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Upstream Propagation of Sea-Level Signals in Fluvio-Deltaic Environments : Time-Lags, and the Dynamics of the Fluvial Surface

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Abstract

The sedimentary record of fluvio-deltaic environments holds clues to past climate and sea level change. Although theories for stratigraphic interpretation generally rely upon the assumption that the fluvial surface responds uniformly to sea level changes, recent theoretical work suggests that changes in the relief and concavity of the fluvial surface can influence the propagation of sea level information upstream, and result in geologically long-lived lags in the system response. We test this theoretical result using measurements from an evolving experimental delta subject to sea-level cycles. As predicted by the theoretical results, during sea-level fall the relief increases and the fluvial surface curves concave down, whereas during sea level rise the relief decreases and the fluvial surface curves concave up. Although the changes in relief and concavity of the fluvial surface are subtle, these dynamics result in the upper portion of the profile being out phase by approximately half a period with respect to changes in sea level, whereas the nearshore region is in phase. Overall, these results suggest that changes in the upper portion of the fluvio-deltaic surface do not necessarily reflect synchronous changes in sea level, which has implications for the reconstruction of the paleo sea level record.

MONTCLAIR STATE UNIVERSITY

Upstream propagation of sea-level signals in fluvio-deltaic environments: time-lags, and the dynamics of the fluvial surface

by

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Acknowledgments

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Particular thanks to the Tulane Sediment Dynamics and Quantitative Stratigraphy Group, who conducted the experiment, and collected the data I use in my analysis.

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1. Introduction

Fluvial deltas are dynamic features of the world's coastlines, home to over 300 million people, and particularly vulnerable to flooding, and sea level rise due to their low lying topography (Edmonds et al. 2020). Additionally, their subsurface architecture holds clues to past allogenic (external) forcing signals, such as variations in relative sea-level, sediment supply, or tectonics that can potentially be reconstructed from stratigraphy (Paola 2000; Catuneanu et al. 2009; Hajek and Straub 2017; Blum and Törnqvist 2000; Blum et al. 2013). In particular, since sequence stratigraphy was developed in the 1970's, sea-level variations have often been described as the main allogenic forcing that influences the stratigraphic architecture of coastal-plain transport systems (Vail et al. 1977; Van Wagoner et al. 1990; Van Wagoner 1995; Catuneanu et al. 2009; Blum et al. 2013). An idealized version of these systems in cross-section includes a basement, on top of which the sedimentary prism evolves, and the topset or fluvial surface and the subaqueous foreset, which are separated by the shoreline (Figure 1A). Based on a similar geometric configuration, sequence stratigraphy assumes that periods of sea-level fall are linked to a seaward shift (i.e., regression) of the depositional environment, which involves a uniform lowering of the fluvial surface elevation (Figure 1B). In contrast, periods of sea-level rise are linked to a landward shift (i.e., transgression) in depositional facies with enhanced sediment deposition along the fluvio-deltaic plain (i.e., aggradation) (Figure 1C). Although these studies provide a broad conceptual framework for evaluating ancient deposits and inverting stratigraphic successions for basin-filling histories, a number of modeling and experimental studies during the past decades suggest that periods of sea-level fall are not necessarily erosional and periods of sea-level rise are also not necessarily depositional (Blum and Price 1998, Holbrook 2001, Strong and Paola 2008, Lorenzo-Trueba et al. 2013, Li et al. 2016, Anderson et al. 2019).

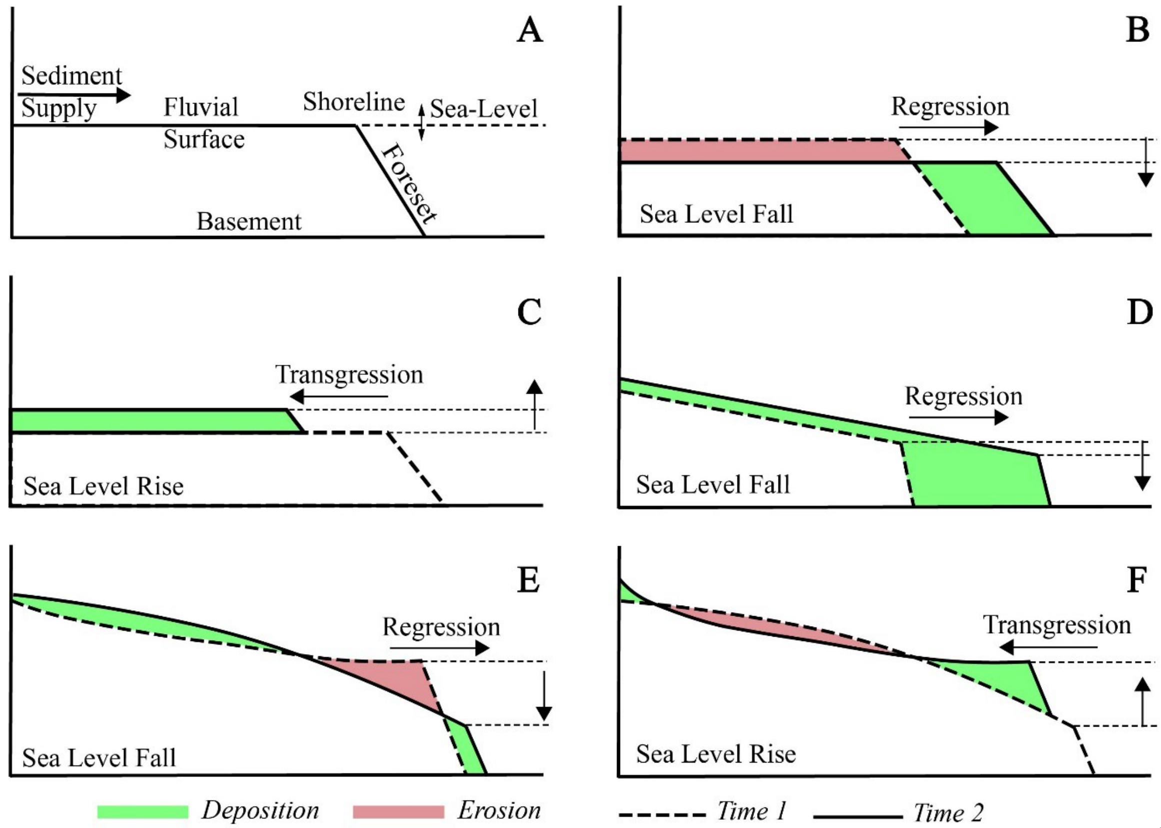

Figure 1 A) Schematic of an ideal longitudinal cross section of a delta, including key processes and domains. B) Delta with a negligible fluvial surface slope under sea-level fall. C) Delta with a negligible fluvial surface slope under sea-level rise. D) Delta with a sloped fluvial surface under sea-level fall. E) A non-linear fluvial surface depicted under sea-level fall. F) A non-linear fluvial surface depicted under sea-level rise.

Patterns of erosion and deposition of the fluvio-deltaic surface are a function of not only allogenic factors, but also autogenic (internal) factors (Paola et al. 2009, Hajek and Straub 2017), that complicate the dynamics presented in Figures 1B and 1C. For instance, a high sediment supply relative to the length of the fluvial surface and the change in accommodation associated with sea-level fall can result in a geologically long-lived aggradation of the fluvio-deltaic surface before the fluvial surface begins to degrade (Figure 1D). This result is supported by both theoretical and laboratory flume experimental efforts (Swenson 2000; vanHeijst and Postma 2001, Swenson and Muto 2007, Lorenzo-Trueba et al. 2013). Additionally, recent numerical efforts (Lorenzo-Trueba et al. 2013; Anderson et al. 2019) show that changes in the concavity and relief of the fluvial surface under sea level cycles can result in contemporaneous erosion and deposition along the fluvial surface during either sea-level fall (Figure 1E) or sea-level rise (Figure 1F). In particular, these numerical results suggest that these changes in the geometry of the fluvial surface can lead to an asynchronous response of the upper portion of the fluvial surface, including geologically long-lived erosion during sea-level rise (Figure 1F). Here, we aim to validate these theoretical results with flume experimental data from the Tulane Delta Basin (Li et al. 2016; Yu et al. 2017), which provided sufficient spatial and temporal resolution to quantify the geometric changes of the fluvial surface under sea level variations and the associated timelags in the system's response.

2. Upstream Propagation of the Sea-Level Signal

In order to quantify the dynamics of the fluvial surface under sea-level cycles we analyzed a flume experimental data set (Li et al. 2016; Yu et al. 2017) wherein a fluvial delta evolved under two sea-level cycles: Low Magnitude, Long Period (LMLP), and a High Magnitude, Short Period (HMSP) (Figure 2B) both superimposed on a background sea-level rise rate of 0.25mm/hr. The LMLP scenario had a sea level cycle period that lasted 98 hours, with an amplitude of 3.06mm, while the HMPS had a sea level cycle period that lasted 24.5 hours, and an amplitude of 12.25mm. Sediment (quartz dominated) and water input were held constant at the respective rates of 3.9 x 10^{-4}kg/s, and 1.7 x 10^{-4}m^3/s, and entered the basin via a weir. The experiment was well documented with photographs taken every 15 minutes (Figure 2A), and a laser scanner gathered topographical information every hour. This topographical information was then converted into a digital elevation model (DEM) that we used to observe how the fluvial surface changed with time, initially focusing on the HMSP scenario in which the dynamics of the fluvial surface are more pronounced, and in a later section we analyze the LMLP scenario.

We took the strike-averaged profile using the DEM (Figure 2C) (A2 and A3) in order to limit the influence of autogenic processes such as channel avulsions. In Figure 2D we indicate the elevation residuals over time after removing the background sea level rise rate (A2) at three locations on the fluvial surface (Figure 2D). Despite some variability associated with changes in channel characteristics, such elevation changes demonstrate that the entire fluvial surface responds non-uniformly to sea level variations, and the strength of the sea-level signal is mildly reduced towards land (Figure A1.1). In particular, the location in the downstream follows changes in sea level, whereas the location in the upstream reflects changes in sea level roughly half a sea level period later, increasing in elevation as sea-level falls and decreasing as sea-level rises. We found this lag in the response of the upstream elevation change in both the sea-level fall and sea-level rise phases of the experiment, supporting previous theoretical results (Swenson 2005; Lorenzo-Trueba et al. 2013; Anderson et al. 2019). We quantified the lag across the entire strike averaged fluvial surface by cross correlating the residual elevation changes throughout the profile with the sea level curve (A3). We found that the timelag across the strike averaged profile increases towards the upper portion of the fluvial surface reaching a maximum value of ~11 hours, roughly half of the sea-level cycle period (Figure 2E).

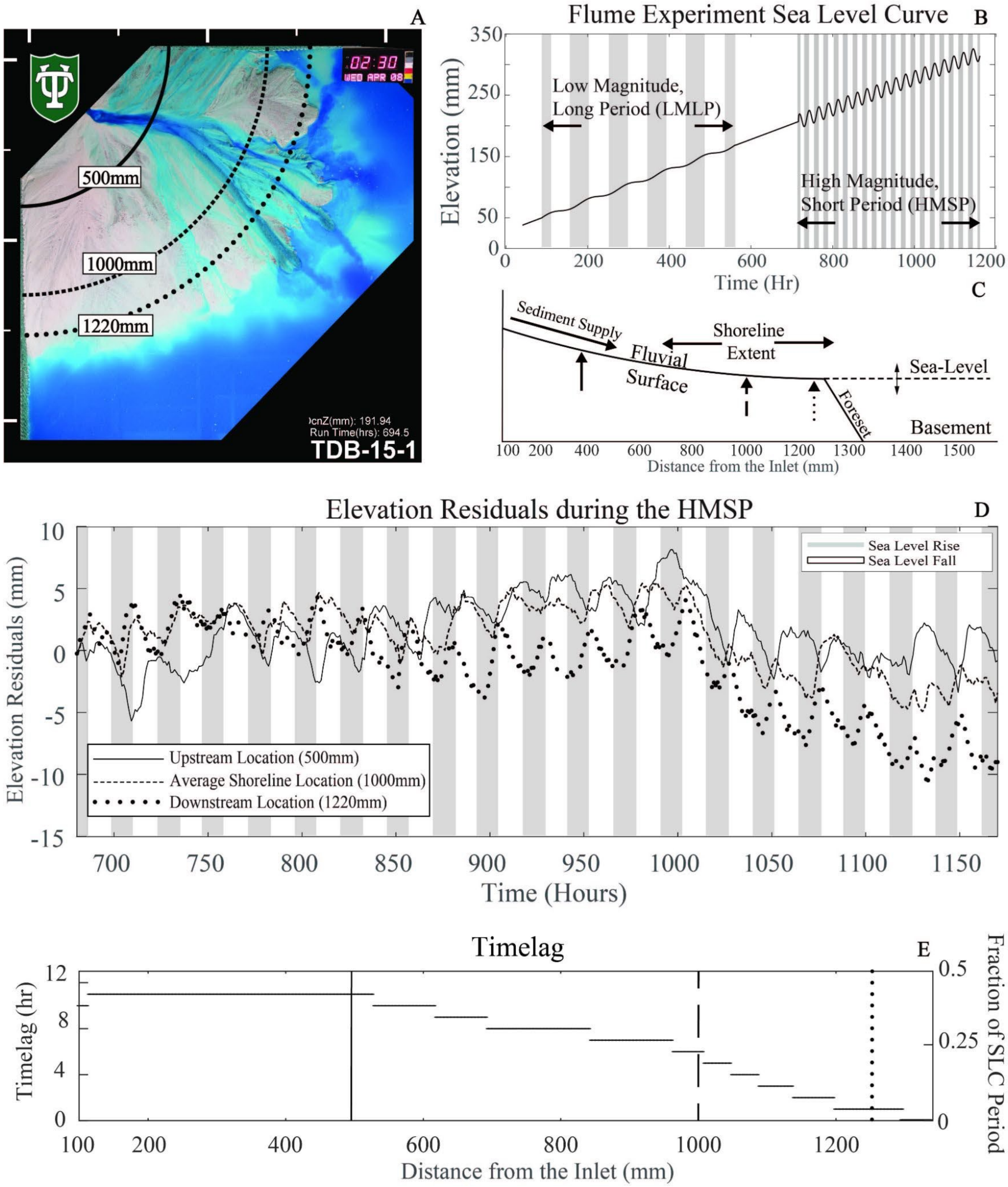

Figure 2 A) Plan view of the experimental delta showing the three locations used in this analysis indicating their associated distance measured from the inlet. B) Experimental sea level curve depicting the two stages of sea level change. C) Idealized diagram of the delta in cross-section. D) Plot of the change in elevation overtime at the three locations from 2A under the HMSP. E) Time-lag across the fluvial surface. Left y axis corresponds to the timelag in hours. Right y axis: the approximate fraction of a sea level cycle (SLC).

3. Fluvial Surface Dynamics Under High Magnitude Sea Level Oscillations

In this section we quantify changes in the geometry of the fluvial surface in terms of the average slope and concavity. We calculated the average slope S of the fluvial surface by dividing the relief R of the profile by the length L (i.e., $S=R/L$) (Figure 3A and 3B). We estimated the concavity of the profile δ as the ratio of the area difference between the strike averaged profile area and the linear profile area divided by the length of the profile (i.e., $\delta = Area/L$) (Figures 3A and 3B). Therefore, a concave down profile corresponds to a negative δ value (Figure 3B), and a concave up profile corresponds to a positive δ value (Figure 3A).

Our analysis reflected the expected dynamics throughout the experiment, with the average slope and concavity of the fluvial surface changing as a function of sea level (Figures 3C and 3D). The average slope S decreases during sea-level rise, reaching a minimum at the highstand, and increases during sea-level fall, reaching a maximum at the lowstand. The concavity metric δ increases during sea-level rise and decreases during sea-level fall, reaching local maxima and minima at the highstands and lowstands as well. Moreover, the patterns of sedimentation over the sea-level rise and sea-level fall phases are consistent with such shifts in concavity (Figure A1.2). These results are supportive of the numerical modeling results presented by Lorenzo-Trueba et al. 2013 and Anderson et al. 2019, and highlight the importance of changes in the geometry of the fluvial surface under sea level cycles, which in turn provide a mechanistic explanation for the lag in the response of the upstream region.

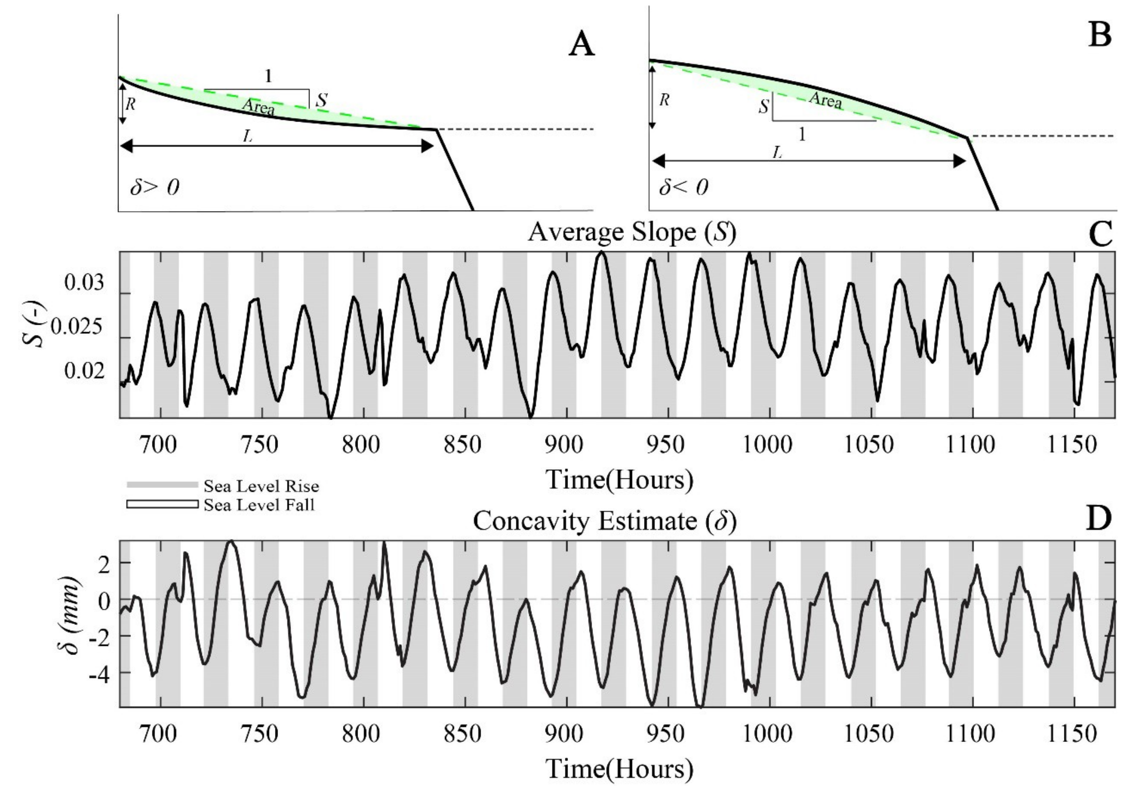

Figure 3. A) Schematic of a concave up profile. R is the relief (difference in elevation between the inlet and the shoreline) of the fluvial surface, S is the slope, and L is the length of the fluvial surface. The dashed green line represents the idealized linear fluvial surface. B) Schematic of a concave down profile. C) Average slope of the fluvial surface through time in the HMSP. D) Concavity estimate of the fluvial surface through time in the HMSP.

4. Fluvial Surface Dynamics Under Low Magnitude Sea Level Oscillations

Our analysis of the HMSP in previous sections supports that changes in the slope and concavity of the fluvial surface are driven by changes in sea level. Although, these dynamics are not so obvious for the LMLP scenario, in which the amplitude of the sea level oscillations is lower and changes in channel flow characteristics play a larger role (Yu et al. 2017), we were able to identify a sea level signal along the fluvial surface (Figure 4).

Similar to our analysis of the HMSP scenario, we examined the change in elevation residuals (i.e., elevation minus the background sea-level rise rate) overtime across the fluvial surface (Figure 4A). During sea-level fall, the elevation residual in the upstream location is more likely to increase whereas the elevation residual in the downstream is more likely to decrease

(Figure 4B). In contrast during the sea-level rise phase, the elevation residual in the downstream is more likely to follow sea level and increase, while the elevation residual in the upstream is more likely to decrease than increase. Both the changes in average slope (Figure 4D) and the changes in concavity (Figure 4F) through time are also consistent with our finding for the HMSP, and with recent numerical modeling results (Lorenzo-Trueba et al. 2013 and Anderson et al. 2019). That is, during sea-level rise the fluvial surface typically decreases in slope, and changes into a more concave up profile (i.e., δ increases). As sea-level falls, the profile steepens and shifts to concave down (i.e., δ decreases).

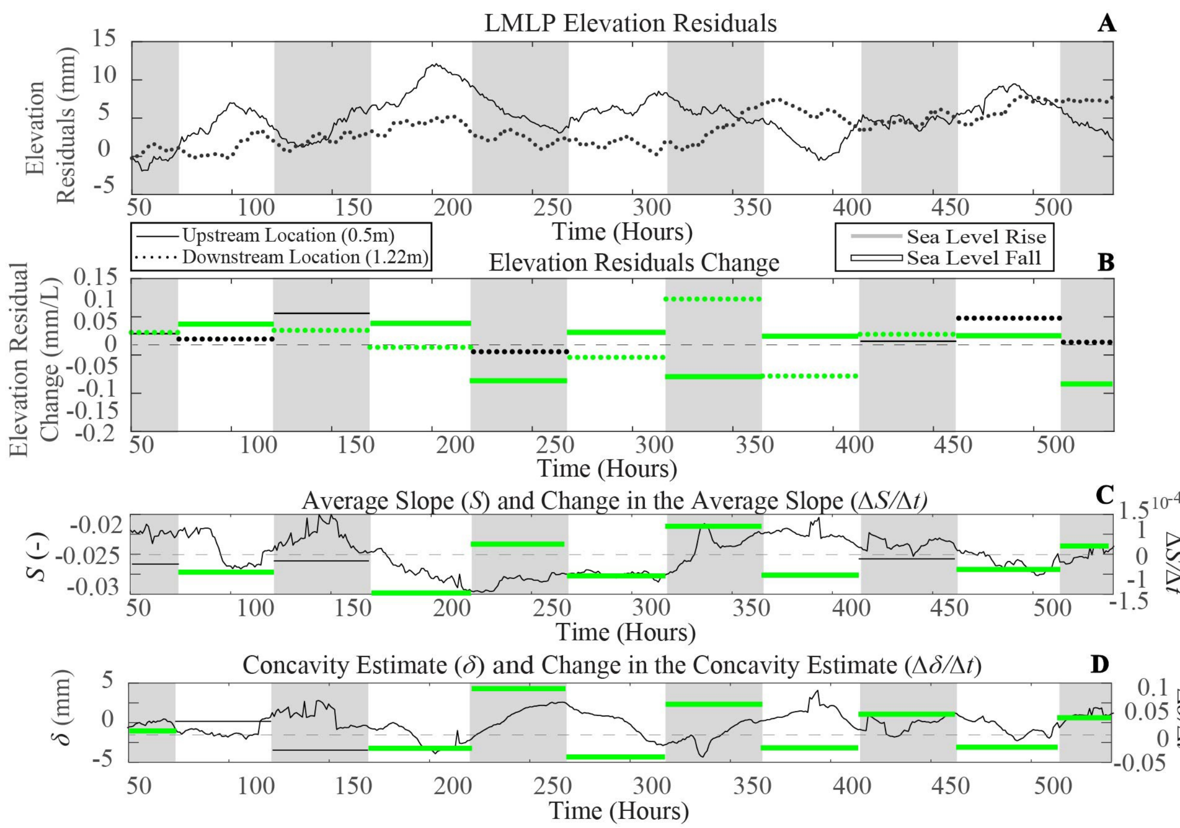

Figure 4. A) Change in residual elevation overtime at the two end member locations from 2A under the LMLP. B) Average residual elevation changes for the two locations in each sea level phase (i.e., rise and fall). C) Left y axis: Average slope of the strike averaged fluvial surface through time in the LMLP. Right y axis: Average slope change rate in each sea-level phase (ΔS/Δt). D) Left y axis: Concavity estimate of the fluvial surface through time in the LMLP. Right y axis: Average concavity change rate in each sea level phase (Δδ/Δt). For panels B, C, and D the green color represent the periods of the experiment in which the expected dynamics of the fluvial surface associated with sea-level changes based on theory are detected.

5. Discussion and Field Implications

One important time scale identified in relation to the response of river systems to sea-level cycles is the equilibrium time, defined as:

$$TT = \frac{LL^2}{vv} \qquad (1)$$

where LL is a characteristic length scale and vv is the diffusion coefficient (Paola et al., 1992). Following numerous numerical modeling and laboratory experimental efforts (Paola 2000; Swenson and Muto, 2007; Postma et al., 2008; Lorenzo-Trueba et al. 2009), we can estimate the fluvial diffusivity vv as a function of the volumetric water discharge per unit width q_w. Here, for simplicity we assume a linear relationship as follows: $vv = kk \cdot qq_{ww}$, with a representative value for kk approximately equal to 1 (Swenson et al. 2000; Lorenzo-Trueba et al. 2009). In the flume experiment, assuming a flow width of ~1m (i.e., $qq_{ww} \sim 1.7 \cdot 10^{-4} mm^2/ss$), and a length scale for the flume experiment of LL~2m, we can estimate the time scale of response to be approximately 7 hours. This back of the envelope calculation suggests a time scale of response that is in the same order of magnitude than the timelag estimated for the HMSP portion of the flume experiment. If we change the length scale and water discharge to have values that better represent field scales the time scale of response can cover a wide range of values to an excess of 1,000 kyr (Metivier and Gaudemer 1999; Swenson et al. 2000; Castelltort and Van Den Driessche 2003; Swenson 2005; Anderson et al. 2019), suggesting that many fluvio-deltaic systems do not fully equilibrate to sea-level perturbations at Milankovitch time scales, which have been shown to drive cyclic global changes in ice volume and sea level over ~100 kyr rhythms (Hays et al., 1976).

Sequence-stratigraphic models link periods of sea-level fall to widespread erosion along the fluvial surface, and the formation of incised valleys and associated river terraces, whereas periods of sea-level rise are linked to deposition on the fluvial surface and eventual filling of incised valleys (Vail et al. 1977; Van Wagoner et al. 1990; Van Wagoner 1995; Catuneanu et al.

2009; Blum et al. 2013). Our analysis, however, supports previous efforts that suggest that the response of the fluvial surface is not uniform to sea-level variations (Swenson 2005; Lorenzo-Trueba et al. 2013; Anderson et al. 2019). River aggradation can be long-lived under sea-level fall under sufficient sediment supply (Swenson and Muto 2007) and this effect can be enhanced and extended due to adjustments of the fluvial surface geometry to sea-level variations. Moreover, alluvial degradation and sediment bypass from the upper to the lower portions of the fluvial surface can also be long-lived during the sea-level rise phase due to a reduction of the average relief and shift in the concavity of the fluvial profile (Lorenzo-Trueba et al. 2013, Anderson et al. 2019). These results also imply that the formation of river terraces, a process often associated with periods of sea-level fall (Anderson et al. 2016), could take place under sea-level rise to delayed adjustments of the fluvial profile geometry to the fall in sea-level.

In essence, here we show for the first time a flume experiment that relates changes in the relief and concavity of the fluvial surface profile during sea level cycles with the delay of the response of the upper portion of the fluvial surface. These results do not aim to reproduce the evolution of any particular system, and therefore do not account for field heterogeneities and complexities such as multiple grain sizes, deep crustal processes, etc. Such model simplifications allow us to focus our analysis on the role of the dynamics of the fluvial surface on the system's response to changes in sea level.

6. Conclusions

We study the propagation of sea level change information along the fluvial surface on deltaic systems by analyzing experimental data from a flume experiment with two sea level oscillations. In both sea level scenarios, we identified changes in the slope and concavity of the fluvial surface that highlight the role of sea level on the dynamics of the fluvial surface on the systems response. These changes in slope and concavity are associated with a substantial timelag in the response of the upstream portion of the fluvial surface to changes in sea level. In particular, we find that the sedimentation rate in the upstream location is out of phase by ~11 hours in the HMSP scenario (i.e., roughly half a period of the sea level oscillation). If the mechanics of the fluvial surface under sea level cycles are similar at field scales, as both flume experiments and theory suggest, timelags in the response of river systems associated with these dynamics could be on the order of tens of thousands of years.

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8. Appendix

A1. Additional Figures

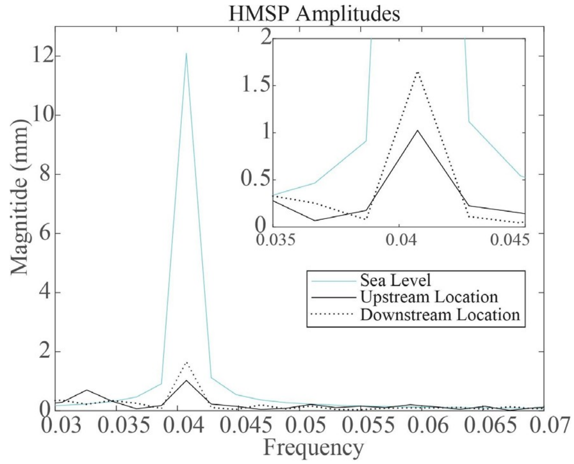

Figure A1.1. HMSP elevation amplitudes across the fluvial surface. Note how the farther upstream, the smaller the amplitude, indicative of a dampening effect, or reduction in the sea level signal strength.

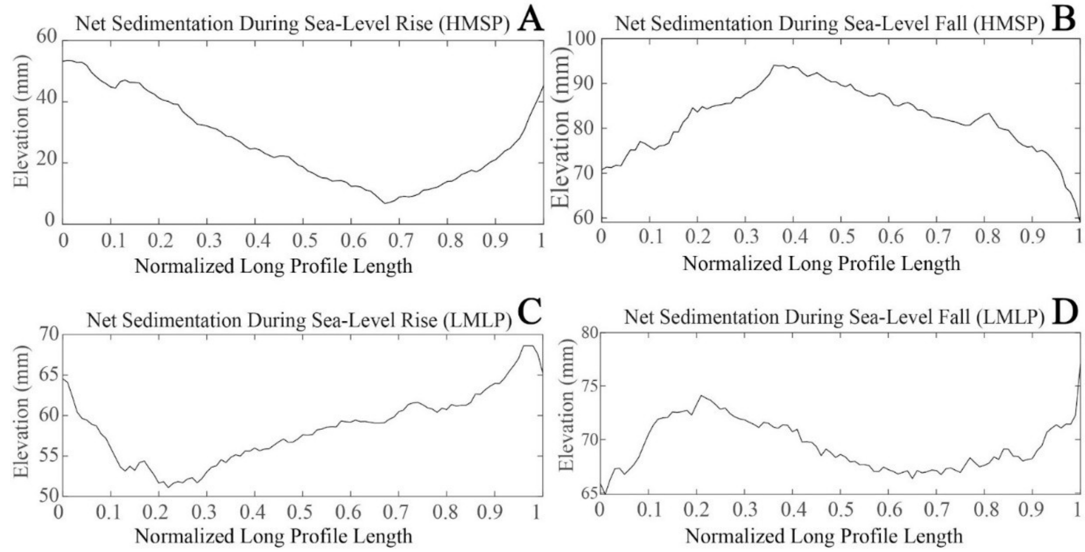

Figure A1.2. To further understand the mechanism behind the changes in slope and curvature, we calculated the cumulative net sedimentation in each phase of sea level. To generate these cumulative profiles, we normalized the length of the fluvial surface as changing sea level forces the shoreline to move, and the length to change every hour. Therefore, in Figures 3F and G the x axis is normalized between 0 and 1, with 0 being the fixed sediment input, and 1 being the shoreline. Once normalized, we added the elevation change in each profile together, to quantify the cumulative net sedimentation across the fluvial surface. The net sedimentation in the sea-level rise phase produced a profile that reflects higher sedimentation in the upstream, and a substantial transport of sediment from the upper portion of the profile to the nearshore region. These sedimentation patterns cause an increase in concavity in each sea-level rise phase (Panel A and C). In contrast, the net sedimentation of the sea-level fall phase reflects more sedimentation in the middle of the fluvial surface with less sedimentation in the upstream portion of the profile and at the foreset (Panel B and D).

A2. Additional Methods

We averaged the topographical data at every 5mm radial interval from the inlet to the shoreline to generate this profile. We also limited the extent of the fluvial surface by removing 100mm of elevation data from the inlet into the fluvial surface to limit the influence of boundary effects from the basin set up, while an additional limit was set by the data, as the DEM only covers 1.3m of the delta from the inlet into the basin. Therefore, for hours 746-748 where the shoreline extends beyond 1.3m into the basin we used the shoreline location in hour 745.

A3. Code Descriptions

Computer Code Availability: The following scripts, developed by Madeline Kollegger and Jorge Lorenzo-Trueba can be accessed at https://github.com/JorgeMSU.

For details about this code, contact Jorge Lorenzo-Trueba via email (lorenzotruej@montclair.edu) or by phone (973-655-5320). Jorge Lorenzo-Trueba's office is at 1 Normal ave., Montclair State 437 University, NJ 07043. The code can run on a standard laptop and is written in MATLAB.

The following is a description of each code used in the analysis of this paper:

Combine
The experimental data we used was downloaded from this SEAD repository (https://sead2.ncsa.illinois.edu/datasets/58dd9ac4e4b0b223acc5ff80#folderId=58ddbea2e4b0b223acc6468b&page=0) from the "Matrix_DryZ" folder. This particular code is used for the hours of the HMSP phase, and we downloaded the associated folders (hours 680-1170). These files are then extracted to a desktop folder entitled (HMSPdryZ). The code is written to cycle through all the files in this folder turning the DEM data into a matrix and saves each hour into a 3D Matrix called A. This matrix was then manually renamed "ThisisHMSPmatrix," saved to the desktop, to be used in other codes.

LMLPCombine
The experimental data we used was downloaded from this SEAD repository (https://sead2.ncsa.illinois.edu/datasets/58dd9ac4e4b0b223acc5ff80#folderId=58ddbea2e4b0b223acc6468b&page=0) from the "Matrix_DryZ" folder. This particular code is used for the hours of the LMLP phase, and we downloaded the associated folders (hours 50-540). These files are then extracted to a desktop folder. The code is written to cycle through all the files in this folder turning the DEM data into a matrix and saves each hour into a 3D Matrix called A. This matrix was then manually renamed "LMLP," saved to the desktop, to be used in other codes.

AverageProfile
The following code is written to manipulate data from the paper Yu et al 2017 wherein they study channel dynamics in a deltaic system using a flume experiment. Here we use the scans (Data compiled by the "Combine" script) taken in their experiment to observe the dynamics of the fluvial surface as influenced by the allogenic factors (sea level). For each hour of the experiment (of their last phase HMSP) we calculate the average elevation along the profile and generate the profile in cross-section. We then locate the shoreline at each hour, (Using the curve intersect function written by S. Hölz, TU Berlin, Germany). For each profile, we calculate the first derivative which

we use as a proxy for the relief as a function of the shoreline. We then calculate the difference in the area of each profile to understand the shape of the profile. We also calculate the volume change in each profile and identify the change as erosion or deposition and its location along the fluvial surface. The stratigraphy movie at the bottom uses the shade function (2018 Javier Montalt Tordera).

RadialAverageMatrixResiduals
The following code is written to manipulate data from the paper Yu et al 2017 wherein they study channel dynamics in a deltaic system using a flume experiment. Here we use the scans (Data compiled by the "Combine" script) taken in their experiment to observe the dynamics of the fluvial surface as influenced by the allogenic factors (sea level). For each hour of the experiment (of their last phase HMSP) we calculate the average elevation along the profile and generate the profile in cross-section. We then track three locations and store their elevation changes over time. This code has additional lines to run analysis for "dampening" and "timelag."

LMLPAverageProfile
The following code is written to manipulate data from the paper Yu et al 2017 wherein they study channel dynamics in a deltaic system using a flume experiment. Here we use the scans (Data compiled by the "LMLPCombine" script) taken in their experiment to observe the dynamics of the fluvial surface as influenced by the allogenic factors (sea level). For each hour of the experiment (of the LMLP) we calculate the average elevation along the profile and generate the profile in cross-section. We then locate the shoreline at each hour, (Using the curve intersect function written by S. Hölz, TU Berlin, Germany). For each profile, we calculate the first derivative which we use as a proxy for the relief as a function of the shoreline. We then calculate the difference in the area of each profile to understand the shape of the profile. We also calculate the volume change in each profile and identify the change as erosion or deposition and its location along the fluvial surface. The stratigraphy movie at the bottom uses the shade function (2018 Javier Montalt Tordera).

LMLPRadialAverageMatrixResidual
The following code is written to manipulate data from the paper Yu et al 2017 wherein they study channel dynamics in a deltaic system using a flume experiment. Here we use the scans (Data compiled by the "LMLPCombine" script) taken in their experiment to observe the dynamics of the fluvial surface as influenced by the allogenic factors (sea level). For each hour of the experiment (of their LMLP phase) we calculate the average elevation along the profile and generate the profile in cross-section. We then track three locations and store their elevation changes over time.