

EuroSTRATAFORM: A Moving-Boundary Framework for the Formation of Strata on Continental Margins

John B. Swenson

Large Lakes Observatory and Department of Geological Sciences

University of Minnesota Duluth

Duluth, MN, 55812

Phone: (218) 726-6844 fax: (218) 726-8275 email: jswenso2@d.umn.edu

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LONG-TERM GOALS

My overarching goal is the development of two- and three-dimensional, moving-boundary, morphodynamic models of continental-margin sedimentation on geologic time scales. The late-Quaternary stratigraphic package on continental margins is a complex juxtaposition of depositional and erosional surfaces that reflects the response of intrinsically coupled, fluvial and shallow-marine sediment dynamics to eustatic cycling. My morphodynamic modeling approach averages over characteristic events, e.g. floods and coastal storms, and represents the evolution of the sediment surfaces in the fluvial and shallow-marine environments with differential equations that are coupled at the shoreline. A key focus of my work is the rigorous treatment of the shoreline as a dynamic moving boundary and, by extension, its response to changes in sea level. Model results will provide important insight into the dynamic response of continental margins to changes in sea level (Task **D4**) and the prediction of large-scale acoustic properties in the upper few tens of meters of the stratigraphic record.

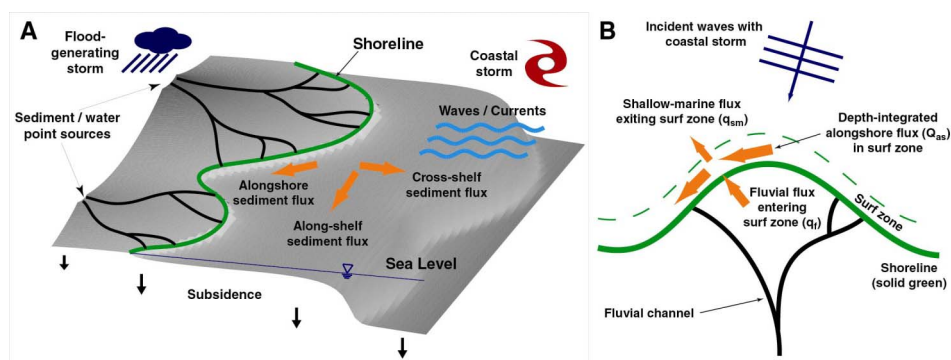


Figure 1. Conceptual sketch of (A) three-dimensional, moving-boundary, morphodynamic model of clinoform development illustrating the characteristic-event (flood and coastal storm) approach and (B) the treatment of the shoreline as a dynamic moving boundary.

OBJECTIVES

My primary objective is to supply ONR with a moving-boundary framework for analyzing continental-margin sedimentation that couples fluvial, shelf, and slope environments and addresses the dynamic response of continental margins to changes in sea level (Task **D4**). My objectives for the year were to:

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1. Extend to three dimensions our two-dimensional, moving-boundary model of coupled fluvial and shallow-marine morphodynamics (Swenson et al., submitted).
2. Investigate how flood/storm parameters control the partitioning of sediment between transport regimes and the interference patterns of point-source highstand (Holocene) clinoforms.
3. Explore how the interplay of high-amplitude sea-level cycles with fluvial and shallow-marine sediment dynamics modulates the interference of point-source clinoforms and the corresponding morphology of continental margins.
4. Quantify how flood/storm parameters affect phase relations between shoreline and clinoform rollover during sea level cycling and, by extension, the timing of margin progradation.
5. Investigate to what extent underlying basin physiography (structure) controls the large-scale patterns of sediment dispersal during sea level cycling and how this affects margin morphology.
6. Analyze the time-transgressive aspects of sequence-boundary development in the fluvio-deltaic settings that comprise the late-Quaternary stratigraphic section at the EuroSTRATAFORM field sites.

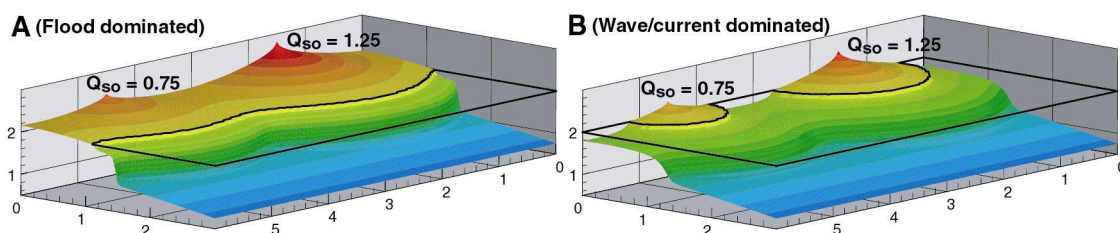


Figure 2. Interference of point-source clinoforms on continental margins dominated by (A) floods and (B) coastal storms and their associated wave/current climate. Bold trace delineates sea level and shoreline. Warmer colors indicate higher elevations with respect to sea level.

APPROACH

1. Extend our two-dimensional, moving-boundary, morphodynamic theory of shelf-clinoform evolution (Swenson et al., submitted) to three dimensions. I work closely with Chris Paola and Juan Jose Fedeles (UMN) on theoretical aspects of sediment dynamics; with Mike Steckler (LDEO) on sequence-stratigraphic and geodynamic components of model development; and with Lincoln Pratson (Duke U.) on developing models of mass flows and turbidity currents on the continental slope.
2. Modify our two-dimensional, moving-boundary theory of fluvio-deltaic sedimentation (Swenson et al., 2000) to treat the point of coastal onlap as a moving boundary.

WORK COMPLETED

1. I completed development of a three-dimensional, moving-boundary, morphodynamic model of clinoform evolution. The model combines our theory for three-dimensional fluvio-deltaic progradation with an extension of our two-dimensional shelf-clinoform theory (Swenson et al., submitted). The

repeated occurrence of “characteristic” floods and coastal storms, with specified water/sediment discharge and wave/current field, respectively, drives long-term evolution of the fluvial and shallow-marine sediment surfaces (Fig. 1A). This approach replaces the complicated time series of fluvial discharge, wave height, and current strength with impulse functions of specified periodicity and magnitude and, as such, circumvents the need for detailed hydrologic and meteorologic information, which generally is unavailable in ancient systems. A strongly non-linear (depth dependent) advection-diffusion equation governs shallow-marine morphodynamics (Coco, 1999; Swenson et al., 2003). I treat the shoreline as a dynamic moving boundary and collapse the surf zone to a shock condition at the shoreline. In plan view, the combination of alongshore-flux divergence and discontinuity in shore-normal flux drives shoreline translation (Fig. 1B). I implemented the model numerically using a variation on a fixed-grid, enthalpy-based approach for two-dimensional solidification problems (e.g., Voller and Cross, 1981; Crank, 1984). I used this model to address objectives 2 – 5 listed above.

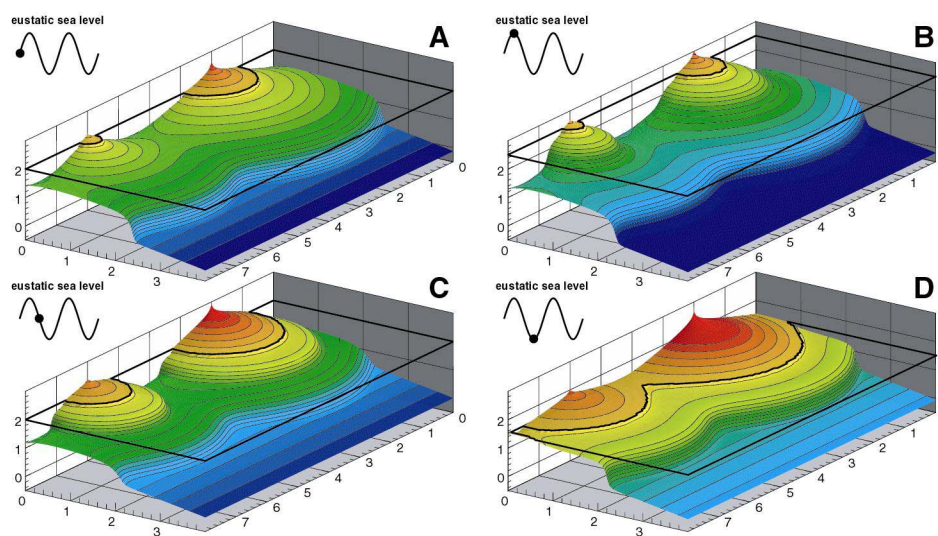


Figure 3. Three-dimensional morphologic response of point-source clinoforms to a single, high-amplitude cycle of sea level change. Warmer colors indicate higher elevations with respect to sea level. Bold trace delineates sea level and shoreline.

2. I extended our two-dimensional, moving-boundary theory for fluvio-deltaic sedimentation (Swenson et al., 2000) to (1) include the point of coastal onlap as a third moving-boundary and (2) track rigorously the time-transgressive development of erosional surfaces. The model now captures the partitioning of sediment between coastal-plain onlap and progradation of the shoreline and associated deltaic wedge during sea level cycling. After implementing the model numerically using a deforming-mesh approach (e.g., Crank, 1984), I used it to explore objective 6 listed above.

RESULTS

1. The three-dimensional clinoform model naturally develops quasi-radial fluvial environments coupled to subaqueous deltas. The interference patterns and resultant highstand margin morphology are sensitive to the frequency and magnitude of floods and coastal storms. In flood-dominated systems, the fluvial systems interfere relatively rapidly and highstand margin morphology quickly loses its

strike dependence (Fig. 2A). In contrast, fluvial interference is slow in wave/current-dominated systems, producing long-lived three-dimensionality in margin morphology (Fig. 2B).

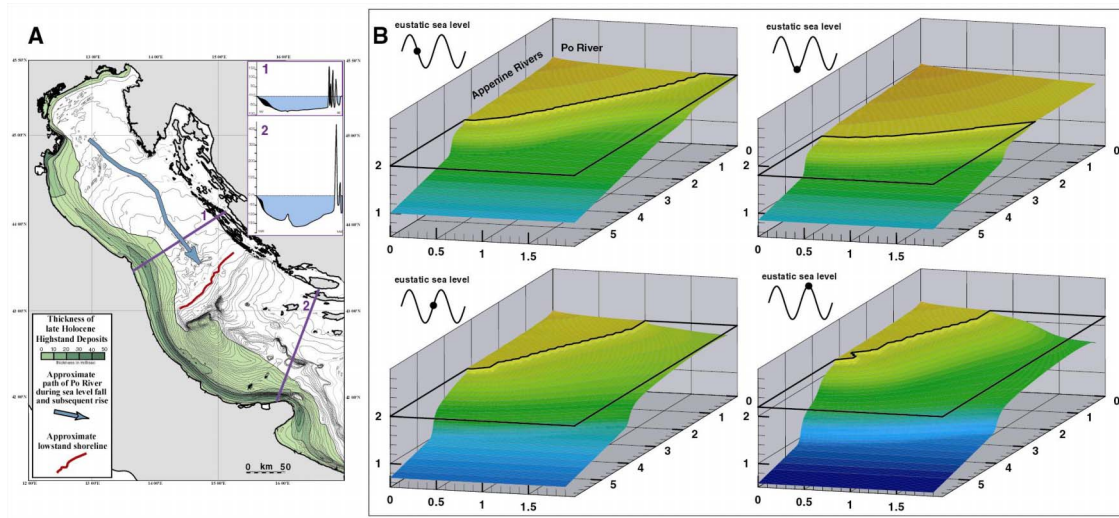


Figure 4. (A) Highstand (Holocene) sediments (green), direction of clinoform progradation (arrow) during falling sea level, and lowstand shoreline (red curve). (B) Numerical experiment demonstrating how the interplay of sea level and basin physiography (structure) controls the large-scale patterns of sediment dispersal in the Adriatic Sea.

2. The development of compound clinoforms during high-amplitude sea level cycling strongly affects margin morphology (Fig. 3). The active clinoform rollover is abandoned during rapid sea level rise and associated shoreline transgression, leaving a broad, sediment-starved subaqueous topset (Fig. 3A). As the rate of sea level rise wanes, renewed progradation generates a pair of compound clinoforms with actively prograding rollovers that separate regressive shorelines from the previously abandoned clinoform rollover (shelf edge) (Figs. 3B and 3C). Falling sea level drives rapid expansion of the fluvial systems, rejuvenation of the relict shelf edge by the active subaqueous delta, and an increase in foreset gradient (Fig. 3D). The timing (relative to lowstand) of rejuvenation of the relict shelf edge varies with flood/storm parameters. Clinoform interference is strongest during sea level fall and lowstand, thereby rendering margin morphology largely two-dimensional; in contrast, margin morphology is strongly three-dimensional near highstand.

3. On “bounded” margins with strong underlying structure (e.g., margins in complex, collisional regimes such as the Adriatic Sea), high-amplitude changes in sea level affect profoundly the large-scale patterns of sediment dispersal (Fig. 4A). During sea level highstands, e.g. the Holocene, sediment dispersal and clinoform progradation are dominantly normal to the long axis of the margin (Fig. 4B). Conversely, during sea level lowstands, the dominant direction of sediment dispersal and clinoform progradation is parallel to the long axis of the margin.

4. Sequence boundary nucleation and evolution are sensitive to the age of the fluvio-deltaic clinoform and the dimensionless amplitude and frequency of sea level cycling (Fig. 5). The age dependence reflects the continual sequestering of sediment in the expanding fluvial wedge and the corresponding reduction in sediment supply reaching the shoreline. Figures 5B and 5C illustrate the sensitivity to

small changes in the dimensionless amplitude (ε) of eustatic forcing. In both cases, sequence boundaries nucleate early in the fall and propagate both upstream and—tracking the erosional shoreline—downstream; the shoreline becomes depositional before lowstand; the landward limit of erosion continues to expand; and the seaward limit of erosion retreats as the sequence boundary “heals” via onlap of fluvial strata. In the response to low-amplitude forcing, the erosional surface heals via combined fluvial onlap and downlap soon after the shoreline returns to a depositional state (Fig. 5B). However, slightly higher amplitude forcing is accompanied by long-lived upstream propagation of a shrinking zone of fluvial erosion that survives well into the sea-level rise (Fig. 5C). Many aspects of the time-transgressive behavior shown in Figure 5 have been documented in physical experiments (Heller et al., 2001) and field studies (Plint et al., 2001; Tornqvist et al., 2003) but are not predicted by current models (e.g., Posamentier et al., 1988).

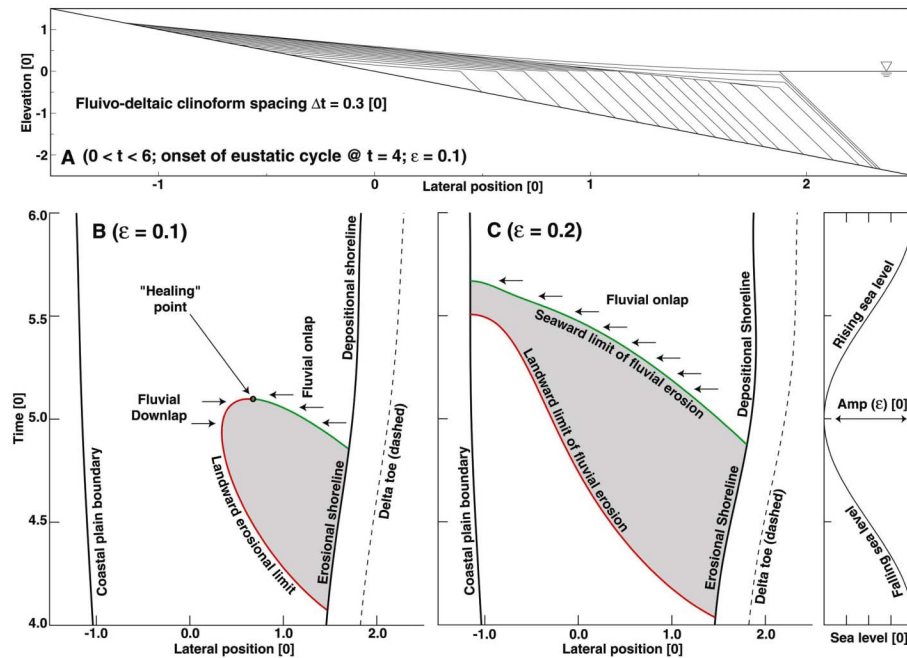


Figure 5. Sequence-boundary development in a fluvio-deltaic setting: (A) Stratigraphic response to sea-level change; trajectories of coastal onlap, shoreline, delta toe (dashed), and the landward (red) and seaward (green) limits of fluvial erosion for sea-level amplitudes of (B) $\varepsilon = 0.1$ and (C) $\varepsilon = 0.2$. Shaded regions are erosional.

IMPACT/APPLICATIONS

Clinofoms are the fundamental constructional units of stratigraphic sequences on continental margins (e.g., Pirmez et al., 1998; Rabineau et al., 1998; Steckler et al., 1999). Model results reported here are testable and begin to quantify how the repeated occurrence of floods and coastal storms combines with changes in sea level to control the long-term morphologic evolution of clinoforms and the time-transgressive aspects of sequence-boundary development. Model predictions benefit the Navy because the three-dimensional geometry of individual clinoforms, successions of clinoforms in stratigraphic sequences, and sequence boundaries control the acoustic signature of late-Quaternary strata on

continental margins. In a broader scientific context, model results are a significant step towards someday inverting clinoform and sequence-boundary geometry for the history of climate and tectonics.

RELATED PROJECTS

I continue to work closely with Chris Paola (UMN) on efforts to test fundamental predictions of stratigraphic theory in physical experiments. In addition, I work with Brad Murray (Duke U.) on modeling alongshore transport and its control on continental-margin morphology.

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- Swenson, J.B., A. Murray, C. Paola, and M. Steckler, A three-dimensional, moving-boundary model of shelf clinoforms. *Geophysical Research Abstracts*, **5**, 10444, European Geophysical Society, 2003.

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Swenson, J.B., C. Paola, L. Pratson, V.R. Voller, and A.B. Murray, A moving-boundary, integrated-morphodynamic model of clinoform progradation: Basic controls on sediment partitioning and morphologic evolution. Submitted to *J. Geophys. Res.*

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