Complex Patterns of Sediment Erosion and Deposition under Sea-Level Variations Change: Insights from a Coupled Stratigraphic Experiment and Moving Boundary Modelling Approach for Fluvio-Deltaic Evolution.

Md Nurul Kadir¹, Jorge Lorenzo-Trueba¹, Anjali M Fernandes², and Arvind Singh³

¹Department of Earth and Environmental Studies, Montclair State University
²Department of Earth and Environmental Sciences, Denison University
³Department of Civil, Environmental, and Construction Engineering, University of Central Florida

May 21, 2024

Abstract

Fluvial deltas have worldwide socio-economic importance as human development and infrastructure centers and provide several ecosystem services, including storm protection and nursery habitats. Their subsurface architecture also holds clues to past climate and sea-level change that can be reconstructed from stratigraphy. A significant challenge in inverting stratigraphy is separating the signals of external forcing, such as variations in sea level, and internal processes, such as the dynamics of the fluvial surface and channel network variations. In a previous work, we analyzed laboratory flume data from the Tulane Delta Basin using an experimental run with oscillating sea level conditions and constant sediment supply. We found that the dynamics of the fluvial surface play an important role in delaying the response of the upper portion of the subaerial topset. To further quantify this phenomenon, we couple this flume experiment with a numerical modeling framework that integrates the topset with a subaqueous offshore region or foreset. The numerical model can explain the topset slope, convexity dynamics, and sediment partitioning between the topset and the foreset under sea level variations. For example, it captures how during sea-level rise (SLR), low sedimentation near the topset’s center reduces the subaerial slope and increases convexity, while during sea-level fall (SLF), high sedimentation increases the slope and concavity. Moreover, the model can explain the counterintuitive observation of higher sediment topset bypass to the foreset under SLR than SLF due to the reduction in subaerial slope, partially explained by a higher presence of active channels during SLR than SLF. These results underscore the importance of internal processes such as fluvial surface and channel dynamics, which can result in net erosion during SLR and net deposition during SLF, potentially complicating the reconstruction of paleo sea-level from deltaic deposits.
Introduction
- Fluvio-deltaic evolution refers to the dynamic changes in river deltas over time, driven by factors such as sediment deposition, erosion, and fluctuations in sea level.
- Fluvio-deltaic systems are highly sensitive to changes in sea level, which influence sedimentation patterns, shoreline positions, and deltaic morphology. These changes can trigger periods of erosion or deposition that significantly impact delta evolution.
- Understanding the evolution of fluvial-deltaic systems is essential for grasping coastal geomorphology, evaluating risks related to natural hazards like (coastal) flooding, and interpreting the geologic record to reconstruct past environmental changes.

Background
Previous studies found that the dynamics of the fluvial surface play an important role in delaying the response of the upper portion of the subaerial topset, which contradicts the sequence Stratigraphy theory (Kollegger et al., 2022).

Objectives
- Couple stratigraphic experiments with a numerical modeling framework to better understand how fluvial deltas evolve under different sea level curves.

Methodology
- Stratigraphic Experiment
- Numerical Model
- Fluvio-Deltaic Evolution

Tulane Delta Basin
- The experimental basin is 4.2 m long, 2.8 m wide, and 0.6 m deep (Yu et al., 2017).
- More active channels are present during the rising phase of the sea-level cycle compared to the falling phase.

Numerical Model using Moving Boundary Framework

Governing Equation:
\[
\begin{align*}
\frac{\partial h}{\partial t} + \nabla \cdot (h \mathbf{v}) &= R(t), \\
\mathbf{v} &= \nabla \cdot \left( \alpha \left( \frac{\partial h}{\partial t} + \nabla \cdot (h \mathbf{v}) \right) \right),
\end{align*}
\]
where:
- \( h \) = Water depth
- \( \alpha \) = Diffusivity
- \( R(t) \) = Discharge

Results
- The numerical model can explain the topset slope, convexity dynamics, and sediment partitioning between the topset and the foreset under sea level variations.
- It captures how during sea-level rise (SLR), low sedimentation near the topset’s center reduces the subaerial slope and increases convexity, while during sea-level fall (SLF), high sedimentation increases the slope and concavity.
- Moreover, the model can explain the counterintuitive observation of higher sediment topset bypass to the foreset under SLR than SLF due to the reduction in subaerial slope, partially explained by a higher presence of active channels during SLR than SLF.

Future Work
- The numerical model effectively captures the complex responses of deltaic systems to sea level variations, elucidating the modulation of topset slope, convexity dynamics, and sediment partitioning between the topset and foreset.
- These results emphasize the importance of internal processes such as fluvial surface and channel dynamics, which lead to net erosion during SLR and net deposition during SLF, complicating the reconstruction of paleo sea levels from deltaic deposits.

Conclusion
- The numerical model effectively captures the complex responses of deltaic systems to sea level variations, elucidating the modulation of topset slope, convexity dynamics, and sediment partitioning between the topset and foreset.
- These results emphasize the importance of internal processes such as fluvial surface and channel dynamics, which lead to net erosion during SLR and net deposition during SLF, complicating the reconstruction of paleo sea levels from deltaic deposits.

References