fan. The age spectra from bulk sediment samples and sub samples from the late Pleistocene fluvial system presented here agree with the existing hypothesis that a combined Missouri – Upper Mississippi River once flowed through the Western Lowlands of the Mississippi Valley, west of Crowley's Ridge, and was separate from the Ohio River at ~25 ka. After 25 ka, this river system avulsed into the Eastern Lowlands through the Bell City – Oran Gap, and later through Thebes Gap, where downstream DZ sample age spectra and mixture modeling results are inconsistent with contributions of DZs from an early deglacial Ohio River. The strong similarity of late Pleistocene fluvial DZs to published DZ samples from the LGM to deglacial Mississippi deep-sea fan suggests that no significant modifications of DZ mixtures occurred en route to the deep-sea fan, and confirms that fans are robust recorders of their continental drainage basins. Our preliminary analyses of DZ ages across grain sizes, and the similarity of those sample age spectra to samples of the LGM deep-sea fan, suggests that down system grain size fining may not play a major role in the age populations found in deep sea environments in the Gulf of Mexico. The large autogenic river avulsions experienced by the Mississippi-Missouri River across ~25 – 15 ka did not significantly influence the downstream fluvial DZ signature of the glacial Mississippi River, nor those of deposits measured in the deep sea fan. First order controls on detrital mixtures in the Mississippi River to fan system appear to be tectonic-induced relief, and relative erodibility of catchment substrates. Second order controls on detrital mixtures appear to be ice sheet fluctuations that affect sediment source area disproportionately, and variable climatic conditions across the Mississippi catchment, such as temperature, hydroclimate, and glacially modified hydrology of major tributaries. Our interpretations are consistent with the idea that older and deeper samples from the Mississippi deep-sea fan, and others fans globally, should also record the primary riverine signature of their ancient terrestrial river segments.

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FIGURE CAPTIONS:

Figure 1. **A**: Map of United States and portions of Canada showing major features discussed in this paper, including the location of the Lower Mississippi Valley (modified from Rittenour et al., 2007). **B**: Quaternary surficial geology and fluvial deposit ages of the Lower Mississippi Valley, with sample locations discussed in this paper (modified from Rittenour et al. 2007; Blum, 2019).

Figure 2: A lithostratigraphic column for Deep Sea Drilling Project (DSDP) Leg 96, Site 615 with detrital zircon samples from Fildani et al. (2018). MIS = marine isotope stage. SH = seismic horizon. **B**: Proportions of U-Pb detrital zircon (DZ) ages from samples above and below seismic horizon H-20. Note the systematic shift in young, western derived DZs above H-20.

Figure 3. **A**: Shaded elevation map of the central Mississippi alluvial Valley (GeoMapApp; http://www.geomapapp.org; Ryan et al., 2009). **B**, **C**: Using a vibracore device to sample buried late Pleistocene sands at sample locations MV01 (25 ka) and sample location MV03. **D**: Bar graph of sample bulk weight % and grain size for sands recovered from sample locations MV01 (blue) and MV03 (red).

Figure 4. Results of U-Pb detrital zircon (DZ) geochronology of bulk sediment samples (captioned “bulk sed”), and sub samples from very fine (63 – 125 µm) and fine sand (125 – 250 µm) grain size fractions. Shown in the top panel are cumulative distribution functions (CDFs) for each sample, with a color coded key to DZ source terranes of North America. Lower panels are kernel density estimates (KDEs) displaying detrital age signatures of each sample and pie

diagrams with proportions keyed to the colors of the inset key. Lower case "n" = number of individual U-Pb DZ ages per sample.

Figure 5. Cumulative distribution functions (CFs) and kernel density estimates (KDEs) for amalgamated samples (= bulk sed + fine grain size + very fine grain sizes) from the late Pleistocene Mississippi River, plotted with published DZ samples from modern large rivers of the Mississippi system (Blum and Pecha, 2014), and plots of U-Pb DZ samples from late Pleistocene (marine isotope stage 2) Mississippi deep-sea fan (Fildani et al., 2018). Pies color coded to major North American zircon source terranes as in Figure 3.

Figure 6. **A, B**: Probability density plots for observed detrital zircon (DZ) samples from the Western Lowlands (25 ka; MV01 amalgamated) and Eastern Lowlands (15 ka; MV03 amalgamated), expressed as bold black lines. Red bold line shows results of a forward mixture model that distributes mixing weights equally across potential sediment sources, represented by detrital zircon samples from modern tributaries to the Mississippi River (thin colored lines). **C, D**: Probability density plots for observed DZ mixtures from the Western and Eastern Lowlands (bold black lines) and best fit models (bold red lines) found by forward Monte Carlo simulations (10^6 iterations) of potential combinations of each parent tributary. Results reported as % contribution to the downstream observed mixture.

Figure 7. Multidimensional scaling map (MDS map) for samples plotted in Figure 4. In this plot, axes are unitless Euclidean distances that relate to sample similarity (See Vermeesch, 2013 for explanation). Here, new detrital zircon samples from the late Pleistocene (marine isotope stage 2;

MIS-2; ~25 – 15 ka) Mississippi Valley samples plot closest to the age correlative deep-sea fan deposits, and also close to the modern Missouri River. See text for further explanation.

Figure 8. Google Earth satellite image of the lower Mississippi River Valley and interpreted ancient river courses. Pies are U-Pb detrital zircon (DZ) age signatures of samples from this study (MV01, MV03; 25 – 15 ka), and the DZ samples from the modern Missouri, Upper Mississippi, and Ohio Rivers, as well as the marine isotope stage 2 (MIS-2) deep-sea fan (~30 – 12 ka).

Table 1: mixture model results

modern river sample	**Western Lowlands ~25 ka**	**Eastern Lowlands ~15 ka**
(parent component)	MV01 amalgamated (composite mixture)	MV03 amalgamated (composite mixture)
Ohio River	0%	2%
Upper Mississippi River	21%	13%
Missouri River	79%	80%
Arkansas River	0%	5%

Table 1: Results of unmixing detrital zircon samples from the Western Lowlands (amalgamated grain sizes and bulk sediment for MV01), and the Eastern Lowlands (amalgamated grain sizes and bulk sediment for MV03).

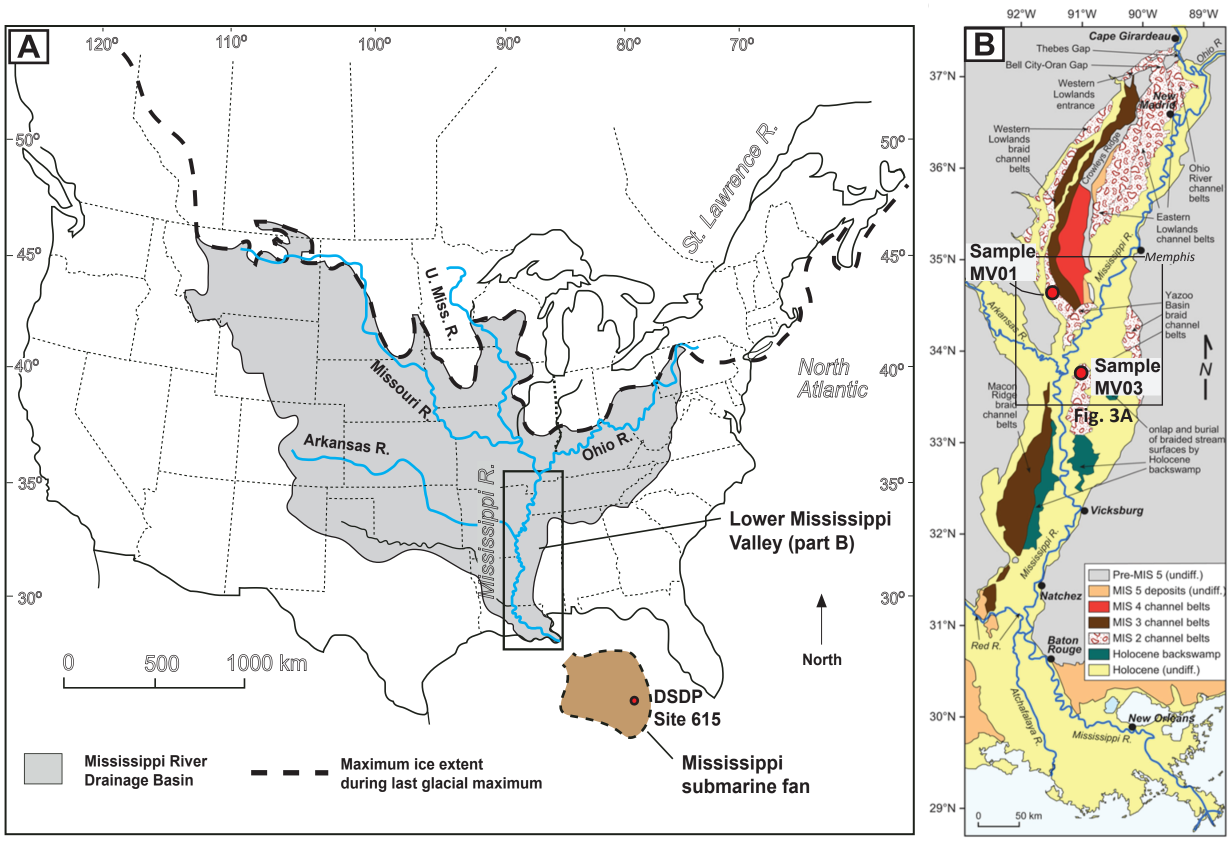


Figure 1 A and B

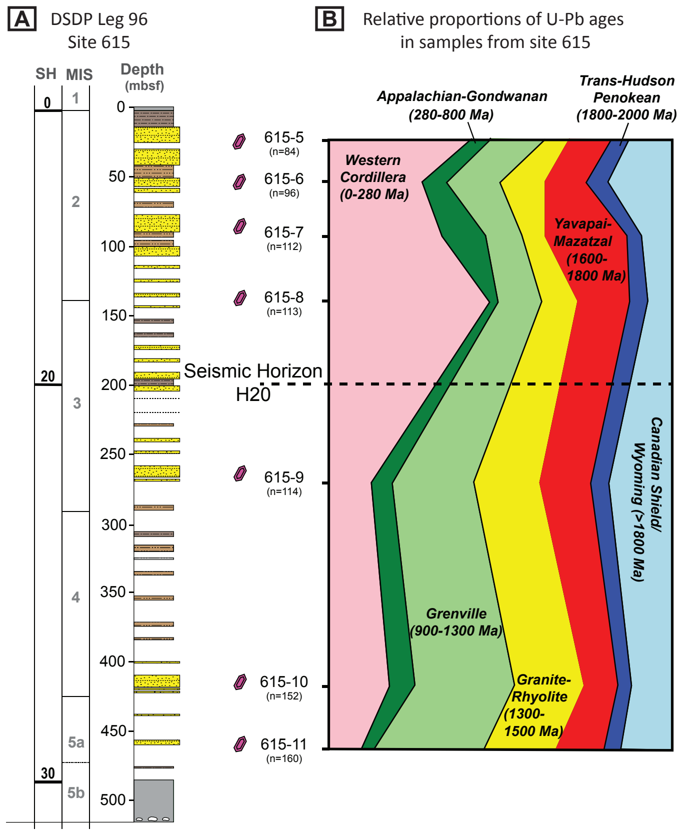
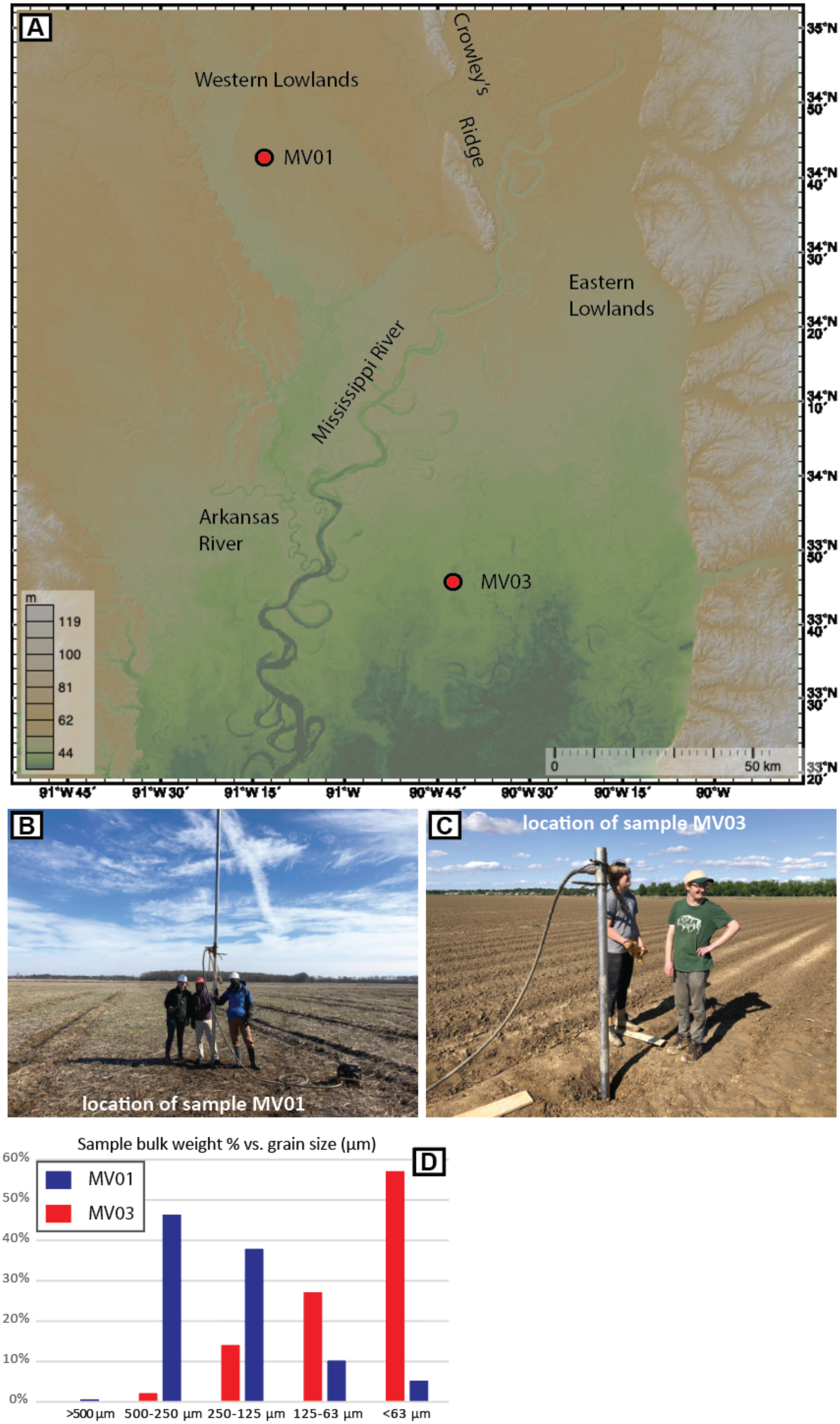
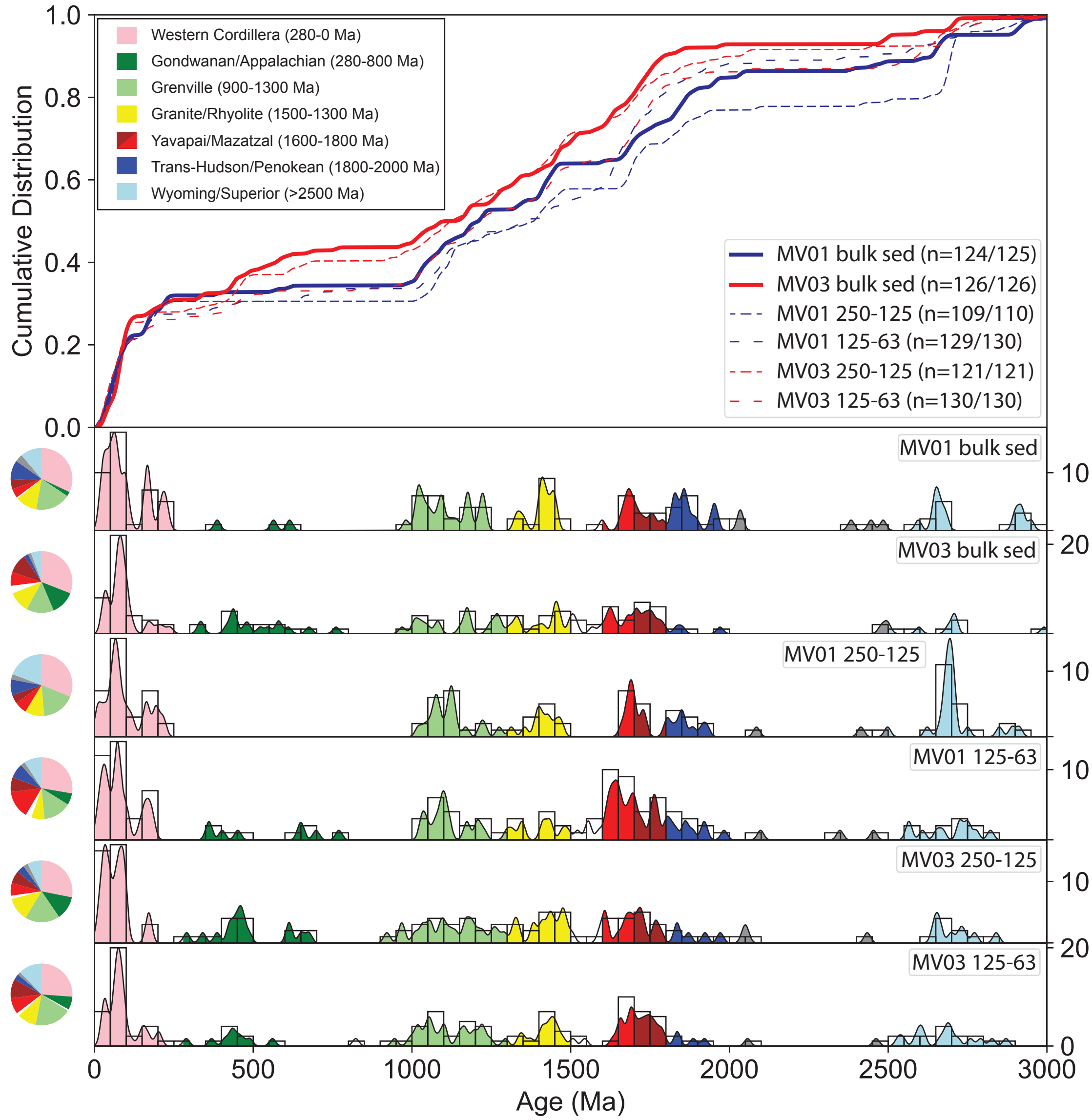

A DSDP Leg 96
Site 615
SH
MIS
Depth
(mbsf)
0
20
30
1
2
3
4
5a
5b
0
50
100
150
200
250
300
350
400
450
500
615-5
(n=84)
615-6
(n=96)
615-7
(n=112)
615-8
(n=113)
Seismic Horizon
H20
615-9
(n=114)
615-10
(n=152)
615-11
(n=160)
B Relative proportions of U-Pb ages
in samples from site 615
Appalachian-Gondwanan
(280-800 Ma)
Trans-Hudson
Penokean
(1800-2000 Ma)
Western
Cordillera
(0-280 Ma)
Yavapai-
Mazatzal
(1600-
1800 Ma)
Canadian Shield/
Wyoming (>1800 Ma)
Grenville
(900-1300 Ma)
Granite-
Rhyolite
(1300-
1500 Ma)

Figure 2 A-B

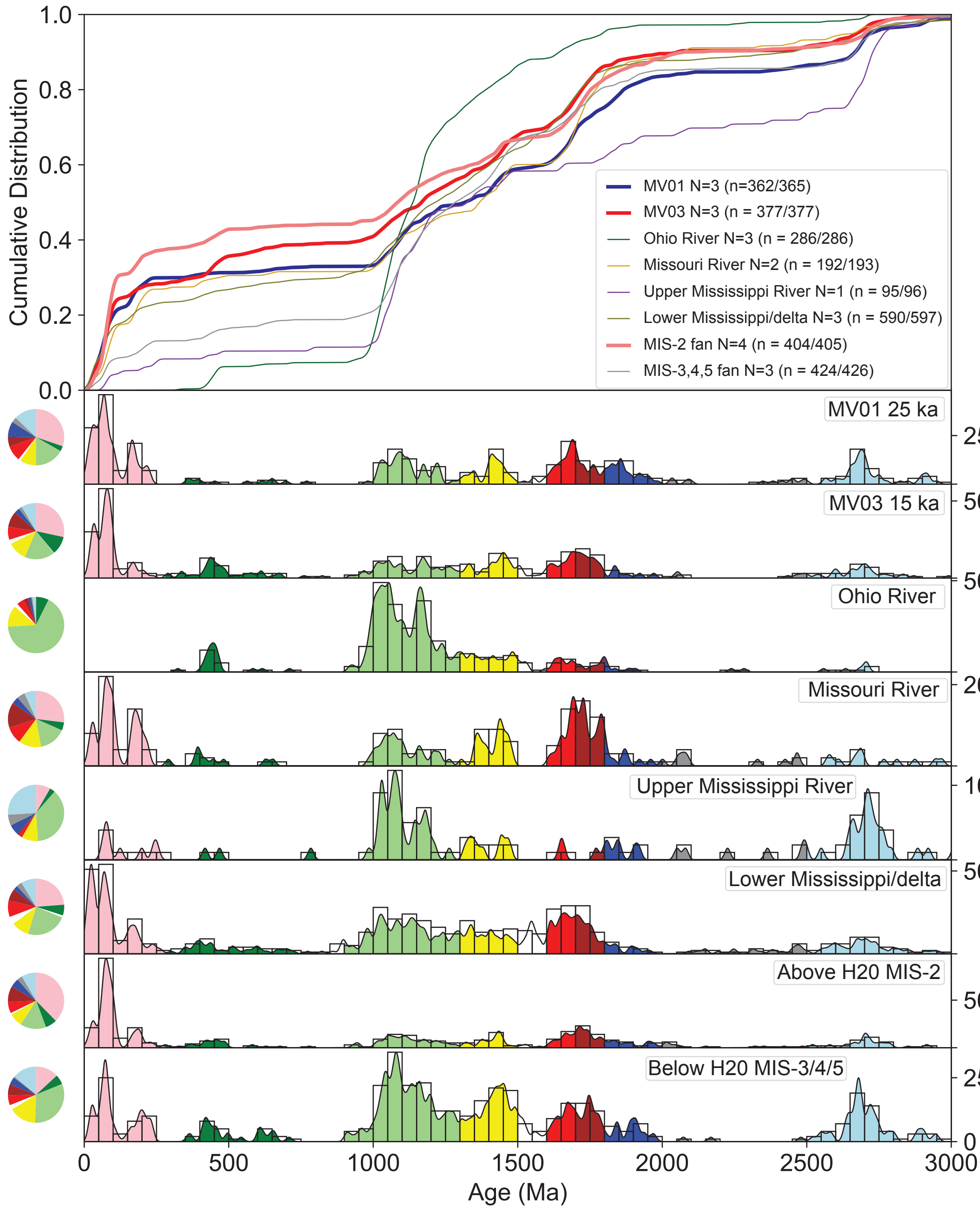


A
Western Lowlands
Crowley's Ridge
MV01
Eastern Lowlands
Mississippi River
Arkansas River
MV03
m
119
100
81
62
44
0
50 km
35°N
34°N 50'
34°N 40'
34°N 30'
34°N 20'
34°N 10'
34°N
33°N 50'
33°N 40'
33°N 30'
33°N 20'
91°W 45'
91°W 30'
91°W 15'
91°W
90°W 45'
90°W 30'
90°W 15'
90°W
B
location of sample MV01
C
location of sample MV03
Sample bulk weight % vs. grain size (μm)
D
MV01
MV03
60%
50%
40%
30%
20%
10%
0%
>500 μm
500-250 μm
250-125 μm
125-63 μm
<63 μm



1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Distribution
Western Cordillera (280-0 Ma)
Gondwanan/Appalachian (280-800 Ma)
Grenville (900-1300 Ma)
Granite/Rhyolite (1500-1300 Ma)
Yavapai/Mazatzal (1600-1800 Ma)
Trans-Hudson/Penokean (1800-2000 Ma)
Wyoming/Superior (>2500 Ma)
MV01 bulk sed (n=124/125)
MV03 bulk sed (n=126/126)
MV01 250-125 (n=109/110)
MV01 125-63 (n=129/130)
MV03 250-125 (n=121/121)
MV03 125-63 (n=130/130)
MV01 bulk sed
MV03 bulk sed
MV01 250-125
MV01 125-63
MV03 250-125
MV03 125-63
10
20
0
0
500
1000
1500
2000
2500
3000
Age (Ma)

Figure 4



1.0
0.8
0.6
0.4
0.2
0.0
Cumulative Distribution
MV01 N=3 (n=362/365)
MV03 N=3 (n = 377/377)
Ohio River N=3 (n = 286/286)
Missouri River N=2 (n = 192/193)
Upper Mississippi River N=1 (n = 95/96)
Lower Mississippi/delta N=3 (n = 590/597)
MIS-2 fan N=4 (n = 404/405)
MIS-3,4,5 fan N=3 (n = 424/426)
MV01 25 ka
MV03 15 ka
Ohio River
Missouri River
Upper Mississippi River
Lower Mississippi/delta
Above H20 MIS-2
Below H20 MIS-3/4/5
25
50
50
20
10
50
50
25
0
0
500
1000
1500
2000
2500
3000
Age (Ma)

Figure 5

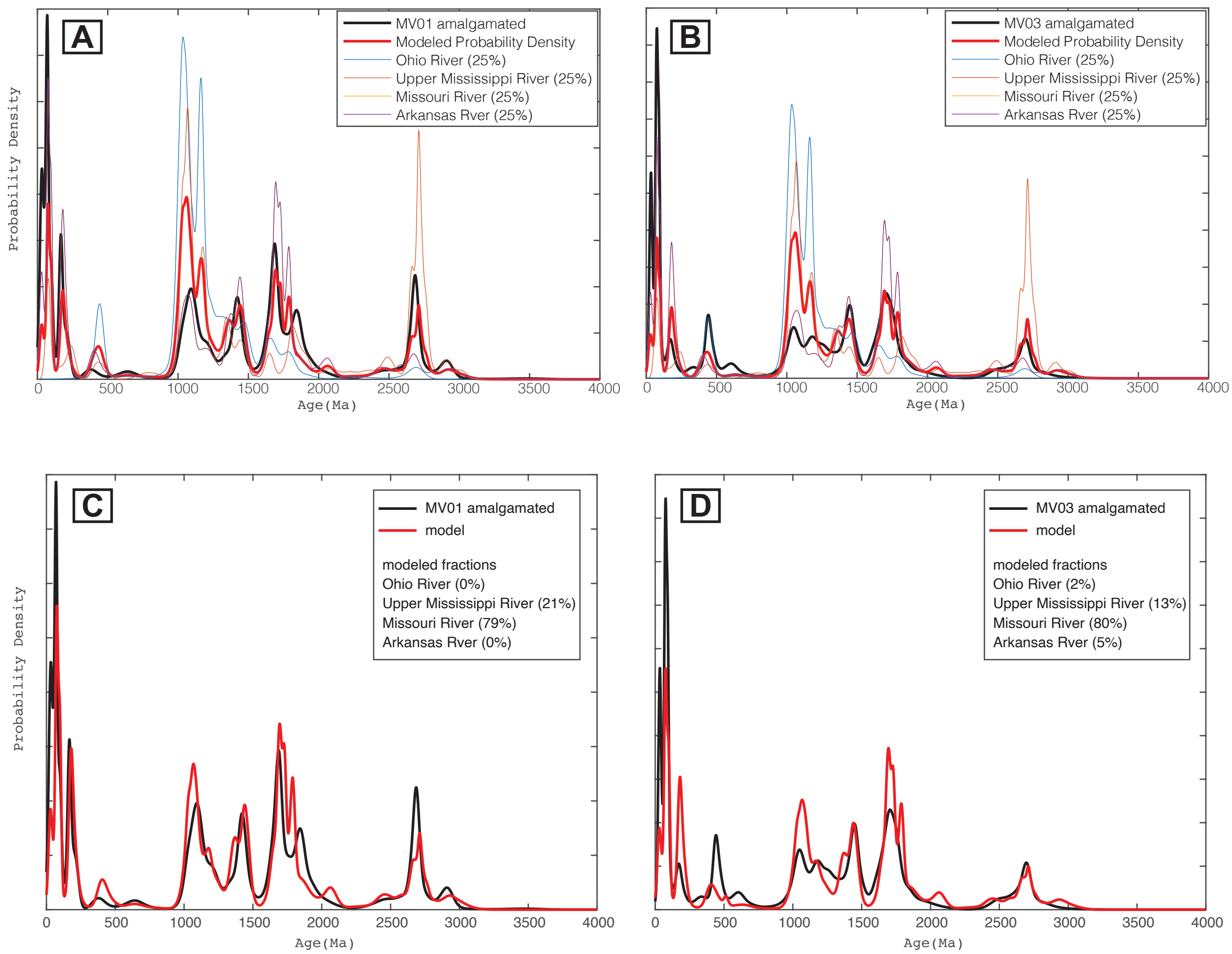
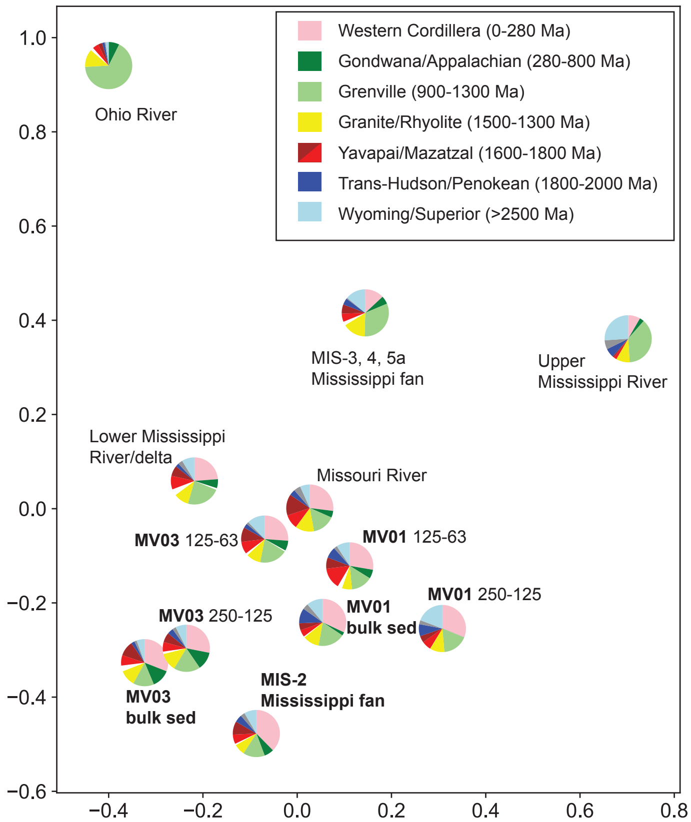


Figure 6 A-B-C-D



Western Cordillera (0-280 Ma)
Gondwana/Appalachian (280-800 Ma)
Grenville (900-1300 Ma)
Granite/Rhyolite (1500-1300 Ma)
Yavapai/Mazatzal (1600-1800 Ma)
Trans-Hudson/Penokean (1800-2000 Ma)
Wyoming/Superior (>2500 Ma)
Ohio River
MIS-3, 4, 5a
Mississippi fan
Upper
Mississippi River
Lower Mississippi
River/delta
Missouri River
MV03 125-63
MV01 125-63
MV01 250-125
MV01
bulk sed
MV03 250-125
MV03
bulk sed
MIS-2
Mississippi fan
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8

Figure 7

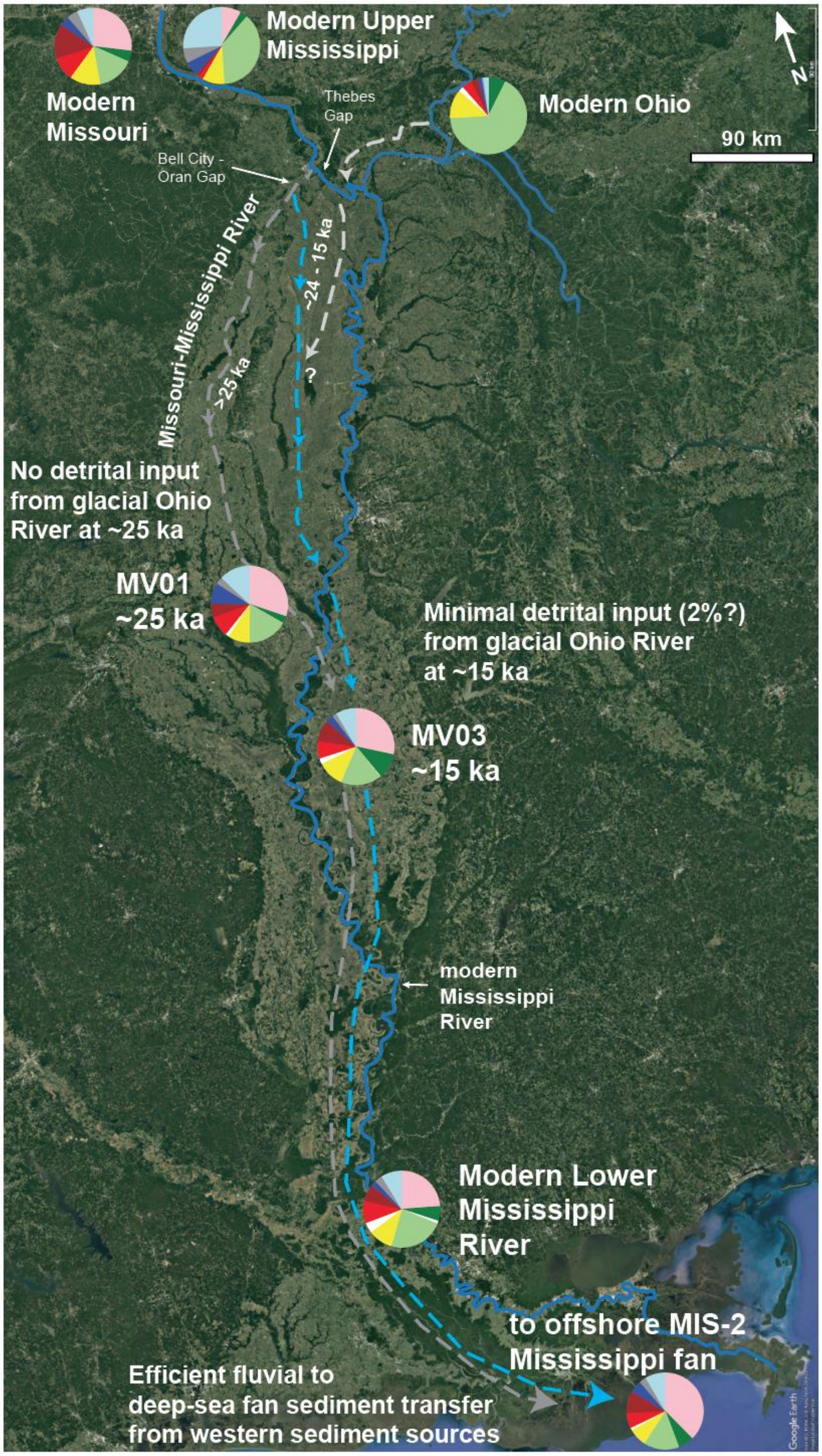

Modern Upper Mississippi
Modern Missouri
Modern Ohio
90 km
N
Thebes Gap
Bell City - Oran Gap
Missouri-Mississippi River
~24 - 15 ka
?
>25 ka
No detrital input from glacial Ohio River at ~25 ka
MV01 ~25 ka
Minimal detrital input (2%?) from glacial Ohio River at ~15 ka
MV03 ~15 ka
modern Mississippi River
Modern Lower Mississippi River
to offshore MIS-2 Mississippi fan
Efficient fluvial to deep-sea fan sediment transfer from western sediment sources
Google Earth

Figure 8