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

Award Number: N000140210233
http://www.onr.navy.mil/oas/322_processes/prog_mg.htm

LONG-TERM GOALS

My overarching goal is the development of two- and three-dimensional, multiple-grain-size, moving-boundary, morphodynamic models of continental-margin sedimentation on relatively long time scales, i.e. $10^4 – 10^5$ years. Continental margins consist of multiple transport environments coupled at key internal boundaries, e.g. fluvial and shelf environments are coupled at the shoreline. A morphodynamic approach averages over characteristic events, e.g. floods and coastal storms, and represents the evolution of the sediment surface in each transport environment with a single differential equation. On long time scales, the positions of the internal boundaries and the transport environments they bound are dependent variables that must be determined as part of the solution to the coupled morphodynamic equations, thereby rendering continental-margin sedimentation a complicated moving-boundary problem.

Model results will provide important insight into the formation of continental-margin strata and, in particular, the dynamic response of continental margins to large-amplitude changes in sea level (Task D4). 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. Ultimately, the moving-boundary models will provide a framework for use by other EuroSTRATAFORM PIs in model-model comparisons. Of interest to ONR, model results will be used to predict the large-scale acoustic properties of upper 100 m of the stratigraphic record.

OBJECTIVES

At the end of the two-year funding cycle, I intend to supply ONR with a moving-boundary model of continental-margin sedimentation that couples fluvial, shelf, and slope environments and addresses the dynamic response of continental margins to large-amplitude changes in sea level (Task D4). The two-dimensional framework will incorporate multiple grain sizes; the three-dimensional framework will be restricted to a single grain size. Key objectives are to:

1. Quantify the partitioning of sediment between continental-margin transport environments during progradation under steady boundary conditions and thus determine the morphology and relative growth rate of each environment, particularly the shelf.

2. Explore the possibility of (quasi) equilibrium profiles, e.g. an equilibrium shelf, in one or more of the transport regimes during progradation under steady boundary conditions. Explore the possibility that some transport regimes are "slaved" to others, e.g. the shelf is slaved to the fluvial environment.

3. Determine if changes in wave or current climate can produce transgressions of comparable magnitude to those driven by sea-level change.

4. Quantify how high-amplitude changes in sea level affect sediment partitioning and margin morphology. Explore the phase relationships between sea level and both shoreline and shelf edge.

5. Investigate how the above are affected by the strong three-dimensionality—including underlying structure—that characterizes the EuroSTRATAFORM field sites.

APPROACH

1. Refinement of a moving-boundary model for shelf morphodynamics.

2. Development of morphodynamic models for the slope (grain-flow dominated) and continental-rise (turbidity-current dominated) environments. Models must ultimately address the partitioning of sand and mud between the slope and rise.

3. Continued scaling work and identification of key dimensionless numbers that control continental-margin sedimentation.

4. Parallel development of a three-dimensional moving-boundary framework, using the fluvio-deltaic theory of Swenson et al. (2000) as a starting point.

5. Testing of basic model predictions with physical experiments in the Experimental Earthscape (XES) Facility at Saint Anthony Falls Laboratory (SAFL).

6. Application of two- and three-dimensional models to the late-Quaternary strata of the Adriatic Sea and Gulf of Lions margins.

I work closely with Chris Paola (UMN) on theoretical aspects of sediment dynamics and with Mike Steckler (LDEO) on sequence-stratigraphic components of model development. In addition, I collaborate with Lincoln Pratson (Duke U.) on submarine mass flows and turbidity currents. I am the principal numerical analyst working on code development; I will share these responsibilities with Juan-Jose Fedele when he begins a post-doctoral appointment in November of 2002.

WORK COMPLETED

1. Completed development of a two-dimensional, moving-boundary, morphodynamic model for constructional shelf clinoforms (Swenson et al., *in review*). Implemented the model numerically using deforming-grid (Landau transformation) and fixed-grid (Enthalpy formulation) techniques (Voller and Cross, 1981; Crank, 1984). Fluvial and shelf morphodynamics are driven by the repeated application of characteristic floods, e.g. Paola (2000), and large coastal storms, respectively, of specified magnitude and intermittency (Fig. 1). Shelf sediment transport is treated via an energetics approach (Bagnold, 1963; Bailard, 1981; Coco, 1999), which yields strongly non-linear advective / diffusive

morphodynamics. The complexities of shoreface sediment dynamics are below model resolution and thus collapsed to a shock condition. Used model to explore objectives 1 – 3 listed above.

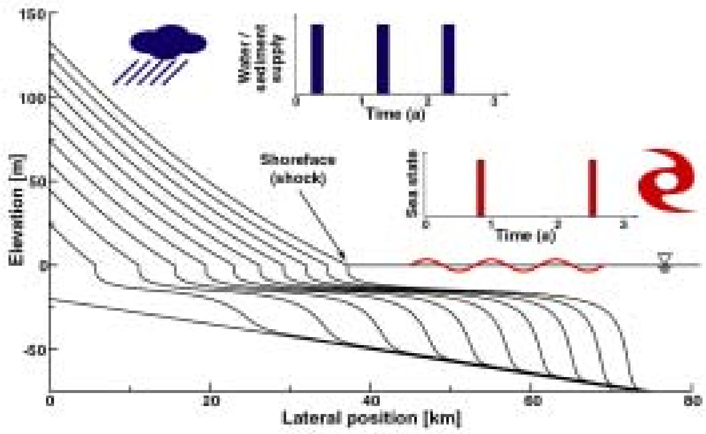

Figure 1. Moving-boundary, morphodynamic model of constructional shelf clinoforms illustrating the characteristic-event (flood and storm) approach.

2. Identified three key dimensionless numbers for constructional shelf clinoforms.

3. Developed and implemented numerically a three-dimensional moving-boundary model of fluvio-deltaic progradation (after Swenson et al., 2000) using a modified enthalpy approach on a fixed grid (Voller and Cross, 1981; Crank, 1984). Used model to explore the interference of deltas, e.g. interference between Apennine river sources (Fig. 2). Fluvio-deltaic model is an important step in the development of a three-dimensional model of continental-margin sedimentation.

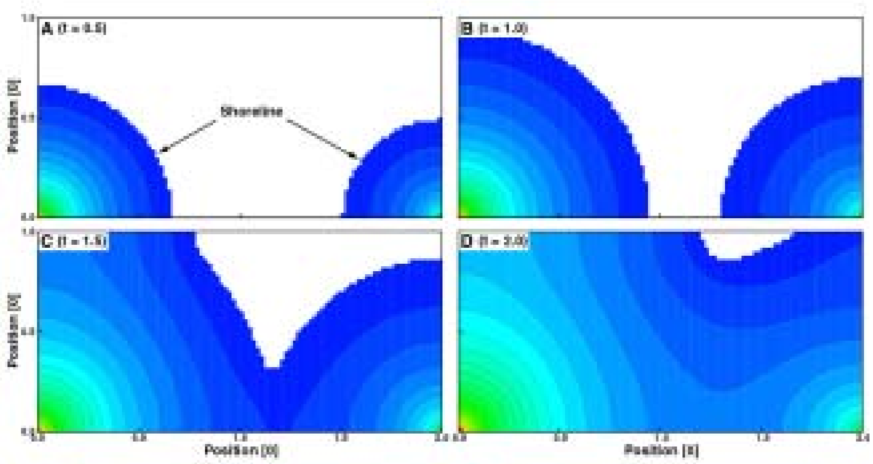

Figure 2. The interference of two fluvio-deltaic systems over the time interval 0 < t < 2. Sediment / water point sources are located in the lower left and right corners of each panel; the sediment source in the left corner is twice as large as that in the right. Only the subaerial (fluvial) elevation is contoured. Warmer colors indicate higher elevations; ocean surface is white.

4. Used two-dimensional moving-boundary model to predict successfully the results of the recent (spring 2002) physical experiment at SAFL on continental-margin response to fluctuations in sea level.

5. Worked closely with Lincoln Pratson (Duke U.) and Chris Paola (UMN) to develop a moving-boundary theory of combined sand/mud transport and deposition on the continental slope and rise by mass flows and turbidity currents, respectively. Numerical implementation is ongoing.

RESULTS

1. The behavior of constructional shelf clinoforms is controlled by three dimensionless numbers that, in a qualitative sense, embody (1) basin physiography, (2) downwelling current strength and overall sediment supply, and (3) wave strength and fluvial water supply; the last pair of numbers also depends on sediment settling velocity (grain size).

2. Sediment partitioning and morphology of shelf clinoforms are sensitive to the magnitude and frequency of floods and large coastal storms and to sediment grain size. Sensitivity is summarized in Figure 3, which shows clinoform progradation over the time interval $0 < t < 10$ into a basin of uniform water depth in response to a steady supply of sediment. The variability in morphology between the four clinoforms results from differences in intensity of storms and floods and sediment grain size. Sediment partitioning to the shelf environment increases either with increasing wave height and downwelling current or with decreasing grain size and fluvial water supply. Increased sediment partitioning to the shelf environment increases the rate of shelf widening and, correspondingly, reduces the rate of fluvial aggradation and progradation (Fig. 3; compare clinoforms B and D, which have wide, rapidly evolving shelves, to clinoforms A and C). Shelf gradient is a strongly non-linear function of downwelling current: A small increase in current strength can produce a nearly planar shelf (compare clinoforms A and B). Finally, an increase in fluvial water supply decreases the sediment partitioning to the shelf environment, reducing the rate of shelf growth relative to the fluvial (compare clinoforms D and C).

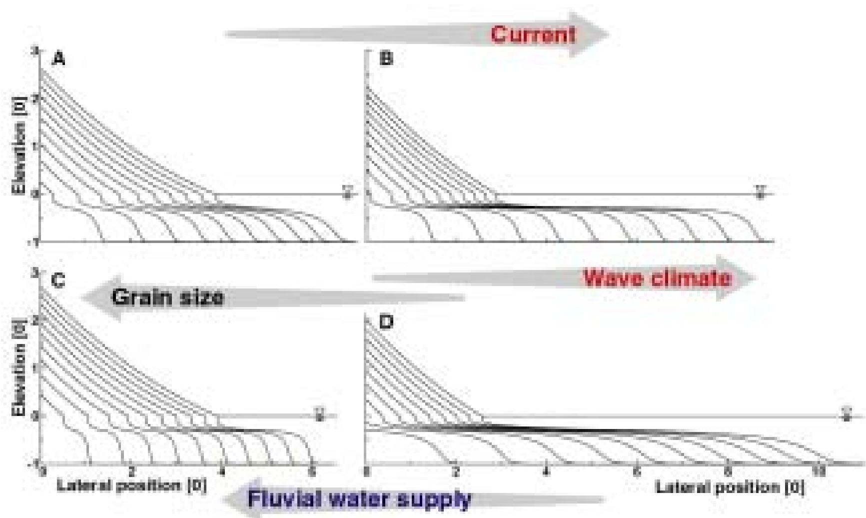

Figure 3. Morphology of shelf clinoforms as a function of grain size, wave and current climate, and fluvial water supply.

3. Under steady forcing (without subsidence), an equilibrium shelf profile *does not* exist (Fig. 3).

4. An increase in wave or current climate can generate significant shoreline transgression in an overall progradational shelf clinoform (not shown). This result has significant implications for the interpretation of the stratigraphic record.

5. My two-dimensional moving-boundary model of fluvio-deltaic sedimentation can predict successfully the stratigraphic response to large-amplitude sea-level changes in a laboratory-scale physical experiment at SAFL (Fig. 4). Although the stratigraphic data are not yet processed, frequent measurements during the experiment suggest that predicted and observed shoreline positions differed by no more than 10%.

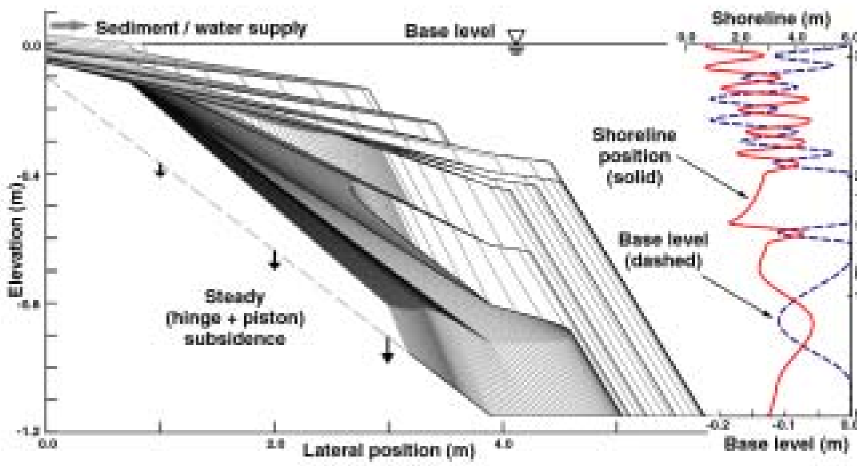

Figure 4. Predicted strata and shoreline position for the recent physical experiment on continental-margin response to sea level in the XES basin at SAFL.

IMPACT/APPLICATIONS

Shelf clinoforms are the basic depositional unit of continental margins (Pirmez et al., 1998; Steckler et al., 1999) and comprise the bulk of late-Quaternary strata at the EuroSTRATAFORM field sites. The large-scale acoustic properties of continental margins are related directly to clinoform morphology and grain-size distribution. Many of the above model results are testable and begin to quantify the poorly-understood, long-term dependence of clinoform morphology and sediment partitioning on the frequency and magnitude of floods and storms, sediment supply, and grain size. Ongoing modeling efforts will provide additional insight into shelf-clinoform response to allogenic forcing, particularly to changes in sea level. Current model results are a significant step toward someday inverting clinoform morphology for the history of climate and tectonics.

TRANSITIONS

The experimental stratigraphy group at SAFL used my two-dimensional, moving-boundary model of fluvio-deltaic sedimentation to design a recent (spring 2002) experiment on continental-margin response to large-amplitude sea-level fluctuations.

RELATED PROJECTS

I continue to work closely with Chris Paola (UMN) to develop further a symbiosis between the development of stratigraphic theory and the testing of theory in laboratory-scale physical experiments.

REFERENCES

Bagnold, R.A., Mechanics of marine sedimentation, in *The Sea: Ideas and Observations*, Interscience, New York, 1963.

Bailard, J.A., An energetics total load sediment transport model for a plane sloping beach, *J. Geophys. Res*., *86*, 10,938-10,954, 1981.

Crank, J., *Free and Moving Boundary Problems*, Cambridge University Press, Oxford, 425 pp., 1984.

Coco, G., Mechanisms for the Formation of Rhythmic Topography in the Nearshore Region, Ph.D. Dissertation, University of Plymouth, 1999.

Paola, C., Quantitative models of sedimentary basin filling, *Sedimentology*, *47*, 121-178, 2000.

Pirmez, C., L.F. Pratson, and M.S. Steckler, Clinoform development by advection-diffusion of suspended sediment: Modeling and comparison to natural systems, *J. Geophys. Res*., *103*: 24,141-24,157, 1998.

Steckler, M.S., G.S. Mountain, K.G. Miller, and N. Christie-Blick, Reconstruction of Tertiary progradation and clinoform development on the New Jersey margin by 2-D backstripping, *Mar. Geol*., *154*, 399-420, 1999.

Swenson, J.B., C. Paola, L. Pratson, and V.R. Voller, A moving-boundary model of sand-dominated shelf-clinoform dynamics, submitted to *J. Geophys. Res*., in review.

Swenson, J.B., V.R. Voller, C. Paola, G. Parker, and J.G. Marr, Fluvio-deltaic sedimentation: A generalized Stefan Problem, *Euro. J. App. Math*., *11*, 433-452, 2000.

Voller, V.R., and M. Cross, Estimating the solidification / melting times of cylindrically symmetric region, *Int. J. Heat Mass Transfer*, 24, 1457-1462, 1981.

PUBLICATIONS

Swenson, J.B., C. Paola, L. Pratson, and V.R. Voller, A moving-boundary model of sand-dominated shelf-clinoform dynamics, submitted to *J. Geophys. Res*., in review.

Swenson, J.B., C. Paola, and N. Strong, Continental-margin sedimentation in a moving-boundary framework, *EOS Transactions of the American Geophysical Union*, 82(47), 2001.