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The Mississippi River source-to-sink system: Perspectives on tectonic, climatic, and anthropogenic influences, Miocene to Anthropocene

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ABSTRACT

The Mississippi River fluvial–marine sediment-dispersal system (MRS) has become the focus of renewed research during the past decade, driven by the recognition that the channel, alluvial valley, delta, and offshore regions are critical components of North American economic and ecological networks. This renaissance follows and builds on over a century of intense engineering and geological study, and was sparked by the catastrophic Gulf of Mexico 2005 hurricane season, the 2010 Deep Water Horizon oil spill, and the newly recognized utility of source-to-sink concepts in hydrocarbon exploration and production. With this paper, we consider influences on the MRS over Neogene timescales, integrate fluvial and marine processes with the valley to shelf to deepwater regions, discuss MRS evolution through the late Pleistocene and Holocene, and conclude with an evaluation of Anthropocene MRS morphodynamics and source-to-sink connectivity in a time of profound human alteration of the system. In doing so, we evaluate the effects of tectonic, climatic, and anthropogenic influences on the MRS over multiple timescales.

The Holocene MRS exhibits autogenic process-response at multiple spatial and temporal scales, from terrestrial catchment to marine basin. There is also ample evidence for allogenic influence, if not outright control, on these same morphodynamic phenomena that are often considered hallmarks of autogenesis in sedimentary systems. Prime examples include episodes of enhanced Holocene flooding that likely triggered avulsion, crevassing, and lobe-switching events at subdelta to delta scales.

The modern locus of the Mississippi fluvial axis and shelf–slope–fan complex was established by Neogene crustal dynamics that steered sediment supply. Dominant Miocene sediment supply shifted west to east, due to regional subsidence in the Rockies. Then, drier conditions inhibited sediment delivery from the Rocky Mountains, and Appalachian epeirogenic uplift combined with wetter conditions to enhance sediment delivery from the Appalachians.

Climatic influences came to the forefront during Pleistocene glacial–interglacial cycles. The fluvial system rapidly responded to sea-level rises and falls with rapid and extensive floodplain aggradation and fluvial knickpoint migration, respectively. More dramatically, meltwater flood episodes spanning decades to centuries were powerful agents of geomorphic sculpting and source-to-sink connectivity from the ice edge to the deepest marine basin. Differential sediment loading from alluvial valley to slope extending from Cretaceous to present time drove salt-tectonic motions, which provided additional morphodynamic complexity, steered deep-sea sediment delivery, diverted and closed canyons, and contributed to modern slope geometry.

Despite the best efforts from generations of engineers, the leveed, gated, and dammed Mississippi still demonstrates the same tendency for self-regulation that confronted 19th century engineers. This is most apparent in the bed-level aggradation and scour associated with changes in sediment cover and stream power in river channels, and in the upstream migration of channel depocenters and fluvial and sediment outlets at the expense of downstream flow, that will ultimately lead to delta backstepping. Like other source-to-sink systems, upstream control of sediment supply is impacting downstream morphology. Even within the strait-jacketed confines of the modern flood control system, the Mississippi River still retains some independence.

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Contents

1. Introduction

On January 30, 1878, James Buchanan Eads spoke on the Mississippi River to the St. Louis Merchant's Exchange, “We … see that the Creator has, in His mysterious wisdom, endowed the grand old river with almost sentient faculties for its preservation. By these it is able to change, alter, or abandon its devious channels, elevate or lower its surface slopes, and so temper the force which impels its floods to the sea” (McHenry, 1884). Eads was the leading fluvial engineer of his time, having developed the engineered levee system used to control the mouths of the Mississippi for navigation purposes. He recognized the self-regulating properties that have made the Mississippi a premier global example of a meandering river and fluvially dominated deltaic system. Scientific study of the river not new, and many of the most important understandings date from research conducted over a century ago. In this review we will examine these self–regulating, or autogenic, properties of the Mississippi River system, as well as the external, or allogenic, processes that control delivery of water and sediment to the Mississippi and its tributaries, within the context of source-to-sink connectivity.

Despite more than 150 years of investigations, there is still much to be learned about the Mississippi system by new research, and continued study of its linked alluvial, deltaic, and offshore components is of critical importance for several reasons. First, 10–20% of the world's population resides on or near large deltas (Vörösmarty et al., 2009), and most of these deltas are disappearing due to the combined effects of rising sea level, natural deltaic processes, and anthropogenic interference (e.g., Syvitski et al., 2009). The Mississippi has a massive record of intensive research on which to ground plans for coastal landscape conservation and restoration. However, much previous research was conducted to understand deltaic environments as analogs for hydrocarbon production, maintain the river channel for river-borne commerce, and prevent flooding of adjacent flood plains and flood basins for agricultural purposes. A more detailed understanding, using modern tools, techniques, and increasingly complex numerical analysis is required to address controversial scientific issues and successfully implement conservation and restoration plans.

As a result, the Mississippi River fluvial–marine sediment-dispersal system (MRS; Fig. 1, Table 1) has become the focus of renewed research during the past decade, driven by the recognition that the channel, alluvial valley, delta, and offshore environments are critical components of North American economic and ecological networks (Day et al., 2014). This renaissance follows and builds on previous intense engineering and geological study, but has been triggered by the catastrophic Gulf of Mexico 2005 hurricane season, the 2010 Deep Water Horizon oil spill, and increased interest in the potential utility of source-to-sink concepts in hydrocarbon exploration and production. A number of basic-research studies and one major review paper (Blum and Roberts, 2012) have resulted from this renaissance. Individual studies have been wide ranging in focus, from climatology to ecology of the alluvial valley to shelf and slope studies.

With this paper, we consider influences on the MRS over Neogene timescales, integrate marine processes and the shelf to deepwater stratigraphic record, and more explicitly discuss the contribution of the Mississippi sediment routing system to development of the Gulf of Mexico continental margin. In doing so, we evaluate the effects of tectonic, climatic, and anthropogenic influences on the MRS over multiple timescales, and the relative roles of allogenic forcing versus autogenic self-organization. We first briefly describe the longer-term integration of the Mississippi system, then focus on the Miocene Epoch (Fig. 2), when Earth's continents assumed their modern configuration (Potter and Szatmari, 2009), and the ancestral Mississippi River assumed a continental-scale, polyzonal tributary network resembling that of the present. We then explore the Pleistocene and early Holocene stratigraphic record, when global climate change brought about continental-scale glaciations (and deglaciations) and coupled high-amplitude cycles of global sea-level rise and fall. Last, we turn to the late Holocene and the time period of strong anthropogenic influences: we first outline processes and products before large-scale human alteration in the early 19th century, and contrast this with the strong anthropogenic impacts on the river basin, valley, and delta from the 19th century to the present.

1.1. The Mid-Cretaceous to Oligocene Mississippi embayment and ancestral Mississippi system

Recent detrital-zircon studies of ancient Gulf of Mexico fluvial deposits (e.g., Mackey et al., 2012; Craddock and Kylander-Clark, 2013; Blum and Pecha, 2014) provide insights on Gulf of Mexico drainage integration that add to views developed from more traditional means (e.g., as summarized in Galloway et al., 2011), and complement new insights from continued exploration of the deepwater Gulf of Mexico.