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Climatic and anthropogenic influences on sediment mixing in the Mississippi source-to-sink system using detrital zircons: Late Pleistocene to recent

Cody C. Mason [a,*], Andrea Fildani [b], Thomas Gerber [b], Michael D. Blum [c], Julian D. Clark [b], Mason Dykstra [b]

[a] *Department of Geoscience, Virginia Tech., 4044 Derring, 24061, Blacksburg, VA, United States*
[b] *Statoil Research Center, Austin, TX 78730, United States*
[c] *Department of Geology, University of Kansas, Lindley Hall, 1475 Jayhawk Blvd. Room 120 Lawrence, KS 66045, United States*

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ABSTRACT

U–Pb geochronology of detrital zircons (DZ) is a robust tool used to elucidate linkages between tectonics, climate, and drainage configurations. However, timescales of sedimentary system response to modulation of up-system boundary conditions are rarely investigated using detrital geochronology. Here we present results of mixture modeling using modern and Late Pleistocene DZ samples from each of the Mississippi system segments, and show that high-frequency changes in up-system boundary conditions—anthropogenic sediment impoundment and late Pleistocene ice sheet dynamics—have measurable effects on detrital compositions. Results of DZ mixing models show a high positive correlation to measured suspended sediment loads for each major tributary (ca. 1970s–2000s). Differences between model results and historical records are explained by recent anthropogenic sediment impoundment. Results of DZ mixing models using late Wisconsin deep-sea samples indicate major increases from the Missouri and Upper Mississippi rivers. Boundary conditions responsible for increased sediment loads from these catchments include ice stream activity, increased transport capacity during deglacial melt-water floods, and an increased gradient of a glacial lower Mississippi Valley. These results suggest sediment mixtures in large rivers respond to icehouse climate change at timescales of 10^{3-4} yrs, in contrast to calculated equilibrium response times of ca. 250–25 ka for the Mississippi system, and indications that anthropogenic river modifications alter relative sediment loads instantaneously. Adjustments in detrital mixtures occur at timescales an order-of-magnitude less than Milankovitch-timescale climate change, indicating rapid environmental signal propagation and preservation within transcontinental source-to-sink systems influenced by continental ice sheets.

1. Introduction

The detrital record of Earth history preserved in stratigraphy offers a rich source of information related to landscape evolution and environmental change through time. It is widely agreed that environmental changes, e.g. tectonic, climatic, and anthropogenic perturbations, affect source-to-sink sediment routing systems, ultimately influencing depositional basins (Allen, 2008; Covault and Graham, 2010; Romans et al., 2016). Changes in mass flux or sediment compositions to basins through time may represent signals of environmental changes affecting sediment yields and loads in routing systems (Allen, 2008). A fundamental goal of stratigraphy is to decode such records of past environmental change; however, disentangling signal from noise along the source-to-sink continuum represents a significant challenge to inversion of the stratigraphic record (review by Romans et al., 2016). Large sediment routing systems may introduce uncertainty related to storage and recycling dynamics, autogenics, and unconstrained mixing in marine environments, which may have the cumulative effect of buffering or shredding signals (Jerolmack and Paola, 2010). It is thus widely debated whether deep-sea deposits should record primary (*unmodulated*) signals of environmental changes on land, or if the majority of signals of environmental change ever become part of the stratigraphic record (Castelltort and Van Den Driessche, 2003). Development and use of quantitative methods that help distinguish signal from noise is necessary in order to re-

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[*] Corresponding author.
E-mail address: cmason80@vt.edu (C.C. Mason).

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fine our understanding of source-to-sink concepts. Detrital provenance studies represent an opportunity to quantify relative sediment fluxes in sediment routing systems (Amidon et al., 2005; Saylor et al., 2013). Comparison of detrital records with independent proxies and chronologies for changes in catchment boundary conditions should yield valuable insight into the system-scale effects of changing climate, tectonic, or anthropogenic regimes on sediment routing systems.

The deep-sea Mississippi fan represents the terminus of the late Pleistocene Mississippi River, and holds a record of sedimentary provenance spanning 10s–100s of thousands of years through glacial–interglacial cycles. Apparent changes in detrital provenance within the Mississippi system, as preserved in the deep-sea fan, indicate a source-to-sink system that may be reactive over timescales $<10^4$ yrs (Fildani et al., 2016), challenging some theories regarding the nature of signal propagation through large sediment routing systems (Castelltort and Van Den Driessche, 2003; Metevier and Guademer, 1999). Detrital provenance studies may thus provide a means of investigating timescales associated with signal propagation and preservation in large sediment routing systems (e.g. Clift and Giosan, 2013). The Mississippi River drainage basin spans latitudinal gradients, has been affected by high magnitude Pleistocene climate change, has acted as a conduit for glacial meltwater megafloods, and seen recent but major anthropogenic modifications, making it an ideal candidate for such a study.

In this project we use mixing models to explore the evolution of detrital compositions in the source-to-sink Mississippi through time. Our data set consists of modern fluvial and deltaic, and late Pleistocene deep-sea DZ samples. We expand on established concepts that: (1) detrital mixtures accurately reflect source mixing, (2) detrital mixtures from modern fluvial deposits represent an integrated, long-term signal, and (3) deep-sea detrital mixtures represent high fidelity archives for changes in relative sediment loads, and provide insights to system-scale responses to climate change. Previous work has characterized the DZ signatures of the modern Mississippi River and some of its major tributaries (Iizuka et al., 2005). We incorporate additional samples (published by Blum and Pecha, 2014) to characterize all major tributaries to the Mississippi River using DZs, and then use mixture modeling to quantify the relative proportions of sediment supplied from major tributaries to the lower Mississippi River, delta, and ca. late Wisconsin (late marine isotope stage 3; MIS-3 through MIS-2) deep-sea fan. Estimates of sedimentary fluxes from late Wisconsin tributaries to the Mississippi deep-sea fan provide valuable insight into the effects of climate change on transcontinental rivers, and demonstrate the timescales of compositional changes within large rivers fed by partially glaciated drainage basins. Perhaps most importantly, these results demonstrate deep-sea fans, specifically lowstand fans at termini of long, well mixed systems accurately record mixtures of DZs in large rivers that feed them, and do not appear significantly diluted by mixing or reworking during transport and deposition in the marine realm; a detail that has significant implications for inversion of stratigraphic records from continental margins or deep-sea strata in deep-time.

2. Background

2.1. The modern Mississippi system

The modern Mississippi source-to-sink system (Fig. 1) is a transcontinental river composed of the longest and second longest rivers in North America—the Missouri and Mississippi Rivers, respectively (Heimann et al., 2011). The Mississippi drainage network is 3,210,000 km^2 and covers 41% of the conterminous United States (National Park Service; https://www.nps.gov). The major tributaries of the Mississippi System are (1) the Missouri River basin, which is 1.37 million km^2, representing 44.6% of the contributing area to the lower Mississippi, (2) the Upper Mississippi basin, which is 0.53 million km^2 (16.5%), (3) the Ohio River basin is 0.49 million km^2 (15.2%), and the Arkansas River basin is 0.5 million km^2 (15.4%) (Heimann et al., 2011). While the contributing area of the Missouri River is the greatest, it is the Ohio River that is hydrologically the most significant to the Mississippi system (Knox, 2007). The Red River (of the South) basin is only ~0.17 million km^2 and would represent ~5% of the total area relative to the other major tributaries, though the Red has relatively high sediment loads (further discussed below). The Red River does not currently contribute to the lower Mississippi; rather outflow from the lower Mississippi joins the Red via the Old River Control Structure, becoming the Atchafalaya River in central Louisiana and western Mississippi. For this reason, contributions from the Red River have not been considered by previous authors when constructing sediment budgets for the Mississippi system. However, in the recent Holocene (e.g. 1400s–1800s), the Red River flowed into the lower Mississippi River and contributed sediment to the delta (see Fisk, 1944) and may have contributed to the deep-sea fan during the Pleistocene.

Before anthropogenic modifications, the Mississippi system may have transported an average of about 400 million metric tons per year (Mt/yr) of sediment through its lower reaches (i.e. the location of gauging station at Tarbert Landing, Mississippi; Fig. 1). Sediment impoundment, and possibly drought have reduced sediment fluxes by ~65–75% since the early 1900s (Meade and Moody, 2010; Heimann et al., 2011). Available data for sediment loads (at Tarbert Landing, Mississippi) in the Mississippi River are presented in Fig. 2, and sediment budgets for major tributaries are presented in Table 2 and summarized in the following. The Missouri River transfers, and has historically transferred the most sediment to the Mississippi River; between 1976 and 2009 the Missouri River had a median suspended sediment load (SSL) of 56.9 million metric tons per year (Mt/yr). The next greatest sediment contribution to the Mississippi was the Ohio River, which had a median SSL of 32.5 Mt/yr. The Upper Mississippi River contributed 22.5 Mt/yr, and the Arkansas River contributed only 2.4 Mt/yr (Heimann et al., 2011). Between 1973–1981 the Red River carried a median total suspended sediment load of ~26 Mt/yr (USGS National Water Information System, accessed August 2016), which if integrated with the above loads, would represent approximately 18% of the total suspended sediment in the Mississippi system (see Table 2 for this alternate sediment budget).

Unfortunately, bedload flux estimates for the Mississippi and its tributaries are unavailable, though typically the coarse fraction of sand transported by downstream-migrating bedforms scales to discharge, and thus scales roughly to total sediment load (Nittrouer et al., 2008). Measurements of suspended sand fractions for a pre- and post-dam lower Mississippi River exist; for the period of 1950–1952, the proportion of suspended sand to total suspended sediment load (SSDL/SSL) was 0.16, while during the period of 1970–2008, the proportion of SSDL/SSL was 0.22 (summarized in Fig. 2; and Blum and Roberts, 2014). An increase of suspended sand fraction is best explained by an overall decrease in suspended sediment concentration associated with damming along the Missouri River and other tributaries since the 1950s. Older pre-impoundment records of relative sediment supply from major tributaries to the Mississippi River are scarce. However, quantitative interpretations of historical observations indicate sediment concentrations in the Missouri River may have decreased by around 70–80% since the early 1900s (Blevins, 2006), which is not surprising given nearly all rivers with mountainous, high-relief drainage basins now flow into impounded systems before reaching the Mississippi River (Meade and Moody, 2010; Bentley et al., 2016).