Dune-scale cross beds across a fluvial-deltaic backwater segment: preservation potential of an autogenic stratigraphic signature

Wu et al.

ADDITIONAL DETAILS ON METHODS AND RESULTS

Multibeam echo sounder (MBES) bathymetric data

Due to the large extent of this survey area, the entire channel area, bank-to-bank, could not be imaged. Instead, local bathymetry was measured using a zigzag pattern, intercepting the bank line at a 45-degree angle, and turning ninety degrees to cross the channel (Fig. S1A, and following the methods outlined in Nittrouer et al., 2011).

Dune measurements

Transects through the multibeam bathymetry data were constructed in ArcGIS. The flow depth was sampled every 0.5 m (Fig. S1B) and the data were then filtered in Matlab using a low-pass band filter function to eliminate high-frequency noise. Local topographic peaks (dune crests) and lows (dune troughs) were located using the "findpeaks()" function in Matlab (Fig. S1C). The location of individual dunes (river kilometer) with reference to the entire river was calculated by projecting the location of the dune crest onto the river centerline. The river kilometer for the projected point at the river centerline was treated as the location of the corresponding dune. Dune height (*h*) was calculated as the difference in flow depth between crest and adjacent downstream trough (Fig. S1D), whilst dune wavelength was approximated by the projected distance between consecutive dune troughs. There are systematic errors associated with this method for estimating wavelength due to the variation of the angle between transect and dune orientation (α) and the angle between transect and river centerline (β). The true wavelength (l_t) with respect to the estimated wavelength (l_e) can be expressed as $l_t = \frac{\sin\alpha}{\cos\beta} l_e$, where the ranges of α and β for the current study are typically 45°-90° and 0°-45°, respectively. Systematic overestimation and underestimation are within 40 and 20 percent of the true wavelength, respectively (Fig. S2). The reach-averaged aggradation rate needs to be several orders of magnitude higher for the dune wavelength to affect cross bed thickness (Fig. 3). Therefore, the error associated with this method for estimating dune wavelength is negligible for the analysis of cross-set thickness in this study. The angle of the dune leeface was approximated by using the arctangent of the ratio between dune height (h) and the projected distance between dune crest and associated downstream dune trough. Dunes larger than 10 m in height, wavelengths larger than 100 m, and lee face angles larger than 45° were excluded from the present analysis.

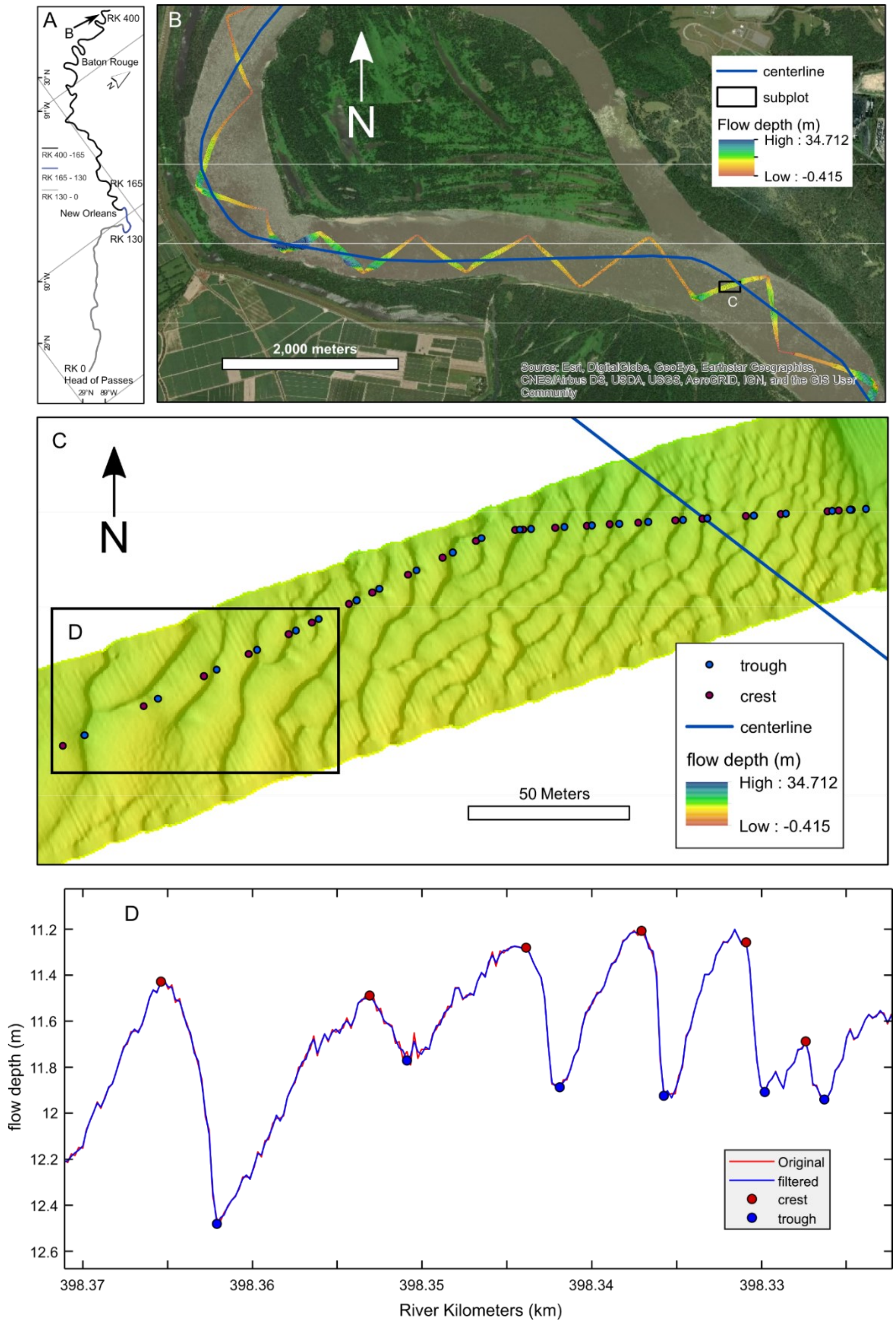

Figure S1. A: Map of the lower 400km of the Mississippi River. B: Representative map of multibeam data and typical zig-zag survey line. C: Detailed plot of multibeam data and identified dunes. The trace of the identified dune crests and troughs mark the location of the transect, where the multibeam data were sampled. D: Example of detection of dune crests and troughs on the MBES transect.

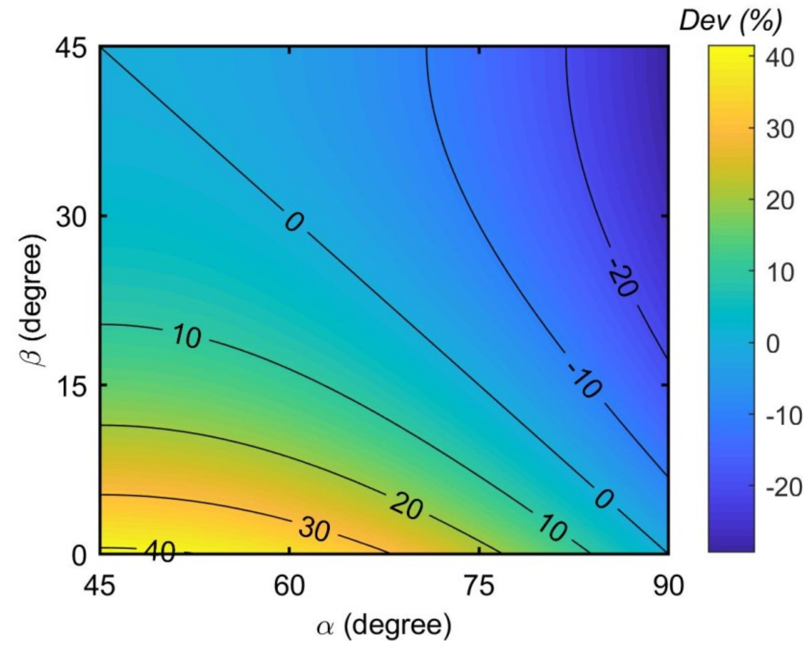

Figure S2. Sensitivity analysis for the angle between transect and dune orientation (α) and the angle between transect and river centerline (β). The color scheme with contours represent the deviation (*Dev*) of the estimated wavelength from the true wavelength, calculated as the percentage of the true wavelength ($Dev = \frac{l_e - l_t}{l_t} * 100\%$). Positive deviation indicates overestimate and negative deviation indicates underestimate.

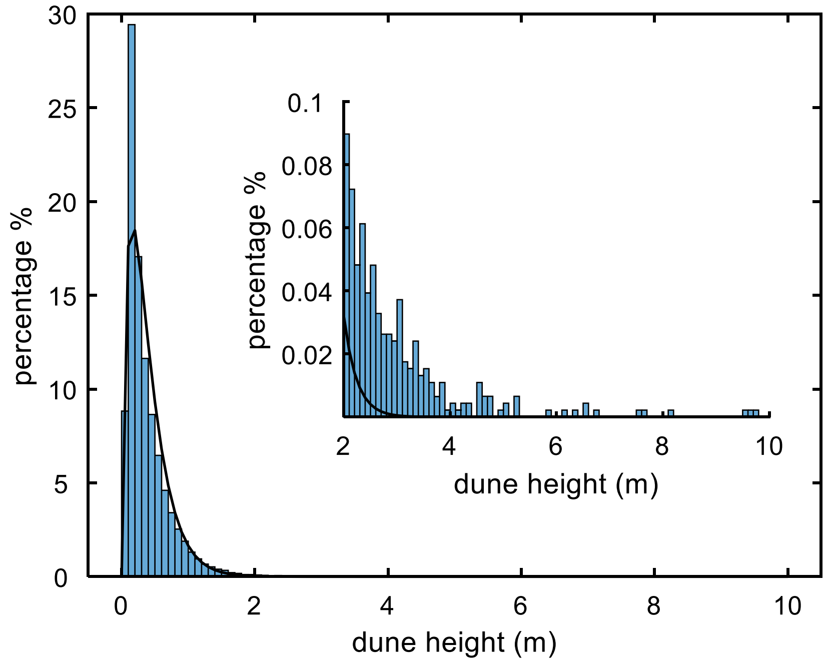

Figure S3. Probability density function plot of dune height as derived from the MBES data. A total of 45,687 dunes were measured and the data were fitted with a heavy-tailed gamma distribution. Insert shows the lower part of the distribution (dunes with height greater than 2 m).

Morphodynamic model for the Mississippi River

The present study adopted the morphodynamic model of Parker et al. (2008a, b) to simulate non-uniform flow hydraulics. The framework of Parker et al. (2008a, b) provides a means to model flow depth, *H*, in the along-stream distance (*x*) (Fig. S4):

$$\frac{dH}{dx} = \frac{S - C_f Fr^2}{1 - Fr^2}, (1)$$

where C_f is friction coefficient, Fr is Froude number, determined by $Fr = U(gH)^{-0.5}$, with *U* the depth-averaged flow velocity and *g* gravitational acceleration.

Sediment flux is calculated using the bed material load equation of Ma et al. (2017) and Ma et al. (2020):

$$q_s = (RgD_{50}^3)^{1/2}\left(\frac{0.0355}{C_f}\right)\tau_*^3, (2)$$

where R is the submerged specific gravity of the sediment, D_{50} is the 50th percentile of the grain size distribution (Fig. S4A) and τ_* is the dimensionless Shields number, determined by:

$$\tau_* = C_f U^2/RgD_{50}, (3)$$

The along-stream variation in sediment flux ($\partial q_s/\partial x$) is calculated and used to assess the rate of channel bed aggradation ($\partial\eta/\partial t$) using a modified Exner equation (Paola and Voller 2005):

$$\frac{\partial\eta}{\partial t} = -\mathrm{A}\frac{\partial q_s}{\partial x}, (4)$$

where A is determined by: $\mathrm{A} = (1+\Lambda)\Omega I_f\left(1-\lambda_p\right)^{-1}{r_B}^{-1}$, λ_p is the mean porosity of the channel-floodplain complex, Λ is the mud/sand ratio, Ω is the channel sinuosity, I_f is the flood intermittency, and r_B is the ratio between channel width and width of the floodplain. In lieu of measuring these parameters from field data, standard values from modern lowland systems that scale with the ancient basins were utilized (Parker et al., 2008b, Moran et al., 2017., Table S1).

The depth-averaged flow velocity U at the upstream normal flow reach (upstream boundary condition) is assumed to be 1.3 ms^{-1} based on field observation from the Mississippi River (Nittrouer et al., 2012). The flow depth at the river outlet (downstream boundary condition) is calculated as the difference between sea level (0 m of elevation) and channel bed elevation (~ -24 m of elevation). Width-averaged water discharge q_w at the upstream boundary can be calculated by combining $\tau_b = \rho C_f U^2$, $\tau_b = \rho g H S$, and $H = q_w/U$, where τ_b is the boundary shear stress, and ρ is fluid density. Depth-averaged flow velocity across the model domain may then be estimated by: $U = q_w/H$, where H is calculated by solving Equation (1). Then by solving equations (2) and (4), the rate of channel bed aggradation ($\partial\eta/\partial t$) can be obtained. Simulations were conducted over spatial steps of 5 km.

Table S1. Key model input parameters

Variable	Value	Description
g	9.81 m/s^2	Gravitational acceleration
I_f	0.1	Flood intermittency
R	1.65	Submerged specific gravity of sediments
λ	0.4	Bed porosity
Ω	1.7	Sinuosity
Λ	1.0	Volume unit of mud deposited in the channel–floodplain complex per unit sand deposited
r_B	60.0	ratio of channel width to flood plain width

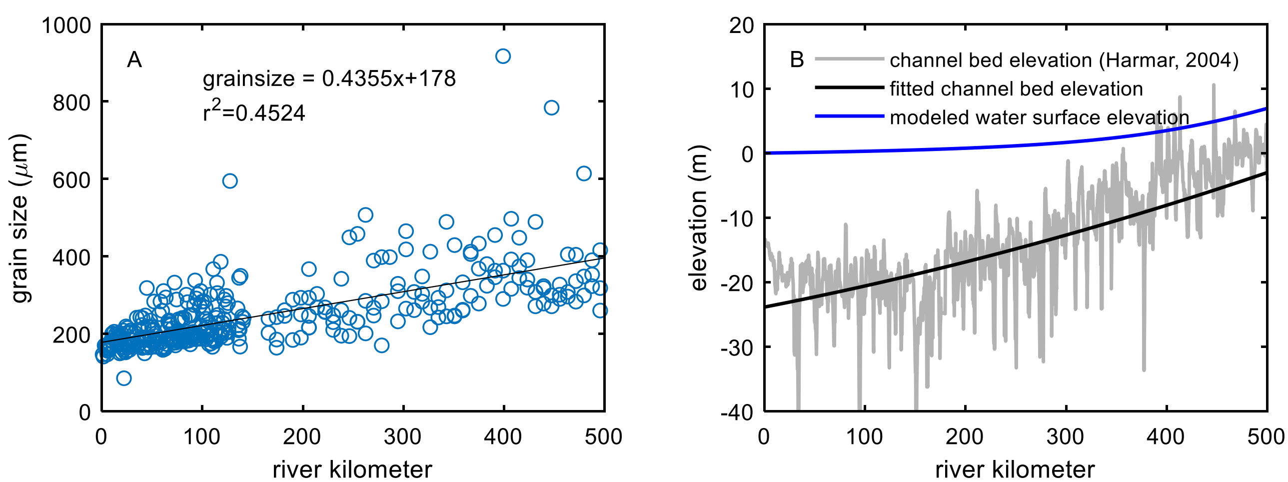

Figure S4. A: Grain size data for the lower 500 km of the Mississippi River collected by the U.S. Army Corps of Engineers (USACE Report 17, 1935). B: Backwater morphodynamic model of the lower Mississippi River. Initial channel bed elevation profile is adopted from Nittrouer et al. (2012) and fitted with a second order polynomial function to generate a smoothed profile.

Flow depth vs backwater control on the dune height in the Lower Mississippi River

It is important to understand what hydraulic information is associated with the formative dunes, before discussing the potential for preserving signals of flow hydrodynamics in cross-strata. For fluvial channels, maximum dune height roughly scales with reach-averaged flow depth (*H*) (for example, $h = 1/6H$ (Yalin, 1964), or $H = 6.96h^{0.95}$ (Bradley and Venditti, 2017)), but may vary by two orders of magnitude (Bradley and Venditti, 2017; Cisneros et al., 2020). However, such a scaling relationship does not hold for the backwater reach of the Mississippi River (Fig. S5A). Most of the dune height data points are scattered through a range of flow depths without any significant trend, as has been found in other large rivers in the world (Cisneros et al., 2020).

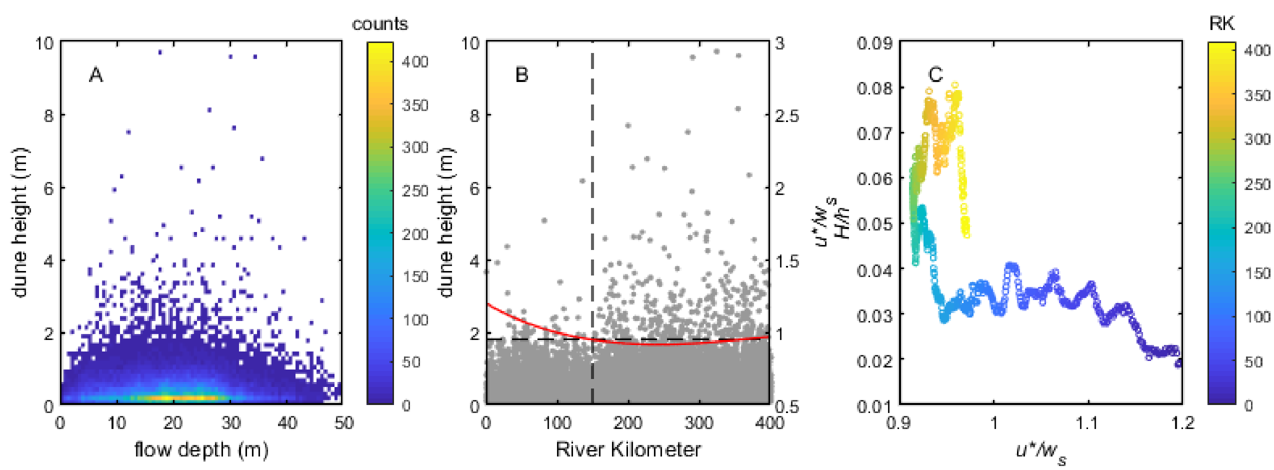

Figure S5. A: Plot of dune height vs flow depth within the backwater reach of the Mississippi River. B: Dune height (grey dots) and calculated suspension number (red line) plotted against river kilometer along the Mississippi River. C: Plot illustrating how relative dune height (*H/h*) decreases as suspension number increases.

To take the hydraulics of backwater flow and grain size of the channel bed into account, the suspension number, defined as the ratio between shear velocity (u*) and settling velocity (w_s) (Karim, 1995), is calculated for a given reach-averaged median channel bed grain size and corresponding reach-averaged flow depth (Fig. S5B). The suspension number is slightly less than 1 from RK 410 to RK 150. Dunes developed in the lower 150 km are associated with u*/ w_s values greater than 1. Field and experimental data show that a u*/ w_s value of 2 corresponds to the hydraulic condition where bedload reaches a significant portion of the total sediment load (Karim, 1995). Based on the analysis for the Mississippi River, the number of larger dunes (with height greater than 2 meters) reduces significantly as the u*/ w_s ratio reaches a threshold value of 1. Similar threshold values have also been reported by Bradley and Venditti (2019), and Ma et al. (*in revision*). This suggests that the decreased bedload and increased suspended load generally reduce dune size downstream over the lower 150 km of the Mississippi River. Moreover, in the lower Mississippi River, the relative dune height (*h/H*) generally decreases from upstream to downstream as u*/ w_s increases (Fig. S5C), suggesting that the backwater hydrodynamics provide a first order control on dune height.

Dune celerity

Dune celerity is estimated using the method of Simons et al. (1965):

$$q_s = \frac{1}{2}hc(1 - \lambda_p), (6)$$

The bed material load, q_s, is calculated using the Mississippi River morphodynamic model. Dune height h (90^{th} percentile of a 10-km average) is used herein since the 90^{th} percentile represents larger dunes developed near the thalweg and thus are more relevant to reach-averaged channel hydraulics.

Influence of anthropogenic activities, specifically dredging, on dune morphology and dynamics

Although dredging is a practiced in the lower Mississippi River, we argue that its impact on the analysis of dune geometry and dynamics in this study are limited if at all existent. Firstly, there were no identifiable features that would indicate the impact of dredging, including burrow pits, in the multibeam data set. Given the relatively short time scale for dredged burrows to be filled (e.g., flood cycle, Yuill et al., 2016), these features are readily filled, or would be identified if recently dredged. Secondly, time scales that dunes equilibrate with flow and topographic conditions is much shorter (e.g., hours, Martin et al., 2013; Bradley and Venditti, 2019) compared to time scales for dredged burrows to be filled, the dunes examined in this study were expected to be in morphological equilibrium with the flow and topographic conditions. Thirdly, while the Mississippi river is “spot dredged”, particularly on the tops of point bars adjacent to the bankline for construction material and accommodating docking of large vessels (Yuill et al., 2016), the impacts of these targeted operations on dune morphology and dynamics is likely to be limited.

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