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Morphodynamic equilibrium of lowland river systems during autoretreat

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ABSTRACT

Lowland river systems (with channel slopes of 10^{-5} to 10^{-4}) inevitably shift away (retreat upstream) from the receiving basin under a sustained rate of base-level rise, even if the system can maintain a period of advance at the onset of rise. This autogenic pattern of transition from progradation to retrogradation through steady base-level rise and sediment supply is termed "autoretreat." Using a morphodynamic model of autoretreat, this study explored the varying channel hydrodynamics of lowland fluvial systems and associated stratigraphic record under sustained base-level rise and constant sediment supply. Results from the numerical simulations show that a fluvial system will reach a state of dynamic equilibrium during autoretreat where both the backwater length and the morphodynamic adjustment of the downdip channel profile become steady. Moreover, when this dynamic equilibrium state is realized, simulated systems display a persistent twofold downstream deepening of flow depth across the backwater zone, a pattern that is also present in many natural systems. In general, backwater effects play a key role in the morphodynamics of a lowland fluvial-deltaic system during autoretreat, and this hydrodynamic condition is therefore critical for predicting river responses to sea-level change.

INTRODUCTION

The morphodynamics of lowland rivers are sensitive to the downstream boundary condition of base-level rise (Blum and Törnqvist, 2000; Parker et al., 2008a, 2008b; Wu and Nittrouer, 2020). It is of value to understand decadal- to millennial-scale morphodynamic responses of rivers to such a forcing mechanism in order to evaluate the economic, ecological, and environmental impacts on human society (Best, 2019) given the current condition of sea-level rise (Wallace and Anderson, 2013). Moreover, this represents a knowledge gap in terms of the linkages between short-term autogenic processes and long-term external forcing mechanisms, and evolving impacts on stratigraphy (Hajek and Straub, 2017; Wu and Nittrouer, 2020).

Current theory has shown that a fluvial-deltaic system progrades and then retrogrades with shoreline retreat under steady external forcing (i.e., constant base-level rise and sediment supply) due to a progressive increase of the surface area of the fluvial-deltaic clinoform (Muto, 2001; Muto et al., 2007, 2016). This autogenic response arises under steady external forcing and is termed "shoreline autoretreat." If the rise of base level persists, a deltaic foreset can be completely abandoned during autoretreat, forming a distinct break (autobreak) in the geometry of a clinoform with an abruptly increasing rate of shoreline retreat (Muto et al., 2007; Parker et al., 2008a). This process is known as sediment-starved (i.e., nondeltaic) autoretreat. During autoretreat, stratal stacking patterns evolve under steady external forcing (i.e., nonequilibrium response), which violates conventional sequence stratigraphic concepts, i.e., that the alluvial profile adjusts only with unsteady external forcing (i.e., equilibrium response; as advocated by Posamentier et al., 1988; Posamentier and Vail, 1988). While existing autoretreat theory clearly demonstrates that a fluvial-deltaic system cannot reach an equilibrium state whereby the alluvial profile becomes steady and fixed, the fact that the evolving alluvial profile becomes steady in its dimension during sediment-starved autoretreat suggests a state of dynamic equilibrium that still is yet to be understood (Muto, 2001; Parker et al., 2008a).

In this study, we sought to understand how the hydraulic conditions, influenced by both autogenic processes and external forcing mechanisms, lead to autoretreat of lowland fluvial systems. We did this by leveraging a fluvial morphodynamic model to simulate this autogenic process and associated patterns of sediment deposition to evaluate the stratigraphic implications. The simulated hydraulic conditions associated with autoretreat were compared with an ensemble of natural rivers.

NUMERICAL MODELING AND RESULTS

We used the numerical methods from Wu and Nittrouer (2020) in this study. These combine the fluvial-deltaic morphodynamic model of Parker et al. (2008a, 2008b) and the grain-size–specific sediment transport relation of Naito et al. (2019) to simulate the impacts to river hydraulics under the condition of constant base-level rise. The ensuing impacts on the autostratigraphic development as a result of the evolving downdip alluvial and deltaic profiles are determined (see the Supplemental Material[1]). We performed 1000 model runs for a range of initial conditions of channel bed slope S (i.e., 4×10^{-4} to 6×10^{-5})

[1]Supplemental Material. Additional details on the numerical model, code availability, and data from natural examples. Please visit https://doi.org/10.1130/GEOL.S.12501923 to access the supplemental material, and contact editing@geosociety.org with any questions.

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and basement slope S_b (i.e., 10^{-5} to 10^{-3}), as are typical of lowland rivers, with values generated by Monte Carlo sampling (see the Supplemental Material). Boundary conditions, including sediment supply (sediment flux q_s of 0.05 m^2/s) and the rate of base-level rise R_{bl} (10 mm/yr), were fixed for the model runs, which were run for a duration of 5000 yr. The first-order estimates of the time and longitudinal alluvial length associated with onset of autoretreat (Muto et al., 2007), which are typically calculated as the autostratigraphic length scale L_a ($L_a = q_s/R_{bl}$) and time scale T_a ($T_a = Sq_s/R_{bl}^2$), were used to nondimensionalize the model results. All model runs showed the development of autoretreat, and 837 runs reached sediment-starved autoretreat.

Key findings from the numerical model are illustrated with the results of one model run ($S = 2 \times 10^{-4}$, $S_b = 10^{-3}$). Stratigraphic development shows initial progradation/aggradation (shoreline advance) and subsequent retrogradation/aggradation (shoreline retreat; Figs. 1A and 1B). The depositional system reaches autobreak, upon which time sediment-starved autoretreat accelerates (Figs. 1C and 1D). This is a well-known shoreline trajectory pattern (Fig. 1D) that characterizes autoretreat (Muto, 2001; Muto et al., 2007). Median grain size of the channel bed fines up-section in the stratigraphy associated with sediment accumulation (Fig. 1E). Flow depth increases downstream, which is a condition characteristic of backwater hydrodynamics (Fig. 1F). The degree of deepening increases through the model run until autobreak, after which flow depth at the river mouth maintains a constant value. Across the time-transgressive flooding surface, grain size fines upstream (Fig. 1E), and flow depth is constant (Fig. 1F). The rate of shoreline migration mostly decreases during the shoreline advance phase and becomes negative at the onset of the shoreline retreat phase (Fig. 2A). The rate of retreat shows an instant eighteen-fold increase (from 2 to 36 m/yr) as sediment-starved autoretreat initiates; it then increases linearly to the end of the simulation. The depositional front (i.e., maximum channel bed aggradation rate) coincides with the shoreline location during the early phase. It then diverges from the shoreline during the retreat phase and eventually migrates upstream simultaneously with the shoreline during sediment-starved autoretreat (Fig. 2B). The calculated backwater length L_b (see the Supplemental Material) of the system increases throughout the simulation, but it plateaus after autobreak (Fig. 2C), when most sediment is sequestered within the alluvial reach (Fig. 2D).

Although the backwater length typically increases in response to sustained base-level rise (Parker et al., 2008b; Moran et al., 2017; Wu and Nittrouer, 2020), herein it is shown for the first time that the increase is not indefinite. The backwater length becomes constant during the sediment-starved autoretreat phase. Together with a steadily retreating shoreline and depositional front (Figs. 2A and 2B), the system evolves into a dynamic equilibrium state during sediment-starved autoretreat. Another line of evidence for a dynamic equilibrium state comes from the fluvial profile. Previous studies have shown that the morphodynamically active reach (i.e., backwater reach in this study) of the fluvial profile becomes similar over time during sediment-starved autoretreat (Parker et al., 2008a), but this effect has rarely been quantified in terms of the degree of similarity. Several statistical methods were run to test this similarity using the detrended channel bed profile (Fig. 3; see the Supplemental Material). First, the root mean square (RMS) of the overall channel bed profile reaches a constant value, suggesting that the total variability (aggradation rate) in overall channel bed profile becomes steady. This result agrees well with the

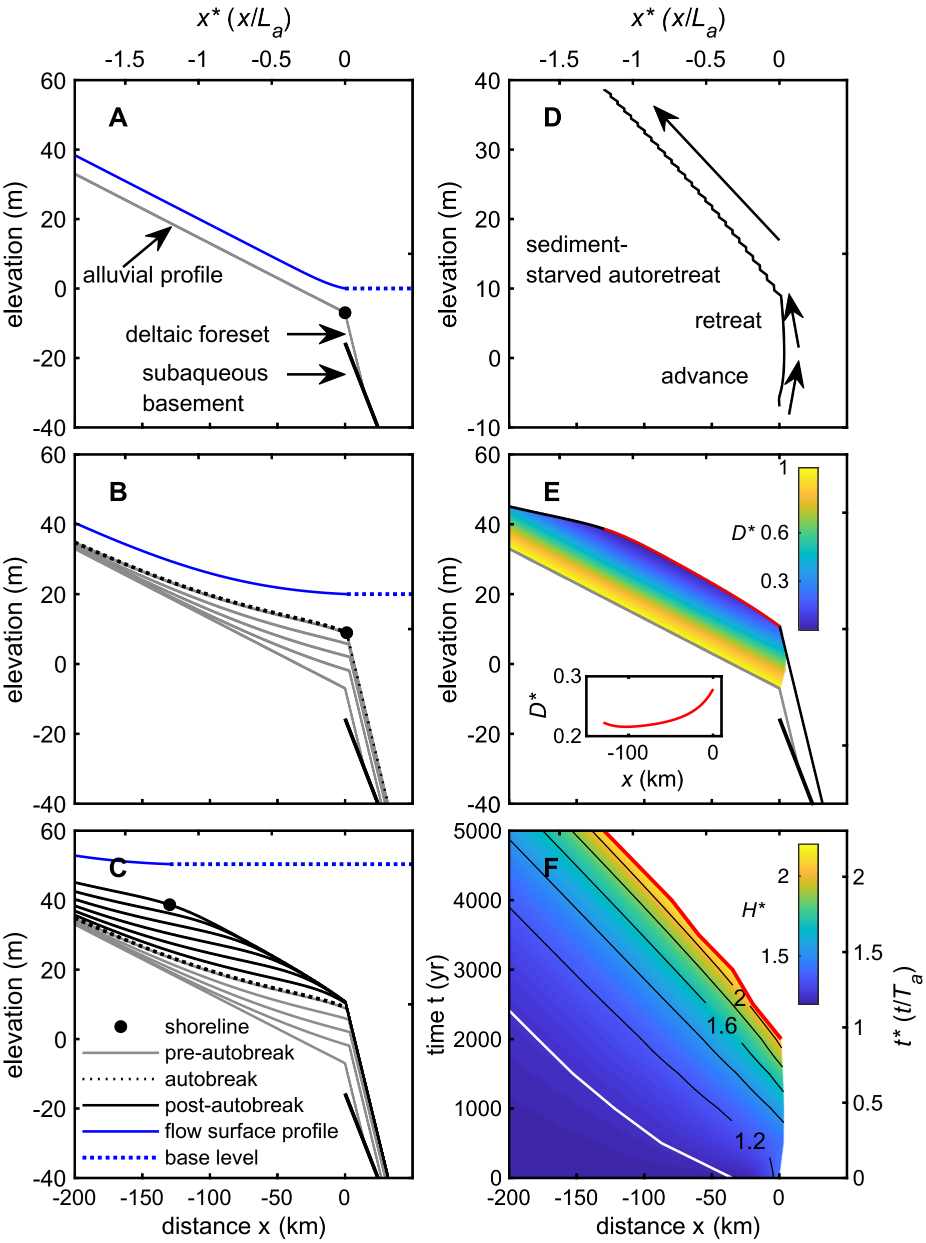

Figure 1. (A) Initial alluvial and deltaic foreset profiles. L_a—autostratigraphic length scale ($L_a = q_s/R_{bl}$ [sediment flux / rate of base-level rise]). (B) Cross-sectional view of the modeled stratigraphy illustrated with downdip profiles of channel bed (alluvial) and deltaic foresets, shown for 500 yr increments before autobreak (alluvial profile marked in gray). (C) Stratigraphic development through sediment-starved autoretreat (alluvial profiles marked in black). (D) Shoreline trajectory. (E) Median grain size (D^*, normalized by initial grain size) of fluvial stratigraphy. Red line marks flooding surface. Inset shows median grain size across flooding surface. (F) Spatial-temporal variability in flow depth (H^*, normalized by uniform flow depth). White solid line marks backwater transition, and red line marks flooding surface. t—time; T_a—autostratigraphic time scale.

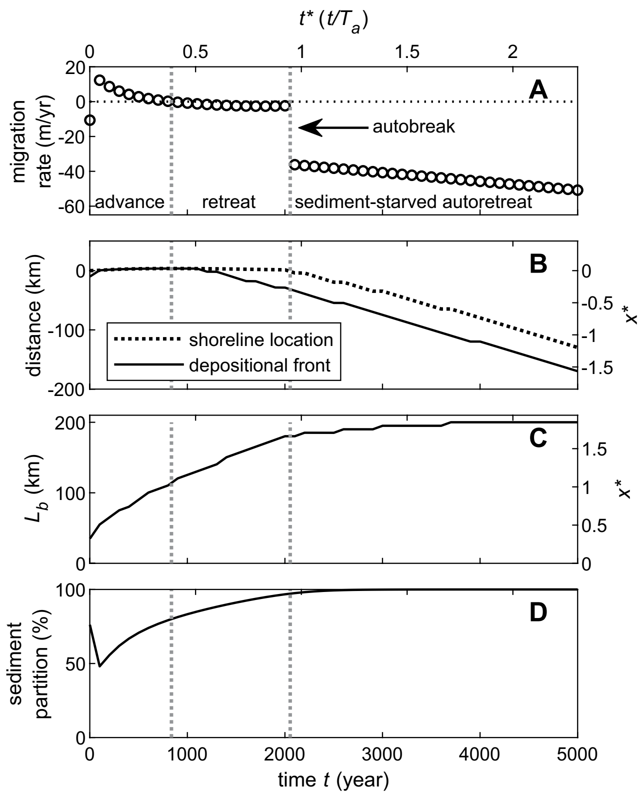

Figure 2. Temporal variabilities in (A) shoreline migration rates (positive values indicate basinward advance, and negative values indicate landward retreat), (B) locations of shoreline and depositional fronts (maximum channel aggradation rates), (C) backwater length, and (D) percentage of sediment sequestered within fluvial reach. T_a—autostratigraphic time scale; L_b—backwater length.

fact that nearly 100% of the sediment supply is consumed within the fluvial reach after the autobreak. Therefore, the average channel bed aggradation at each time step becomes constant because the sediment supply is fixed. Second, the statistical significance of the dynamic equilibrium can be further explored by treating the detrended alluvial profile as a time series, where the cross-correlation between profiles at different time steps can be calculated. The value of

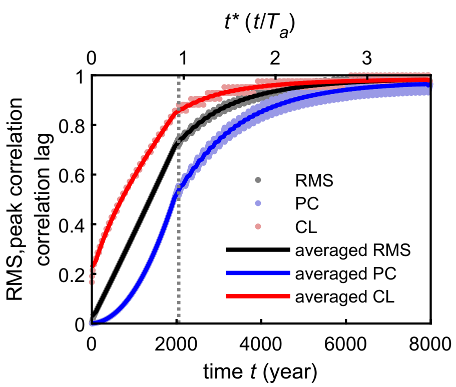

Figure 3. Similarity of river profiles through time. Root mean square (RMS) value of detrended (using initial river slope of 2×10^{-4}) channel profiles measures overall elevation of the channel profile. Peak correlation (PC) measures peak in cross-correlation of the detrended channel bed profile between each time step, and correlation lag (CL) measures the lag in peak correlation. Modeling time period was extended to 8000 yr to better illustrate steady-state behavior. T_a—autostratigraphic time scale.

peak correlation converges to a constant, also indicating that the changes between profiles at successive time steps become steady. A correlation lag represents the displacement of peak correlation (i.e., depositional front) for the detrended channel bed profile at successive time steps. A convergence of the correlation lag to a constant value indicates that the displacement between successive channel profiles becomes steady. This agrees well with the steady upstream shift in the depositional front and shoreline during sediment-starved autoretreat (Figs. 2A and 2B). Therefore, the channel bed becomes steady in profile so that the system can be considered to be in a dynamic equilibrium state, even though the channel bed migrates through time (migrating morphology of permanent form).

DISCUSSION

Previous investigations of autoretreat emphasized the development of the alluvial and deltaic profiles as a function of subaerial and subaqueous bed basement slopes, fluvial slope, and delta foreset slope, where the alluvial/basement transition sets the upstream boundary of the fluvial system (Muto 2001; Muto et al., 2007; Parker et al., 2008a). For lowland systems, the alluvial/basement transition is less likely to show significant adjustment to base-level change, and the upstream boundary of the actively evolving (morphodynamically active) reach of the fluvial system, in the two-dimensional modeling space, is defined by the backwater transition (Wu and Nittrouer, 2020). In lowland systems, the development of different phases in autoretreat is the result of the evolving backwater profile. For example, (1) an increase in the backwater length and an upstream shift in the depositional front cause increased sediment sequestration in the fluvial reach, leading to a retreat phase (Figs. 2B–2D), and (2) as the backwater length establishes a steady value, most of the sediment is trapped in the fluvial reach, and sediment-starved autoretreat is triggered as the delta foreset is abandoned.

In general, the time it takes for a system to reach sediment-starved autoretreat (t_{ssa}) is a function of backwater length and basin slope (Fig. 4A). For a system with a lower channel bed slope (hence, longer backwater length L_b), or a steeper basin floor, more time is required to reach the state of sediment-starved autoretreat compared to the associated autostratigraphic time scale (T_a). Variation of the slope of the basin floor has a similar effect on the morphodynamics of the system to variation in downstream basin depth (Carlson et al., 2018; Wu and Nittrouer, 2020). For example, a system with a steep basin slope requires more time to develop a backwater profile in response to sea-level (base-level) rise, and so the onset of sediment-starved autoretreat is delayed. Moreover, the cases where sediment-starved autoretreat is not achieved during the simulation time frame were all associated with relatively high fluvial slopes (S of 2.6×10^{-4} to 4×10^{-4}, with a mean of 3.4×10^{-4}). This is also the result of a shorter backwater length in systems with steep channel slopes, whereby the sediment supply cannot be completely sequestered within the alluvial reach, and thus progradation of the delta foreset is sustained. This is similar to the effect of a reduced alluvial length during retreat when sediment-starved autoretreat is not realized (Muto et al., 2007).

The hydraulic condition that characterizes the onset of autoretreat can be further evaluated by the degree of backwater-induced downstream deepening of flow depth. Interestingly, the onset of autoretreat corresponds to a downstream flow depth at the river mouth that is about twice the normal flow depth for a given system (Fig. 4B). The degree of downstream deepening of the flow depth associated with autoretreat is consistent across simulated systems with a range of channel beds and basin slopes (Fig. 4B). Flow depth at the river mouth ceases to increase at the autobreak point (Fig. 1F), and the backwater length becomes dynamically invariant (Figs. 2B and 2C). Based on these simulation results, we postulate that a dynamic equilibrium state will be attained if a twofold downstream increase in flow depth across the backwater zone persists. This relation seems to hold for natural systems as well (Fig. 4B). For example, the flow depths of the Mississippi (Nittrouer et al., 2012), Trinity (Smith et al., 2020), Yangtze (Huang et al., 2014), Tombigbee (Dykstra and Dzwonkowski, 2020), middle Fly (Day et al., 2008), and Brazos

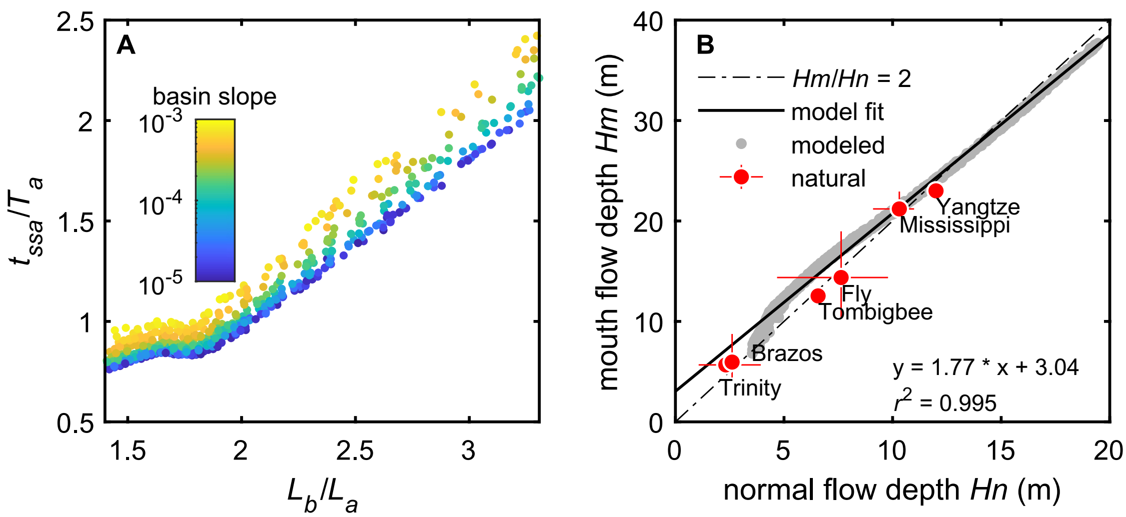

Figure 4. (A) Relation between normalized backwater length (L_b/L_a) and time scale (t_{ssa}/T_a) required for system to reach sediment-starved autoretreat. L_b—backwater length; L_a—autostratigraphic length scale; t_{ssa}—time required for system to reach sediment-starved autoretreat; T_a—autostratigraphic time scale. Color codes represent different basin slopes for 837 simulation cases where sediment-starved autoretreat was achieved. (B) Comparison of flow depths along upstream normal flow reach and downstream river terminus (i.e., river mouth or shoreline break) from model results (gray dots) and modern natural examples (red dots, with error bars as standard deviations). Regression fit (black line) and associated equation and r^2 value are based on simulations from this study. Rivers: Yangtze—China; Mississippi—central USA; Tombigbee—Mississippi and Alabama, USA; Brazos—Texas, USA; Trinity—Texas, USA.

(Carlin et al., 2015) Rivers during low-stage (discharge) conditions show a twofold downstream increase across the respective backwater regions (see the Supplemental Material). These systems have experienced significant base-level rise through the Holocene (Törnqvist et al., 2004; Milliken et al., 2008), and thus they are likely to be close to a state of dynamic equilibrium and thus susceptible to rapid sediment-starved autoretreat under potentially accelerated sea-level rise conditions (Wallace and Anderson, 2013; DeConto and Pollard, 2016).

CONCLUSION

It is critical to understand the morphodynamic responses of fluvial systems during base-level rise in order to evaluate the susceptibility of deltaic retreat under future sea-level rise scenarios. This study shows that under sustained rate of base-level rise, lowland fluvial-deltaic system will retreat, become nondeltaic, and reach a morphodynamic equilibrium state due to a backwater flow condition that is characterized by a twofold downstream increase in reach-averaged flow depth. Besides predicting fluvial response to sea-level rise, the methods presented herein provide a quantitative framework with which to evaluate the impact of environmental boundary conditions (i.e., rate of base-level rise, basin slope, and sediment supply) on stratigraphic patterns, especially for fluvial systems that have experienced retrogradation with the development of flooding surfaces. The methods of this study could potentially be used to better constrain the ancient environmental boundary conditions, which are typically difficult to resolve from the geological record, by minimizing the misfit between model results and field measurements of stratigraphic patterns. This process can provide a basis for understanding deep-time depositional processes and associated geological forcing mechanisms.

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REFERENCES CITED

Best, J., 2019, Anthropogenic stresses on the world's big rivers: Nature Geoscience, v. 12, p. 7–21, https://doi.org/10.1038/s41561-018-0262-x.

Blum, M.D., and Törnqvist, T.E., 2000, Fluvial responses to climate and sea-level change: A review and look forward: Sedimentology, v. 47, p. 2–48, https://doi.org/10.1046/j.1365-3091.2000.00008.x.

Carlin, J.A., Dellapenna, T.M., Strom, K., and Noll, C.J., IV, 2015, The influence of a salt wedge intrusion on fluvial suspended sediment and the implications for sediment transport to the adjacent coastal ocean: A study of the lower Brazos River, TX, USA: Marine Geology, v. 359, p. 134–147, https://doi.org/10.1016/j.margeo.2014.11.001.

Carlson, B., Piliouras, A., Muto, T., and Kim, W., 2018, Control of basin water depth on channel morphology and autogenic timescales in deltaic systems: Journal of Sedimentary Research, v. 88, p. 1026–1039, https://doi.org/10.2110/jsr.2018.52.

Day, G., Dietrich, W.E., Rowland, J.C., and Marshall, A., 2008, The depositional web on the floodplain of the Fly River, Papua New Guinea: Journal of Geophysical Research: Earth Surface, v. 113, F01S02, https://doi.org/10.1029/2006JF000622.

DeConto, R.M., and Pollard, D., 2016, Contribution of Antarctica to past and future sea-level rise: Nature, v. 531, p. 591–597, https://doi.org/10.1038/nature17145.

Dykstra, S.L., and Dzwonkowski, B., 2020, The propagation of fluvial flood waves through a backwater-estuarine environment: Water Resources Research, v. 56, e2019WR025743, https://doi.org/10.1029/2019WR025743.

Hajek, E.A., and Straub, K.M., 2017, Autogenic sedimentation in clastic stratigraphy: Annual Review of Earth and Planetary Sciences, v. 45, p. 681–709, https://doi.org/10.1146/annurev-earth-063016-015935.

Huang, H.Q., Deng, C., Nanson, G.C., Fan, B., Liu, X., Liu, T., and Ma, Y., 2014, A test of equilibrium theory and a demonstration of its practical application for predicting the morphodynamics of the Yangtze River: Earth Surface Processes and Landforms, v. 39, p. 669–675, https://doi.org/10.1002/esp.3522.

Milliken, K.T., Anderson, J.B., and Rodriguez, A.B., 2008, A new composite Holocene sea-level curve for the northern Gulf of Mexico, *in* Anderson, J.B., and Rodriguez, A.B., eds., Response of Upper Gulf Coast Estuaries to Holocene Climate Change and Sea-Level Rise: Geological Society of America Special Papers, v. 443, p. 1–11, https://doi.org/10.1130/2008.2443(01).

Moran, K.E., Nittrouer, J.A., Perillo, M.M., Lorenzo-Trueba, J., and Anderson, J.B., 2017, Morphodynamic modeling of fluvial channel fill and avulsion time scales during early Holocene transgression, as substantiated by the incised valley stratigraphy of the Trinity River, Texas: Journal of Geophysical Research: Earth Surface, v. 122, p. 215–234, https://doi.org/10.1002/2015JF003778.

Muto, T., 2001, Shoreline autoretreat substantiated in flume experiments: Journal of Sedimentary Research, v. 71, p. 246–254, https://doi.org/10.1306/091400710246.

Muto, T., Steel, R.J., and Swenson, J.B., 2007, Autostratigraphy: A framework norm for genetic stratigraphy: Journal of Sedimentary Research, v. 77, p. 2–12, https://doi.org/10.2110/jsr.2007.005.

Muto, T., Steel, R.J., and Burgess, P., 2016, Contributions to sequence stratigraphy from analogues and numerical experiments: Journal of the Geological Society, v. 173, p. 837–844, https://doi.org/10.1144/jgs2015-127.

Naito, K., Ma, H., Nittrouer, J.A., Zhang, Y., Wu, B., Wang, Y., Fu, X., and Parker, G., 2019, Extended Engelund-Hansen type sediment transport

relation for mixtures based on the sand-silt-bed Lower Yellow River, China: Journal of Hydraulic Research, v. 57, p. 770–785, https://doi.org/10.1080/00221686.2018.1555554.
Nittrouer, J.A., Shaw, J., Lamb, M.P., and Mohrig, D., 2012, Spatial and temporal trends for water-flow velocity and bed-material sediment transport in the lower Mississippi River: Geological Society of America Bulletin, v. 124, p. 400–414, https://doi.org/10.1130/B30497.1.
Parker, G., Muto, T., Akamatsu, Y., Dietrich, W.E., and Lauer, J., 2008a, Unravelling the conundrum of river response to rising sea-level from laboratory to field. Part I: Laboratory experiments: Sedimentology, v. 55, p. 1643–1655, https://doi.org/10.1111/j.1365-3091.2008.00961.x.
Parker, G., Muto, T., Akamatsu, Y., Dietrich, W.E., and Wesley Lauer, J., 2008b, Unravelling the conundrum of river response to rising sea-level from laboratory to field. Part II: The Fly-Strickland River system, Papua New Guinea: Sedimentology, v. 55, p. 1657–1686, https://doi.org/10.1111/j.1365-3091.2008.00962.x.
Posamentier, H.W., and Vail, P.R., 1988, Eustatic controls on clastic deposition II—Sequence and systems tracts models, *in* Wilgus, C.K., et al., eds., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publication 42, p. 125–154, https://doi.org/10.2110/pec.88.01.0125.
Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988, Eustatic controls on clastic deposition I—Conceptual framework, *in* Wilgus, C.K., et al., eds., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists (SEPM) Special Publication 42, p. 109–124, https://doi.org/10.2110/pec.88.01.0109.
Smith, V., Mason, J., and Mohrig, D., 2020, Reach-scale changes in channel geometry and dynamics due to the coastal backwater effect: The lower Trinity River, Texas: Earth Surface Processes and Landforms, v. 45, p. 565–573, https://doi.org/10.1002/esp.4754.
Törnqvist, T.E., González, J.L., Newsom, L.A., Van der Borg, K., De Jong, A.F., and Kurnik, C.W., 2004, Deciphering Holocene sea-level history on the US Gulf Coast: A high-resolution record from the Mississippi Delta: Geological Society of America Bulletin, v. 116, p. 1026–1039, https://doi.org/10.1130/B2525478.1.
Wallace, D.J., and Anderson, J.B., 2013, Unprecedented erosion of the upper Texas coast: Response to accelerated sea-level rise and hurricane impacts: Geological Society of America Bulletin, v. 125, p. 728–740, https://doi.org/10.1130/B30725.1.
Wu, C., and Nittrouer, J.A., 2020, Impacts of backwater hydrodynamics on fluvial-deltaic stratigraphy: Basin Research, v. 32, p. 567–584, https://doi.org/10.1111/bre.12385.

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