Linking Short and Long Term Sediment Delivery to Morphology and Seascape Evolution of Continental Margins

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Award Number: N00014-95-1-1281

LONG TERM GOALS

Develop numerical models useful for the simulation of sediment delivery and accumulation on continental margins over tens to thousands of years. Model predictions will help us understand the evolution of bedding architecture and sediment characteristics on continental margins through sea level fluctuations, climate change, and other relevant environmental factors. ONR interests include the development of a numerical predictor of the acoustic signature of remote margins based on a region's geological history.

OBJECTIVES

1) Simulate the Eel River discharge through the Holocene. Hypothesis: observed inter-century variability in a river's sediment load is not adequate to be a proxy for longer-term climate trends driving most rivers through the Holocene period.

2) Simulate the development of a hyperpycnal plume developing from exceptional floods of the Eel River. Hypothesis: only exceptional hyperpycnal events will cross the Eel shelf before losing their driving force.

3) Examine the impact of flood hysteresis on delivery of sediment to the ocean. Hypothesis: rating hysteresis (i.e. rising limb of a flood wave being able to carry more sediment than the falling limb) can produce the data variability observed for many river systems.

4) Develop the HYDROTREND sediment delivery model for use on large to giant rivers (e.g. Mackenzie River, Canada). Hypothesis: HYDROTREND would need to use an integrative approach, and include the simulation of secondary sources of water such as deep, region-wide groundwater pools and distributed convective cells.

5) Complete the 2D SEDFLUX model by combining a STRATAFORM-developed bottom boundary layer model (Wiberg-Harris) into the SEDFLUX model suite. [This objective was postponed and broadened to involve the effort of the larger STRATAFORM modeling community].

6) Use 2D SEDFLUX to simulate deposition within the Eel Basin for the Holocene period and compare results with isopachs of Holocene sediment thickness. Hypothesis: complex sea level fluctuations of an active margin have strong control on the pattern of simulated sedimentary deposits.

7) Given Jurassic Tank experimental set up conditions, use 2D SEDFLUX to simulate tank results. Hypothesis: a numerical model can produce the basic structure of a flume experiment, duplicating sand and clay facies architecture.

APPROACH

• Develop a Sediment Delivery Model (Task B3) to simulate delivery of sediment to a continental slope. Predict delivery to the shelf-slope break from fluvial point and line sources. Compare open-slope sediment delivery (distributed) with canyon-fed delivery (localized).

• Develop a Seascape-Stratigraphic Model (Task B8) and include major influences (climate, sea level, tectonics) on processes that control slope morphology, stratigraphy, and acoustic realizations. Model is to include the effects of: a) external forcing mechanisms; b) short-term and long-term delivery of sediment; c) simulations of individual mass movements (submarine slides, debris flows and turbidity currents); d) slope failure, and e) tectonics and subsidence.

Eric Hutton is the principal numerical analyst working on the code, along with Ph.D. students Mark Morehead (now graduated) and Damian O'Grady.

WORK COMPLETED

1) Simulation of the Eel River (CA) discharge through the transition between ice-age climate and Holocene climate, over a 2500-year period. Simulation of the Kliniklini River (BC) discharge, for the Holocene period and into a warmer future. (Syvitski and Morehead, 1999; Morehead and Syvitski, 1999; Morehead et al., 2000).

2) Simulation of a hyperpycnal plume developing from an exceptional (1995) flood event of the Eel River, and flowing out and across the Eel Margin under different alongshelf current scenarios. (Imran and Syvitski, in press). Demonstrated that rivers may reach hyperpycnal concentrations more often than previously believed (Parsons et al., in press).

3) Analysis of how flood hysteresis affects the delivery of sediment to the ocean. (Morehead, 1999, Ch. 5, p. 101-135; Syvitski et al., in press).

4) Modification of HYDROTREND to simulate the sediment discharge from giant rivers (Liard and Mackenzie rivers, NWT). (unpublished).

5) Modification of 2D SEDFLUX (Syvitski et al., 1999; Bahr et al., in press; Syvitski and Hutton, in press-a; Syvitski and Hutton, in press-b) and applied to the University of Minnesota Jurassic Tank. (unpublished). Application of 2D SEDFLUX to simulate the sediment architecture of the Eel Margin. (Morehead et al., 2000). SEDFLUX upgrades include adding earthquake accelerations to the failure routine, a gravity flow decider, and a tsunami generator.

6) Code architecture for 3D SEDFLUX. (unpublished).

7) Analysis of the morphologic variability of siliciclastic passive margins. (O'Grady et al., 2000).

8) Adaptation of Brownian motion theory to the avulsion of river channels across a river delta plain. (paper in revision).

9) A Lagrangian, 4-equation, turbidity current model. (Pratson et al., 2000). Contrasted how turbidites and debrisites differ because of the inherently different dynamics associated with turbidity currents and debris flows. (Pratson et al., in press)

1999/00 RESULTS

- Rivers with varied hydrological styles can have their discharge simulated: rain-flood dominated (Eel River), snow-melt dominated (Mackenzie River), and glacier-melt dominated (Kliniklini River), large basins, small basins and so on. Model results successfully reproduce the modern flood frequency and sediment-rating curves. HYDROTREND is generally applicable to a variety of river basins with varying climatic and geologic conditions. The naval relevance is in the ability to make predictions for global rivers that have not been gauged, or do not have gauged data readily available.

- The rating coefficients, necessary to model the temporal variability in the sediment load of rivers, can be estimated. The rating parameters (*a* and *b)* are defined by the power law relating daily discharge values of a river (Q) to their sediment concentration (C_s), where $C_s=aQ^b$. Rating coefficient (a) is inversely proportional to the long-term mean discharge, and is secondarily related to average air temperature and topographic relief. Rating exponent (b) correlates strongly with average air temperature and basin relief. The exponent correlates to a lesser extent with the average sediment load of the river.

- River plume models (PLUME) can successfully predict where sediment leaves the surface layer of the ocean.

- Hyperpycnal model simulations of extreme floods of the Eel River (e.g. 1995), show much of the river's sediment load may bypass mooring sites and enter either the Eel canyon or the Humboldt region as a line source turbidity current. Once across the shelf-slope break, flows would act as a line source from which finger flows form and accelerate down the continental slope, causing erosion where the seafloor is steepest and deposition where it levels out. Over geologic time, these flows can be a major source of sediment to the slope, augmenting the sediment delivery from plumes and shelf storms. Episodic turbidity currents coupled to more ambient hemipelagic sedimentation may shape the seafloor and develop landward migrating (antidunal) bedforms.

- The combining of event models into one interactive model is the first of its kind to be developed. The acoustic character of a continental shelf seafloor modified by a river flood, for instance, can be evaluated. The integrated model can simulate deposits in two dimensions (distance from shore and depth). The SEDFLUX model can simulate the evolution of seascape, the continuity of individual beds, and their acoustic characterization from specified seismic source signatures.

- By integrating delivery models with seascape models (HYDROTREND, SEDFLUX) the preservation potential of various modes of river discharge (flood dominated versus steady discharge) can be explored. This includes the effects of weather systems or climate on the sedimentary deposits. Results indicate the complex interplay between the frequency and size of discharge events with the frequency and magnitude of ocean-storm events that control the preservation potential of sediment layers.

- The event-based multi-component model (SEDFLUX) is designed to limit the propagation of error. Although components of the model have each been tested, testing the combined model structure is difficult. SEDFLUX is able to simulate the sediment architecture produced by the St. Anthony Falls Hydraulics Laboratory tank experiments.

- To provide the Navy with spatial seafloor properties, the multiprocess SEDFLUX model is being converted to a full 3D-seascape-evolution model. The 3D code is presently able to handle complex topography, multiple rivers, sea level fluctuations, plumes and diffusion routines. Plans are underway to add 3D-slope stability, with subsequent debris flow and turbidity current routines.

- The basic morphology of a continental passive margin is dependent on the margins' underlying strata architecture, terrestrial sediment flux and the degree of submarine canyon incision. For example, low slope margins are sediment supply dominated with few canyons; steep and rough margins are supply limited, having many canyons. SEDFLUX is able to isolate the effect, on the shape of the slope profile, of river plumes, shelf energy, sediment failure, gravity flows, subsidence, and sea level fluctuations. Hemipelagic sedimentation along with shelf storms provides the basic building block of clinoform geometry. Oblique clinoforms are associated with low-energy conditions and sigmoid geometries associated with more energetic wave conditions. Slope failure steepens the upper continental slope and creates a more textured profile. Topographic smoothing induced by bottom boundary-layer transport enhances the stability of the upper continental slope. Different styles of sediment gravity flows (turbidity currents, debris flows) affect the profile geometry differently. Debris flows accumulate along the base of the continental slope, leading to slope progradation. Turbidite deposition principally occurs on the basin floor and the continental slope remains a zone of erosion and sediment bypass. Sea level and flexural subsidence surprisingly show smaller impacts on profile shape. Initial basin steepness and water depth have a profound influence on the steepness of the equilibrium profile.

IMPACT/APPLICATIONS

SEDFLUX can predict the same suite of morphological profiles of siliciclastic continental margins found around the world, from the low slopes of river-dominated margins to the high slopes (10°) of margins prograding into very deep water. SEDFLUX is able to predict:

• Continental margin equilibrium profiles, i.e. profile morphology that does not change once it is achieved, and is no longer under the influence of the paleo-basin bathymetry.

• Time it takes to achieve an equilibrium profile, given an initial set of boundary conditions. For example, <1Myr for shallow basins, and 4 to 6 Myr for deep basins. The corollary being able to predict which margins have yet to achieve an equilibrium profile and therefore remain between equilibrium states.

These two abilities hold out surprising promise in three essential areas:

1. Because we can isolate the fundamental building blocks and tag on morphological modifiers of the secondary dispersal mechanisms, future effort should produce analytical solutions to the build up of continental margins.

2. Analytical solutions hold the promise of solving the inverse problem, i.e. given paleo-slope profiles (e.g., from seismic time lines), what sediment flux and ocean dispersal conditions have led to these slope profiles.

3. Isolate the influence of tectonics on margin profiles, given our new understanding of the role of sediment dispersal.

We remain on the path to predict acoustic properties of the seafloor of continental margins, based on process-based modeling and remote data input. Models offer the possibility of making predictions where field data are limited. The impact of natural events (floods, storms) on the acoustic character and features of continental margins can now be examined. New efforts related to mine counter measures (MCM) and antisubmarine warfare (ASW) will profit greatly from these modeling and data assimilation efforts.

TRANSITIONS

SEDFLUX model is becoming an integral part of the reservoir characterization effort of MOBIL (and now EXXON-MOBIL) Technology Corporation. HYDROTREND and PLUME are models being used by Raytheon-Hughes Corporation to fuse environmental data records (infrared and visible wavelengths) downloaded from satellites for the purpose of natural-disaster mitigation. The University of Oslo and Delft Technological University now use SEDFLUX to understand sediment architecture in the arctic and the Caspian Sea, respectively. We have helped Lincoln Pratson (Duke U.) develop a 1D Lagrangian turbidity current model (1D BANG). Jasim Imran (U. South Carolina) has provided us with the counterpart 1D and 2D non-steady-Eulerian code. Our seismic simulator (ECHO) has been modified and used in cooperative work with St. Anthony Falls Hydraulic Lab's flume efforts by Duke University (Pratson). Work with Homa Lee has allowed us to include earthquake accelerations in the SEDFLUX failure criteria, while work with Philip Watts has allowed us to add a tsunami generator to SEDFLUX.

RELATED PROJECTS

• MOBIL Technology Center (Cullick, Sarg) supported efforts (Bahr, Pratson, Hutton, and O'Grady) to develop a database on continental margin morphology, sedimentology, oceanography and tectonics. The two STRATAFORM margins are included in the database.

• Worked with G. Parker, C. Paola (U. Minnesota), P. Heller (U. Wyoming), L. Pratson (Duke U.) in developing a continental margin experimental tank, through the support of a NSF grant and consortium support (MOBIL, EXXON, TEXACO, CONOCO, JAL).

• Raytheon-Hughes has linked with the INSTAAR modeling efforts for the development of an algorithm related to fuse satellite data (infrared and visible wavelengths) and provide information on littoral sediment transport.

• ONR-Geoclutter (new): Predicting the distribution and properties of buried submarine topography on continental shelves; ONR-EuroSTRATAFORM (planning stage): Responses of margin sedimentation to natural and human impacts; ONR-Mine Burial Prediction (new): Mine burial models that incorporate dynamic-coupled processes, seafloor-material properties, and different mine types, to enhance mine burial predictive capabilities; ONR-DRI (planning stage): Characterize, calculate and transfer uncertainty in the environment to calculations of acoustic fields and the subsequent use of acoustic fields in estimating and displaying the state of targets of Naval interest.

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