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Dune-scale cross-strata across the fluvial-deltaic backwater regime: Preservation potential of an autogenic stratigraphic signature

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ABSTRACT

Dune-scale cross-beds are a fundamental building block of fluvial-deltaic stratigraphy and have been recognized on Earth and other terrestrial planets. The architecture of these stratal elements reflects bed-form dynamics that are dependent on river hydrodynamic conditions, and previous work has documented a multitude of scaling relationships to describe the morphodynamic interactions between dunes and fluid flow. However, these relationships are predicated on normal flow conditions for river systems and thus may be unsuitable for application in fluvial-deltaic settings that are impacted by nonuniform flow. The ways in which dune dimensions vary systematically due to the influence of reach-averaged, nonuniform flow, and how such changes may be encoded in dune cross-strata, have not been investigated. Herein, we explored the influence of backwater flow on dune geometry in a large modern fluvial channel and its implications for interpretation of systematic variability in dune cross-strata in outcrop-scale stratigraphy. This was accomplished by analyzing high-resolution channel-bed topography data for the lowermost 410 km of the Mississippi River, which revealed that dune size increases to a maximum before decreasing toward the river outlet. This spatial variability coincides with enhanced channel-bed aggradation and decreasing dune celerity, which arise due to backwater hydrodynamics. An analytical model of bed-form stratification, identifying spatial variability of cross-set thickness, indicates a prominent downstream decrease over the backwater region. These findings can be used to inform studies of ancient fluvial-deltaic settings, by bolstering assessments of proximity to the marine terminus and associated spatially varying paleohydraulics.

INTRODUCTION

Sedimentary rocks of fluvial origin are used to infer characteristic paleohydraulic parameters of transport systems (e.g., channel slope *S* and flow depth *H*), which bolster assessments of past surface environments on Earth (Foreman et al., 2012), as well as other terrestrial planets (Goudge et al., 2018). However, a major challenge in paleohydraulic reconstructions arises due to the probable existence of hydraulic variability. For example, lowland fluvial channels nearing a receiving basin experience nonuniform (backwater) flow. This influences the patterns of sediment accumulation (Nittrouer et al., 2012), and thus the development of stratigraphy (Wu et al., 2020; Wu and Nittrouer, 2020), but it cannot be accounted for using empirically based reconstruction methods developed for normal flow conditions (Bradley and Venditti, 2017). To resolve the paleohydraulic signatures of regions impacted by spatially varying flow, it is necessary to account for morphodynamic variations by coupling the adjusting fluid flow field with sediment transport gradients and determining bed elevation changes. Herein, we used detailed observations of bed forms to inform an analytical model that explores the evolution of outcrop-scale cross-set stratigraphy over a large part (lowermost ~410 km) of the backwater-influenced reach (i.e., lowermost ~500 km; Nittrouer et al., 2012) of the Mississippi River (MR).

Nonuniform flow conditions arise where a river channel approaches a standing body of water, and the water-surface profile asymptotically converges to base level. As the bed elevation maintains a uniform slope, channel depth increases, and, assuming a constant channel width, cross-sectional flow area expands downstream (Nittrouer et al., 2012). By principles of conservation, flow velocity must thus decrease, generating reduced sediment transport capacity, in-channel accumulation (Ganti et al., 2014), and downstream fining (Nittrouer, 2013; Smith et al., 2020). Recently, several efforts have sought to evaluate the impact of backwater hydrodynamics on the rock record. A downstream increase in thickness of the fluvial bar forms (flow depth indicator) and a downdip fining in median channel-bed grain size were recognized from the Castlegate Sandstone in Utah (Petter, 2010) and across the backwater reach of Holocene-aged MR deposits (Fernandes et al., 2016). A downstream narrowing of channel-belt deposits was observed in the Ferron Sandstone of Utah (Kimmerle and Bhattacharya, 2018) and in the subsurface of the Mungaroo Formation in Australia (Martin et al., 2018). The spatial variability in the architecture of autogenic scours, assessed to arise due to nonuniform flow, has also been revealed to impact stratigraphy (Trower et al., 2018; Ganti et al., 2019).

To date, most research has focused on the linkages between backwater hydrodynamics and large-scale features (e.g., bars and channel

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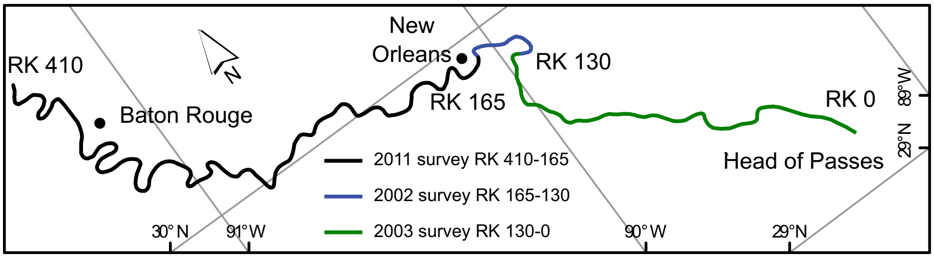

Figure 1. Lowermost Mississippi River (MR), from river kilometer (RK) 410 to Head of Passes (i.e., RK 0). River centerline is color coded by bathymetric survey dates.

belts), arising over hundreds of meters to tens of kilometers, and time scales that include multiple flood events (i.e., decades to centuries). The systematic variability expressed by smaller-scale features, such as dunes and associated cross-strata, due to spatially varying backwater hydrodynamics has not been investigated to our knowledge. This is a critical oversight, as dune-scale cross-strata are ubiquitous in fluvial sediments (Best and Fielding, 2020) and thus are characteristic outcrop-scale features that comprise significant proportions of fluvio-deltaic channel stratigraphy. Importantly, such paleoenvironmental reconstructions often rely upon inverting bed-form strata to assess channel paleoflow depths (Paola and Borgman, 1991; Leclair and Bridge, 2001; Bradley and Venditti, 2017). These models assume that sediment transport and dune geometry are equilibrated in time and space. However, sediment transport capacity varies with nonuniform flow (Nittrouer et al., 2012; Lamb et al., 2012), and the resulting gradients in sediment flux can be expected to affect the size and celerity (c) of the dune and the vertical aggradation rate (r), and thus the geometry of the stratal architecture (Jerolmack and Mohrig, 2005; Leclair, 2006).

Herein, we address the hypothesis that the production and preservation of dune-scale cross-strata vary systematically across the backwater reach of a fluvial-deltaic channel, adjusting to changing bed-form geometry, celerity, and the accumulation of bed material sediment. This hypothesis was tested by assessing the spatial variability of dune height (h) in conjunction with changing hydrodynamic flow conditions and sediment transport capacity across the lowermost MR and by using an analytical model to predict the resulting cross-set thickness.

DATA SET AND METHODS

Multibeam echo sounder (MBES) bathymetric data covering the lowermost 410 river kilometers (RK) of the MR (RK 410–0, as measured upstream of the outlet at Head of Passes) were collected during low-water discharge (8300–9900 m^{-3} s^{-1}) from three surveys conducted during 2002, 2003, and 2011 (Fig. 1). The data were used to evaluate dune geometry (e.g., dune height; Supplemental Material Figs. S1–S3[1]). Because the surveys were conducted at low-discharge conditions following prolonged periods (months) of relatively stable flow, the dunes were expected to be in morphological equilibrium with the water discharge (Martin and Jerolmack, 2013). Anthropogenic influences (e.g., construction of levees and revetments, development of spillways and Old River station, dredging; see Supplemental Material) on the river hydrodynamics and bed forms in the river length examined herein were limited because the backwater hydrodynamics persist, especially during low discharge (Nittrouer et al., 2012), and no apparent dredged regions were identified from the MBES data set.

A one-dimensional morphodynamic model (Parker et al., 2008) was developed and applied to the lowermost MR for a low-discharge (~10,000 m^{-3} s^{-1}) condition to simulate reach-averaged trends in annual channel-bed aggradation arising due to gradients in sediment transport (Fig. S4, Supplemental Material).

RESULTS

In total, 45,687 dunes were identified and measured from the MBES data set, with average dune height being 0.38 m (Fig. S3). The large-scale spatial trend in dune height was evaluated using a 10 km moving window (Fig. 2)—a distance sufficient to include the typical meander wavelength of the MR—so that local variabilities were smoothed, and reach-scale changes were better revealed. Based on this technique, values for the 10th percentile of dune height were nearly consistent across the entire backwater reach. However, the mean and 90th percentile dune heights indicated a downstream increase from RK 410 to a peak near RK 320, and then a progressive decrease toward the river outlet. The standard deviation in dune height demonstrated a similar spatial trend (i.e., maximum at RK 350; Fig. 2B), with the coefficient of variation (C_v), defined as the ratio between the standard deviation and mean height, peaking near RK 350 and decreasing downstream (Fig. 2C).

Results from the MR morphodynamic model (Fig. 2D) revealed that: (1) the rate of channel-bed aggradation (r) continuously decreased across the lower 410 km reach of the system, and (2) dune celerity (c), calculated based on modeled sediment flux (Simons et al., 1965; see Supplemental Material), decreased rapidly between RK 410 and RK 390, but then decreased more gently toward the river outlet. From these assessments, it is noted that the ratio r/c increased between RK 410 and 320 but then decreased toward the river outlet.

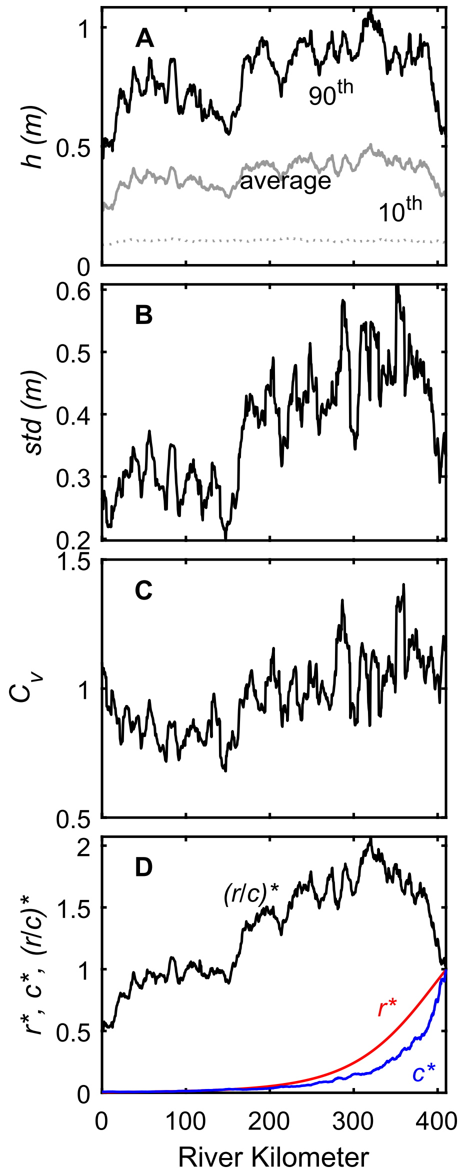

Figure 2. (A) Spatial variation in dune height (*h*). (B) Standard deviation in dune height (*std*). (C) Coefficient of variation in dune height (C_v). (D) Backwater morphodynamic model of lower Mississippi River (MR), showing spatial variations in key modeling parameters (normalized by value of each parameter at river kilometer 410), including normalized aggradation rate (r^*), dune celerity (c^*), and ratio of $(r/c)^*$.

[1]Supplemental Material. Additional details on methods and results. Please visit https://doi.org/10.1130/GEOL.S.12620690 to access the supplemental material, and contact editing@geosociety.org with any questions.

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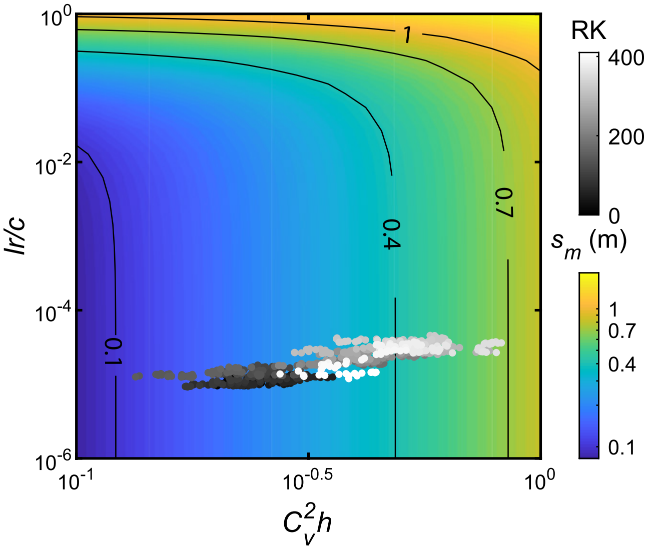

Figure 3. Numerical model of cross-set thickness (s_m; contours) for various rates of aggradation and distributions of dune size. Abscissa (C_v^2h) and ordinate (*lr*/*c*) axes correspond to second and first terms on right side of Equation 1, respectively. Gray-scale color-coded dots are model results of cross-bed thickness for Mississippi River (MR). RK—river kilometer.

A model predicting mean cross-set thickness (s_m; Bridge and Best, 1997; Cardenas et al., 2019) was used to predict the spatial variability of s_m for MR dunes, based on mean dune height (*h*), variability in dune dimensions (C_v), and the reach-averaged channel-bed aggradation to dune celerity (*r*/*c*) ratio:

$$s_m = lr/c + 0.8225(C_v)^2 h, \quad (1)$$

where *l* is dune wavelength. This model indicates that when *r*/*c* values are low (i.e., $<10^{-3}$), the dominant controls on cross-set thickness are *h* and C_v; hence, larger *h* and/or C_v values produce greater cross-set thicknesses (Fig. 3). The influences of *r* and *c* on cross-set thickness are only pronounced when *r*/*c* values are high ($>10^{-3}$). The reach-averaged value of *r*/*c* for the MR is $\sim10^{-5}$ (Fig. 3), indicating that the reach-averaged aggradation rate (~1 mm yr^{-1}) is too low, relative to dune celerity ($\sim10^{-3}$–10^{-4} m s^{-1}), to affect cross-set thickness, despite the downstream spatial variability in *r*/*c* values.

The model results show that mean cross-set thickness increased from RK 410 to RK 350 but decreased progressing from RK 350 to the outlet (Fig. 4). The distribution of cross-set thickness was approximated by random resampling with replacement (i.e., bootstrapping method) for every 0.5 km using a bin size of 10 km to calculate the associated standard deviation. The results were fitted with a variety of polynomial regression functions (Fig. 4), and the Akaike information criterion (AIC; Akaike, 1974) was calculated for each. This revealed that a fourth-order polynomial regression function represents the best fit (i.e., r^2 value of 0.67) and shows the least risk of overfitting. The modeled spatial variability in cross-set thickness thus arises due to a downstream increase in mean dune height (*h*) and variability in dune height (C_v) within the upper reach of the backwater region (Figs. 2B and 2D) together with decreasing C_v and *r*/*c* ratios (Figs. 2 and 3B) in the lower reaches of the backwater region. This is an unexpected result compared to traditional viewpoints: If equilibrium dune height scales with flow depth (i.e., Bradley and Venditti, 2017; Best and Fielding, 2020), and cross-set thickness scales with dune height (Leclair and Bridge, 2001), then the cross-bed thickness should increase monotonically as flow depth increases downstream across the backwater reach. Instead, the opposite result is predicted based on observational data for the lowermost MR.

DISCUSSION

The model results indicate that the impact of backwater-induced long-term channel-bed aggradation on the production of cross-strata is minor compared to changes in dune heights and the distribution of dune heights for the lowermost MR (Fig. 3). However, the role of backwater hydrodynamics, with respect to the linkage between sediment transport and the stratigraphic record, is evident, as the morphodynamic modeling assessments indicate that spatial trends of dune size, as well as *r*/*c* and C_v, are similar (Fig. 2). We argue that this is not a coincidence, because the systematic change in dune morphology is likely the result of spatially varying backwater hydrodynamic properties (Fig. S5). For example, the downstream decreases in boundary shear stress and median channel-bed grain size, both of which are key characteristics of a backwater condition (Nittrouer et al., 2012; Smith et al., 2020), can systematically adjust dune height (Figs. S5B–S5C) by affecting shear velocity ($u*$) and settling velocity (w_s), respectively. Dune height typically increases with $u*$, but finer grains with higher w_s are prone to suspension, a process that may subdue dune growth (Best, 2005; Bradley and Venditti, 2017; Cisneros et al., 2020). Therefore, the peak and plateau in dune size in the upper reaches of the backwater region (Fig. 2A) could arise as the optimal hydraulic condition is met (i.e., suspension criterion, $u*/w_s \approx 0.9$ - 1; Supplemental Material). Moreover, dune height is poorly correlated with flow depth (Fig. S5A) and cannot be well characterized with scaling relations, as also suggested by previous studies (Bradley and Venditti, 2017; Best and Fielding, 2020; Cisneros et al., 2020).

The modeled spatial trend in cross-set thickness is likely to be preserved in the stratigraphy even though the downstream backwater region is a net incisional region during high-flow stage (Nittrouer et al., 2012; Lamb et al., 2012). For example, the Castlegate Sandstone demonstrates the coexistence of autogenic erosional scours (Trower et al., 2018) and depositional bars mantled with dunes (Petter, 2010), and it provides information pertaining to development of backwater hydrodynamic conditions. Three mechanisms can enhance the preservation potential of cross-sets in the lowermost reaches of

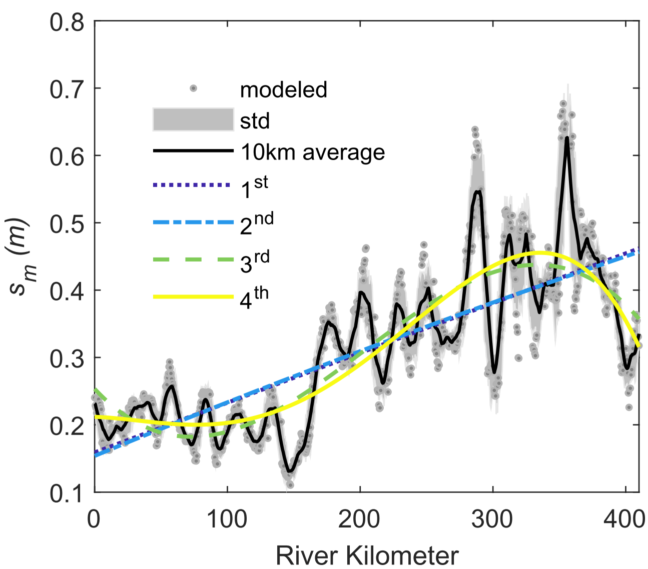

Figure 4. Spatial trend of modeled cross-set thickness, s_m, for Mississippi River (MR). Black solid line is 10 km average in cross-set thickness, with associated one standard deviation (std) marked in gray. Dark blue, light blue, green, and yellow lines represent linear, quadratic, cubic, and fourth-order polynomial regression functions fit to cross-set thickness, respectively.

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rivers. First, the entire channel belt may be abandoned rapidly through avulsion (Ganti et al., 2014), and, therefore, it is no longer subjected to reworking before burial by subsequent sedimentation (Carlson et al., 2020). Second, lateral channel migration facilitates local deposition and produces stratigraphy in the form of scour-fill successions and point bars (van de Lageweg et al., 2016), with lateral migration rates typically decreasing to zero downstream in large rivers (Ikeda, 1989), including the MR (Hudson and Kesel, 2000). Hence, local aggradation can be elevated in the upper portions of the backwater reach through more active lateral migration, so that preservation of cross-sets may be enhanced. Finally, while dune size for a given reach of a river is not static under changing flow discharge (e.g., Julien and Klaassen, 1995; Nittrouer et al., 2008), it is worth noting that dunes formed during high discharge are less likely to be preserved relative to cross-sets generated during falling and low discharge (Leary and Ganti, 2020). Although this does not contradict the mechanisms of cross-set preservation discussed above, it does suggest that further study is needed.

Herein, the morphological variability of dunes was quantified for the lowermost MR, and their preserved cross-set thickness was inferred within the backwater-influenced reach of this river near its delta. The analyses indicate that spatial variability in cross-set thickness can potentially preserve a deterministic autostratigraphic signature of backwater hydrodynamics. Moreover, the findings highlight that paleohydraulic reconstructions of cross-sets from ancient fluvial-deltaic sediment must consider the effect of nonuniform flow, rather than treating the spatial gradient in cross-set thickness simply as a consequence of local variability. In this capacity, reconstructions of ancient fluvial-deltaic channel environments can be improved.

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