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Autogenic delta progradation during sea-level rise within incised valleys

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ABSTRACT

Using a simple conceptual model of incised-valley evolution, we show that the classic sequence stratigraphic phenomenon of bayhead deltaic systems can be generated by purely autogenic progradation during the late stage of valley flooding. This transient "auto-advance" event occurs under conditions of constant base-level rise and sediment supply, and it results from a strong decrease of in-valley accommodation as base level rises toward the valley apex. We present a laboratory experiment to illustrate the plausibility of this mechanism and apply it to the incised valleys of the Trinity and Brazos Rivers (Texas, USA) as field case studies. Auto-advance can produce out-of-sequence regressive bayhead diastems during highstands similar to a transient change in allogenic forcing. Combined with other recent studies, our findings support the idea that mesoscale autogenic patterns are ubiquitous in the fluviodeltaic record and need to be more extensively incorporated into reconstructions of Earth surface evolution and reservoir models.

INTRODUCTION

The rates of accommodation creation (*A*, controlled by sea level and subsidence) and sediment supply (*S*, controlled by erosion and sediment transport) are considered to be the two primary drivers of the advance and retreat of sedimentary landscapes (Cross, 1988; Schlager, 1993). In simple terms, the *A*/*S* theory predicts that when sediment supply exceeds accommodation, there is progradation (shoreline advance), and when accommodation exceeds sediment supply, there is retrogradation (shoreline retreat). However, during periods of constant relative sea-level (RSL) rise and sediment supply, and with $A/S < 1$, a retreat of the shoreline eventually occurs despite the progradational conditions predicted by the *A*/*S* ratio concept (e.g., Muto and Steel, 1992, 2001; Muto et al., 2007). This phenomenon is termed "autoretreat" and is a consequence of the way in which sediment is partitioned within the delta as it evolves (Muto and Steel, 1992). Autoretreat is one of a growing list of observations showing that internal feedbacks within the sediment transport system can generate large-scale stratigraphic patterns (Kim and Paola, 2007; Hajek et al., 2010; Tomer et al., 2011; Hajek and Straub, 2017; Trower et al., 2018). These observations call for a reanalysis of several sequence stratigraphic precepts that assume a deterministic relationship between external forcing mechanisms and stratigraphic products.

Here, we present a simple geometric model, physical experiment, and field case study illustrating a significant autogenic progradation phenomenon complementary to autoretreat. By analogy, we term this effect "auto-advance." It occurs within incised valleys as the valley geometry modifies the *A*/*S* ratio during constant sea-level rise. This causes a three-stage stratigraphic product during bayhead delta progradation and an associated updip diastem. The generated facies association is similar to the one putatively produced by a transient allogenic increase in sediment flux or a shift in the relative strength of waves, tides, and rivers in distributing sediment within an incised valley (Zaitlin et al., 1994).

INCISED VALLEYS

During RSL falls, siliciclastic margins can be dissected by a suite of laterally adjacent incised valleys that feed lowstand deltas. These valleys can subsequently be filled during sea-level rise, forming estuary systems (Fig. 1; Zaitlin et al., 1994; Blum et al., 2013). Incised valleys and their fills are important records of landscape dynamics during sea-level cycles, usually associated with retrogradational facies tracts (e.g., Slatt, 2013). However, out-of-sequence bayhead regressive diastems (Fig. 1; Aschoff et al., 2018) are often documented at the transition between alluvial and deltaic environments and near times of maximum flooding.

Bayhead deltas were initially attributed to external factors such as wave action, punctuated sea-level rise, or increases in sediment flux (Thomas and Anderson, 1994; Zaitlin et al., 1994; Holz, 2003; Greene et al., 2007), but they could also result from autogenic processes (Simms and Rodriguez, 2015). Here, we build on this idea and show that bayhead deltas can result from the interplay between sediment supply and the evolving geometry of incised valleys during steady base-level rise to create an autogenic stratigraphic pattern.

GEOMETRIC MODELING

We consider a V-shape incised valley with a height *H*, a horizontal length *Lv*, a width *W*, a valley basal slope α, a lateral slope θ, and an interfluve (or shelf) slope β (with $\beta < \alpha$; Figs. 2A and 2B). The height *H* is divided into *h*, the valley depth at the system's edge, and *hs*, the height between the system's apex and the slope break (Figs. 2A and 2B). The sea-level height, h_R, is the rate of sea-level rise *R* multiplied by the time step *dt*.

While sea level remains below the edge of the incised valley ($h_R < h$), the volume in the valley *V* is:

$$V = \frac{{h_R}^3}{3\alpha\theta}. \quad (1)$$

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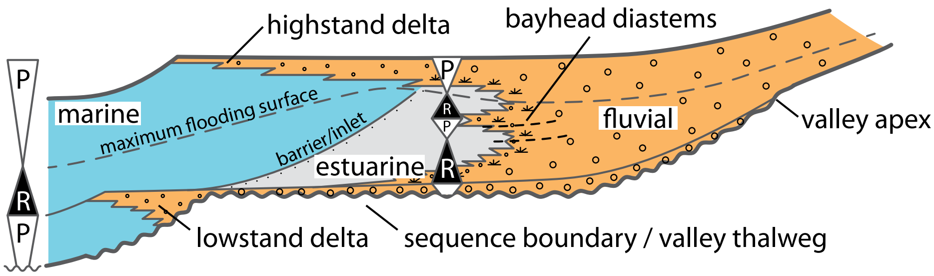


Figure 1. Incised-valley fill model with bayhead diastems and out-of-sequence bayhead progradation at the end of retrogradation (from Zaitlin et al., 1994). P—progradation, R—retrogradation.

When sea level rises above the edge of the valley $h_R > h$), the volume changes to:

$$V = \frac{W}{6Lv}\left(Lv - \frac{h_R - h}{\beta}\right)\left(\frac{h_R}{\alpha} - \frac{h_R - h}{\beta}\right)\left(hs + h - h_R\right). \quad (2)$$

The rate of accommodation creation A is then equal to dV/dt (units: $L^3\ T^{-1}$) and corresponds to the volumetric space available for sediment deposition within the valley at each increment of sea-level rise. Consequently, we also express the rate of sediment supply in three dimensions (units: $L^3\ T^{-1}$).

Under constant S and R, three distinct A/S stages occur during the inundation of the valley (Fig. 2C). During stage 1, A increases (Equation 1) but remains smaller than S ($A < S$). This induces a progradational regime in the lower and distal part of the valley (Fig. 2C) equivalent to the lowstand (wedge) systems tract of classical incised-valley-fill models (Zaitlin et al., 1994). During stage 2 (Fig. 2C), the rate of accommodation creation increases and then decreases as the base-level rises above the shelf edge due to the change in geometry (Equation 2), but A is always larger than S. Deposition within the valley is thus retrogradational as in a classical transgressive systems tract (Zaitlin et al., 1994). During stage 3, A becomes smaller than S, and progradation resumes despite the overall context of RSL rise: This is what we term “auto-advance” (Fig. 2C). By its position in the fill and its progradational character at high RSL, this stage is equivalent to the highstand systems tract. The boundary between stages 2 and 3 would thus be a maximum flooding surface. The progradation predicted here is short-lived with respect to the whole filling sequence as the continuing sea-level rise eventually floods the system and induces marine deposition.

This simple model suggests that under conditions of constant sea-level rise and sediment supply, the deltaic system filling an incised valley could undergo a period of progradation (auto-advance) in the late stage of valley inundation, as a consequence of the prismatic valley geometry. The stratigraphic signature of auto-advance is similar to the one that would result, for example, from a transient increase in sediment supply. In our model, we make the assumption that deposition is restricted to the valley only. However, this assumption might be violated when sea-level rises above the break in slope and inundates the interfluves. To explore how this may limit the applicability of our model, we studied the evolution of incised valley filling during a laboratory experiment.

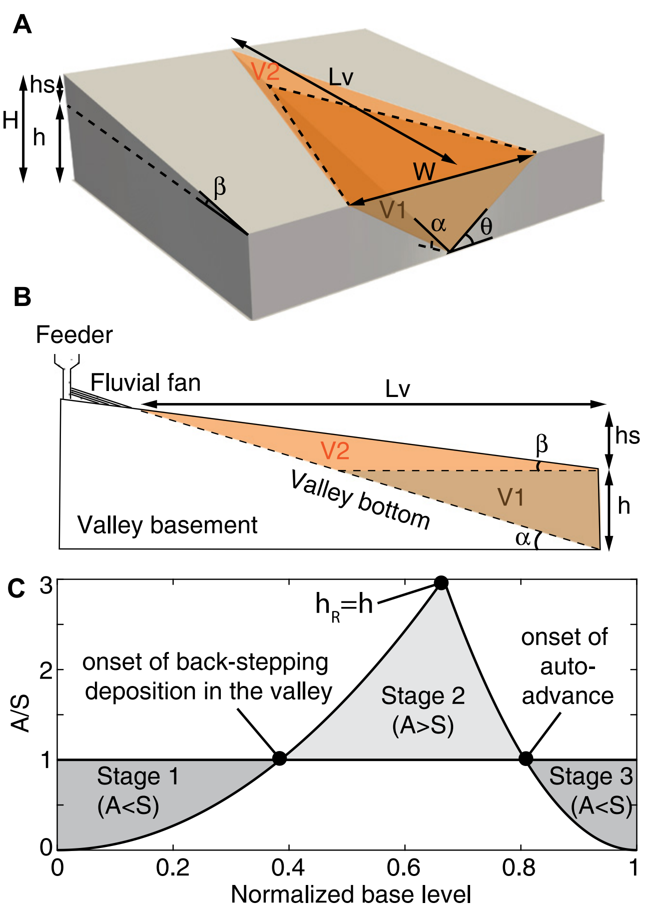


Figure 2. Three-dimensional schematic (A) and cross-section views (B) of incised valley of height *H* (*h* = elevation at slope break, *hs* = height between slope break and valley apex), length *Lv*, width *W*, valley slope α, valley side slope θ, and interfluve slope β. Sea level is h_R. V1 and V2 are the volumes within the incised valley while *h*R < *h* (Equation 1) and while *h*R > *h* (Equation 2), respectively. (C) Ratio of the rates of accommodation creation (*A*) and sediment supply (*S*), *A/S*, in an incised valley filled during constant sea-level rise. Shape of the curve is a function of geometry and rates (see the Supplemental Material; Fig. S1 [see footnote 1]). Three stages may appear: during stage 1, *A* < *S*, and the system progrades. During stage 2, *A* > *S*, and the system retrogrades. During stage 3, *A* < *S*, and the system progrades again despite constant sea-level rise.

PHYSICAL EXPERIMENT

Details and video of our experiment, performed at the St. Anthony Falls Laboratory (University of Minnesota, USA), are presented in the Supplemental Material[1] and are summarized here. The setup consisted of a nonerodible 2.05-m-long V-shape valley with a slope α of 0.06 (Figs. 2A and 2B; Fig. S2 in the Supplemental Material) inserted within a 5 × 5 × 0.6 m tank. Water and sediment discharge were provided at constant rates using a computer-controlled feeder, and constant base-level rise was achieved by raising a computer-controlled weir (Fig. S2A). We used a 50:50 mixture of quartz (white) and anthracite coal (black) grains to simulate the coarse and fine fractions of the sediment load, respectively. Base level in the tank was set at the base of the valley outlet (“lowstand”) at the beginning of the experiment. The experiment ended once the entire fan-valley system was flooded after a total run time of 130 min. We extracted the position of the coarse-grained delta front from orthorectified images taken every minute throughout the experiment (Fig. 3).

During stage 1, a fluvial fan developed at the proximal feeder with sheet-flow–dominated channels. Sediments not deposited in the fluvial fan were transported outside the incised valley and built a prograding, lowstand delta fan (Fig. S2B). During stage 2, sediment largely bypassed the proximal fluvial domain and built

[1]Supplemental Material. Three supplemental figures, one table, and supplemental text. Please visit https://doi.org/10.1130/GEOL.S.13046516 to access the supplemental material, and contact editing@geosociety.org with any questions.

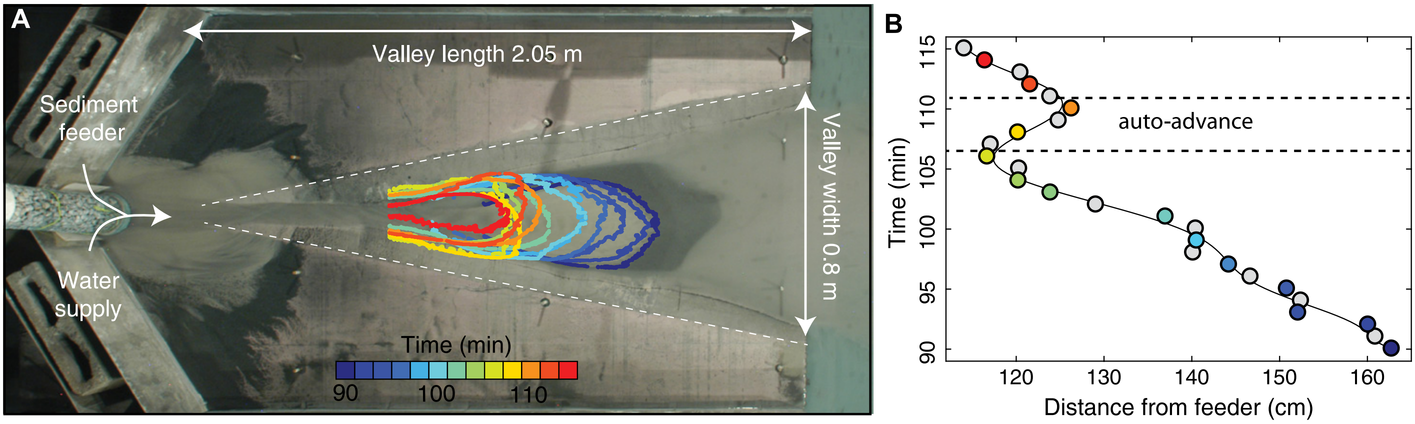


Figure 3. (A) General experiment setup seen from above, and the position of the coarse-grain delta. (B) Trajectory of the coarse-grain delta front between 90 min (dark blue) and 124 min (red). Colored dots correspond to the delta-front position mapped in panel A.

a back-stepping delta confined within the valley. We thus observed a landward migration of the delta front shoreline (Fig. 3; Fig. S2C). During stage 3, the delta was still confined to the valley, but the rate of accommodation creation decreased and eventually became smaller than the sediment supply. As a consequence, auto-advance occurred, and the delta front prograded on the top of previous back-stepping strata (Fig. 3; Fig. S2D). Overall, the patterns observed over the course of this experiment replicated those predicted by the geometric model (Supplemental Material; Fig. S3). The delta did not prograde enough to cover the whole valley, and after this transient advance, the delta retrograded, and the whole system was rapidly flooded (Fig. 3; Fig. S2E). Eventually, the sea level flooded the shelf, and our model was no longer applicable as accommodation was no longer restricted to the incised valley.

FIELD CASE STUDY

We then modeled the Quaternary Trinity River (TR) and Brazos River (BR) incised valleys near Houston, Texas, USA (Fig. 4A). Both systems have roughly similar incised valley length, width, and depth scales (Table S1) and have experienced the same sea-level and climatic history over the past several tens of thousands of years (Rehkemper, 1969; Rodriguez et al., 2005; Simms et al., 2006; Taha, 2007; Milliken et al., 2008). The BR valley exclusively contains amalgamated fluvial deposits along its length (Fig. 4B). In contrast, within the TR valley, the lithologic succession is more diverse, with fluvial facies overlain by a distinct flooding surface, then a progradation bayhead delta lithofacies, and then an estuarine basin mud facies, followed by a progradational bayhead delta in proximal areas of Trinity Bay and a flood-tidal delta unit in the distal portions (Simms et al., 2006; Anderson et al., 2015). This succession captures the overall transgression and infilling of the valley during Holocene sea-level rise (Figs. 4C and 4D).

We applied our geometric model to both incised valleys to see if it was able to capture these differing first-order stratigraphic patterns. We did not seek to reproduce the exact patterns of deposition, which would require a full three-dimensional reconstruction of the incised valleys, including the nuances of the fluvial terraces within the valleys (Fig. 4C), which is currently not available. We calculated A from Equations 1 and 2 and used published values for S (Table S1).

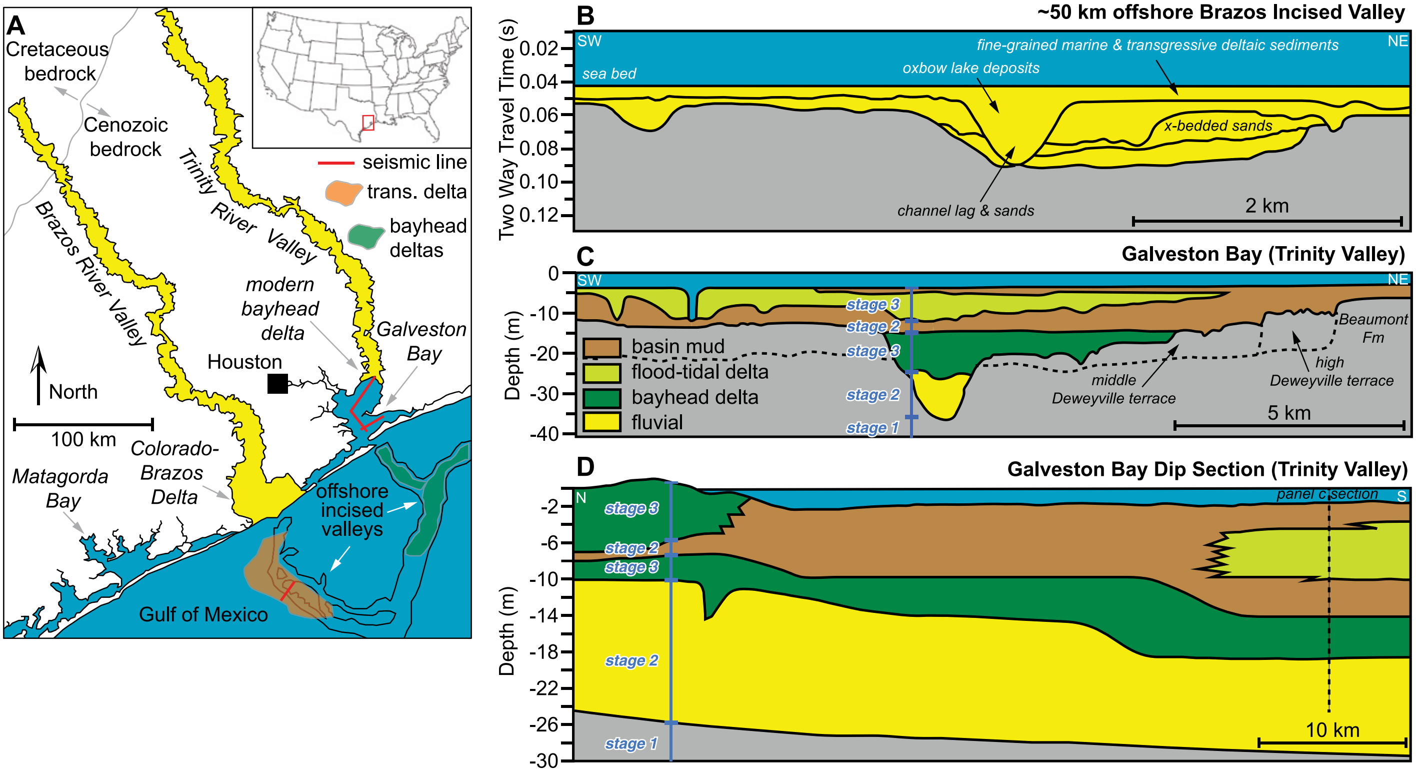
Our geometric model captured the first-order stratigraphic patterns within both incised valleys. Using constraints on the model from the field, the BR valley case study indicates that sediment supply is always larger than accommodation, resulting in an incised valley filled with fluvial units only (Fig. 4E). In contrast, the TR valley model displays an A/S pattern that predicts the occurrence of auto-advance (Fig. 4F). The modeled stage 1 (lowstand wedge deposition) is ~35 m thick and not recorded within the valley (as observed during our experiment). Stage 2 (retrogradation) is predicted to be up to 20 m thick, and stage 3 (auto-advance and bayhead delta formation) is predicted to occur after 10–15 k.y. of sea-level rise and to be ~50 m thick.

The major departure between our model and field observations in the TR valley is the presence of two Holocene back-stepping bayhead deltas (Fig. 4D; Anderson et al., 2016), rather than a single one as the model predicts. This comes from the simplified geometry we used for the valley, which contained just one interfluve, comparable to the terrace associated with the Pleistocene Beaumont Formation. In fact, several bayhead deltas within the TR valley have been attributed to punctuated sea-level rise, transient sediment shifts, and/or antecedent topographic controls on bay flooding rate (Thomas and Anderson, 1994; Rodriguez et al., 2005; Simms and Rodriguez, 2014). However, the co-occurrence of the bayhead delta with the tops of Deweyville alluvial terraces, which formed during marine oxygen isotope stages (MIS) 4–3 relative sea-level fall and MIS 2 lowstand within the Trinity incised valley, led Rodriguez et al. (2005) to propose an autogenic origin. Our model provides a possible mass-balance mechanism behind this autogenic origin, with the Deweyville terraces acting as interfluves.

IMPLICATIONS

Understanding the evolution of incised valleys is critical in developing predictive, source-to-sink sequence stratigraphic models (Aschoff et al., 2018; Simms et al., 2018). Many incised-valley systems are filled with transgressive-regressive sediment wedges interpreted as a nearly complete depositional sequence responding to RSL rise followed by highstand conditions (e.g., Allen and Posamentier, 1993). However, it is clear from our analysis and previous work (e.g., Rodriguez et al., 2005) that valley morphology must be taken into account if sea-level curves reconstructed from incised-valley deposits are to be interpreted accurately. For a given basin geometry and sediment/water discharge condition, "slow" sea-level fall might produce a relative wide and shallow incised valley with relatively minimal topographic expression, whereas the opposite is predicted for "fast" sea-level fall (Strong and Paola, 2008). Because auto-advance is a function of in-valley accommodation, we predict that fast sea-level fluctuations favor the occurrence of auto-advance by favoring rapid change in accommodation while incised valleys are being filled. This is the case for bayhead deltas formed where coastal plains and shelves act as interfluves, but also within the incised valley itself. Slow sea-level fall is expected to minimize alluvial terrace formation within the incised valley, reducing the available "nucleation" sites for progradational bayhead deltas during the subsequent sea-level rise.

Our analysis suggests that bayhead deltas and their paired flood-tidal and barrier complexes may as well result from autogenic events related to the interplay of accommodation and sediment supply (auto-advance) as from enhanced tidal and wave action due to sea-level



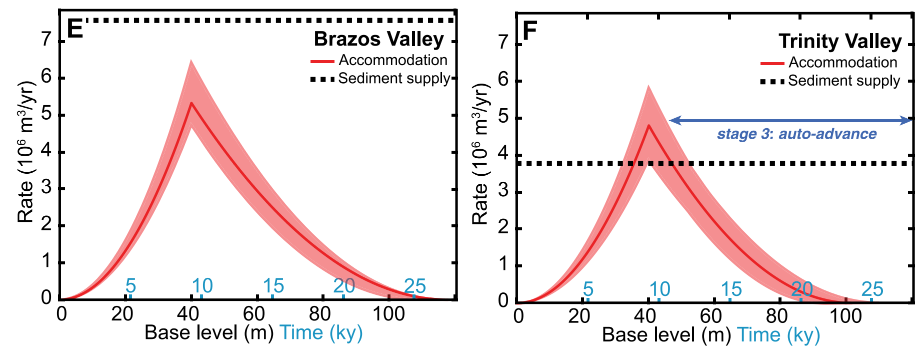


Figure 4. (A) Study area in Texas Gulf Coast (USA). Trinity River mouth is located at 29°20.58′N, 94°42.88′W; Brazos River mouth is located at 28°56.18′N, 95°17.99′W. (B) Cross section of Brazos River Valley (x-bedded—cross-bedded). (C) Cross section and (D) dip section of the Trinity River valley (modified from Simms et al., 2006; Anderson et al., 2008) showing possible stages defined from our model. Locations of sections are indicated in panel A (red). (E,F) Model outputs for the Brazos and Trinity systems, respectively, with auto-advance time window for the Trinity River indicated.

inundation (e.g., Zaitlin et al., 1994) or from increased sediment flux. Probabilistic methods could be used to assess whether the bayhead delta is more likely to have resulted from one mechanism or the other (e.g., Burgess and Steel, 2017). Auto-advance could occur if geometric conditions are right (see the Supplemental Material; Fig. S1), perhaps enhanced by the existence of a barrier complex and/or by autogenic behaviors involving backwater dynamics during sea-level rise (Moran et al., 2017). Importantly, the pertinent parameters for development of bayhead deltas can be estimated for paleo–case studies and provide additional constraints on sequence stratigraphic reservoir models.

Our finding provides more evidence that geometry and mass-balance interactions play a major role in dictating large-scale stratigraphic patterns and overall sensitivities of sediment transport systems. These phenomena appear ubiquitous enough to warrant consideration of autogenic controls on stratigraphy at the outset of any stratal analysis. Deltaic auto-advance, autoretreat, and backwater dynamics as well as fluvial sand-body clustering impart structure on the stratigraphic record that is, in part, deterministic in nature (Toby et al., 2019; Burgess et al., 2019; Straub et al., 2020). Without recognizing autogenic processes, this stratigraphic variability can be misinterpreted via inaccurate externally forced models for reservoirs and incorrect reconstructions of boundary conditions (i.e., climate, tectonics, and/or eustasy).

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