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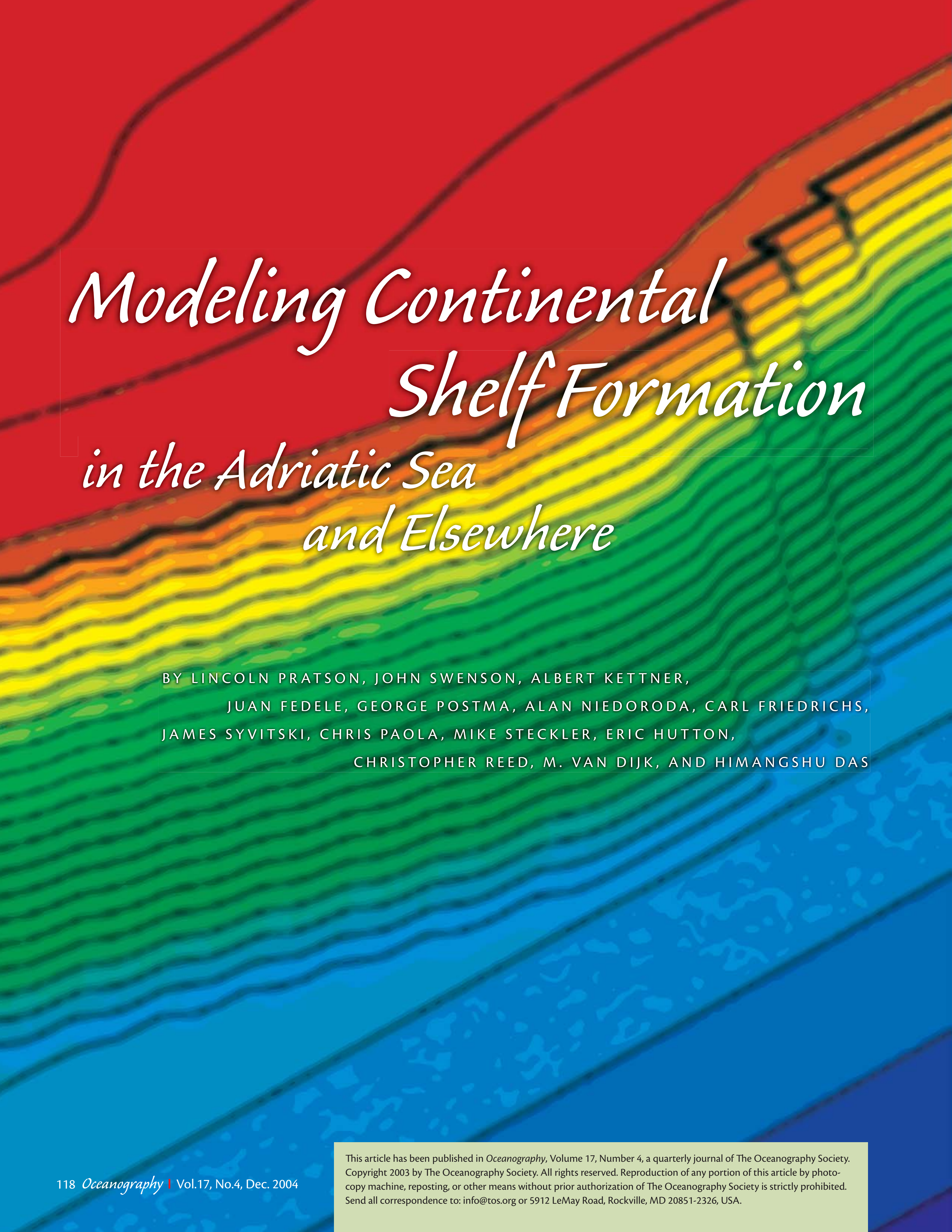

Modeling Continental Shelf Formation in the Adriatic Sea and Elsewhere

BY LINCOLN PRATSON, JOHN SWENSON, ALBERT KETTNER, JUAN FEDELE, GEORGE POSTMA, ALAN NIEDORODA, CARL FRIEDRICHS, JAMES SYVITSKI, CHRIS PAOLA, MIKE STECKLER, ERIC HUTTON, CHRISTOPHER REED, M. VAN DIJK, AND HIMANGSHU DAS

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Over geologic time, continental shelves are repeatedly flooded and exposed by relative rises and falls in sea level. As such, shelves are shaped and reshaped by subaerial, coastal, and submarine processes. While these processes can be studied today, the temporal and spatial scales over which shelf morphology and strata are created are beyond the realm of direct observation. The incompleteness of the stratigraphic record and of records of past environments complicates matters even further for it riddles geologic interpretations of strata with uncertainties about what formed when, where, why, and how.

The Office of Naval Research STRATAFORM program used numerical and experimental modeling as a means of telescoping the erosion, transport, and deposition caused by sedimentary processes up to the temporal and spatial scales over which continental shelves evolve (Nittrouer and Kravitz, 1996). This same approach is now being used in the EuroSTRATAFORM program. Models developed during STRATAFORM are being integrated with new models to ultimately simulate event-based margin sedimentation in three dimensions from minutes to millions of years. Sherwood et al. (this issue) explain how this linkage is being achieved. Here, we focus on major accomplishments reached thus far in the longer-term modeling of shelf development.

Because of the Adriatic shelf's polygenic origin, our paper is divided into three major sections. The first deals with modeling of fluvial sedimentation, which molds shelf settings during lowstands in relative sea level and governs the supply of clastic sediments to shelves at all times. The second section concentrates on modeling of offshore sedimentation and the formation of shelf morphology and strata under the influence of currents, waves, and submarine gravity flows. The final section summarizes modeling that couples subaerial and submarine development of the shelf and movement of the intervening shoreline.

The modeling in EuroSTRATAFORM complements the field studies highlighted elsewhere in this special issue of *Oceanography*. And because the fieldwork during the first half of the program has focused on the Adriatic, so too has much of the modeling. The longer-term modeling is not margin-specific, and the findings highlighted here have bearing on shelf formation in general.

SUBAERIAL STRATA FORMATION

As with many other basin settings, the first-order controls on the formation of the continental shelf are subsidence, sediment supply, and global sea level or eustasy (Vail et al., 1977). The large and rapid glacio-eustatic fluctuations that occurred during the Quaternary overwhelmed thermal subsidence along nearly all continental margins and wrought corresponding fluctuations in fluvial sedimentation as river systems responded to the vacillations in base level (Haq et al., 1988). Drainage areas grew and shrank, and river channels aggraded, avulsed, incised, and infilled. A number of these changes have continued to occur since the Holocene sea-level rise due in large part to human engineering of rivers and coasts.

Past changes in sediment supply are being simulated using *HydroTrend*, a numerical model that predicts the daily discharge and sediment loads from a river based on empirical relationships with drainage-basin characteristics and climate (Syvitski and Moorehead, 1999; Moorehead et al., 2003). The independent variables used in the model include hypsometry, relief, river networks, dams (if present), basin temperatures, evapotranspiration, and precipitation. Other sources of runoff such as groundwater and glaciers (if present) are factored in as well. The drainage basin characteristics are ideally derived from high-resolution digital elevation models, while the climatological variables are obtained from historical records or, if not available, climate model simulations.

HydroTrend is used to hindcast sediment discharge from the Po River since the Late Glacial Maximum (LGM) (Kettner and Syvitski, in press). The exercise indicates that the rise in eustasy over this period is the dominant influence on the hydrology of the Po river. Drainage basin area has shrunk by more than 50 percent over the last 18,000 years, reducing the average sediment flux that coursed through the Po River during the Late Pleistocene by an estimated 70 percent during the Holocene to Modern Period. *HydroTrend* predicts that the sediment load of the Po is highest during the Würm Stadial (21-17.5 thousand years ago [ka]), and that the river transported its coarsest-grained sediments during extreme floods caused by glacial ablation in the Bølling (15.6-13.9 ka) and Younger Dryas (12.9-11.1 ka) periods. In fact, the Younger Dryas cooling and warming may have led to the single largest excursion in sediment delivery from the Po and if so should have produced a significant signal in the offshore sediment record. The Po River of today is far less flashy than during the LGM, a result of the Holocene sea-level rise that has been augmented by dams emplaced along the river over the last half of the twentieth century (Surian et al., 2003).

In addition to the supply of sediments from rivers, modeling is also being done of the size distributions of the sediments delivered to the coast or left behind in river channels and flood plains. The sediments output by rivers differ from their input as a result of the downstream fining of grain sizes in channels. Because flow within river channels tends to maintain a constant dimensionless shear stress (Parker et al., 1998), hydraulic controls on sorting appear to play a secondary role to the initial size distri-

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bution of sediments supplied to a river and the subsequent rate of sediment extraction by deposition. These overriding influences are parameterized in a new downstream sorting model analogous to that of Paola and Seal (1995). The model uses a self-similar mobility function, in which the downstream transportability of sediments with an initial size distribution depends only on grain size relative to mean local size and the variance of all sizes being transported (e.g., Figure 1A). Comparison of model results against a 5000-year simulation produced using a detailed hydraulic model (Wright, 2003) suggests the simplified treatment forms a good first-order approximation for estimating channel sorting on long time scales.

Modeling of the larger-scale effects of floodplain formation on grain size distributions is being done heuristically. The modeling scheme is based on three different time scales in fluvial-basin evolution: a short time scale related to channel processes, an intermediate time scale associated with channel belt formation and flooding, and a long time scale linked to channel belt avulsions. This last aspect is influenced by the rate at which space for accommodating sediments is created by subsidence versus infilled by flood deposition between and away from channel belts. Figure 1B shows variations in the fraction of a fluvial-basin cross-section occupied by channel-belt deposits (sand) computed for different patterns of subsidence using this three-part formulation.

The evolution of fluvial channels is also being examined experimentally. A study at Utrecht University is testing the hypothesis that avulsion frequency is related to the rate of delta growth. Experiments have been run in which the only difference is water discharge. In these experiments, water carrying fine (D50 = 220 µm) sands enters a shallow basin through a narrow (3 cm) valley that forces constant inflow conditions to the basin. The inflow then segments into a system of distributary channels, which through channel avulsions and overbank deposition, builds and progrades a delta (Figure 2A). The growth of the delta and the frequency with which the channels

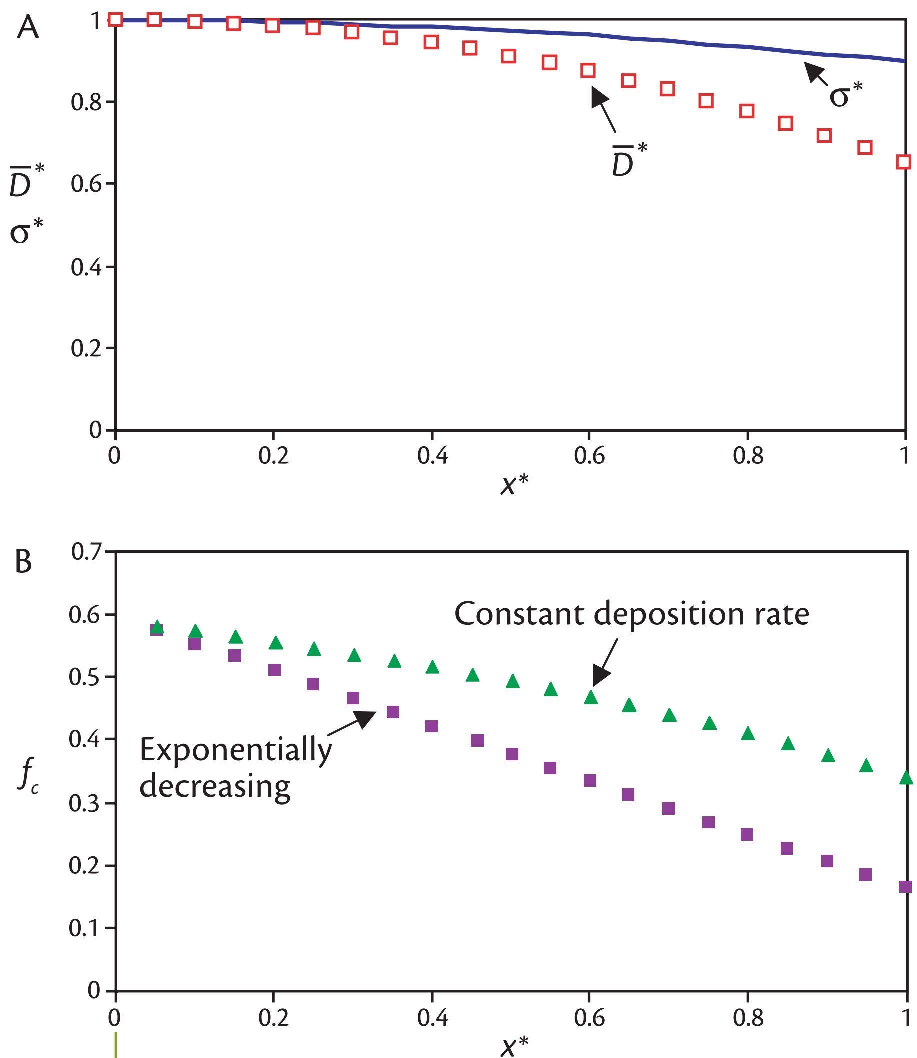
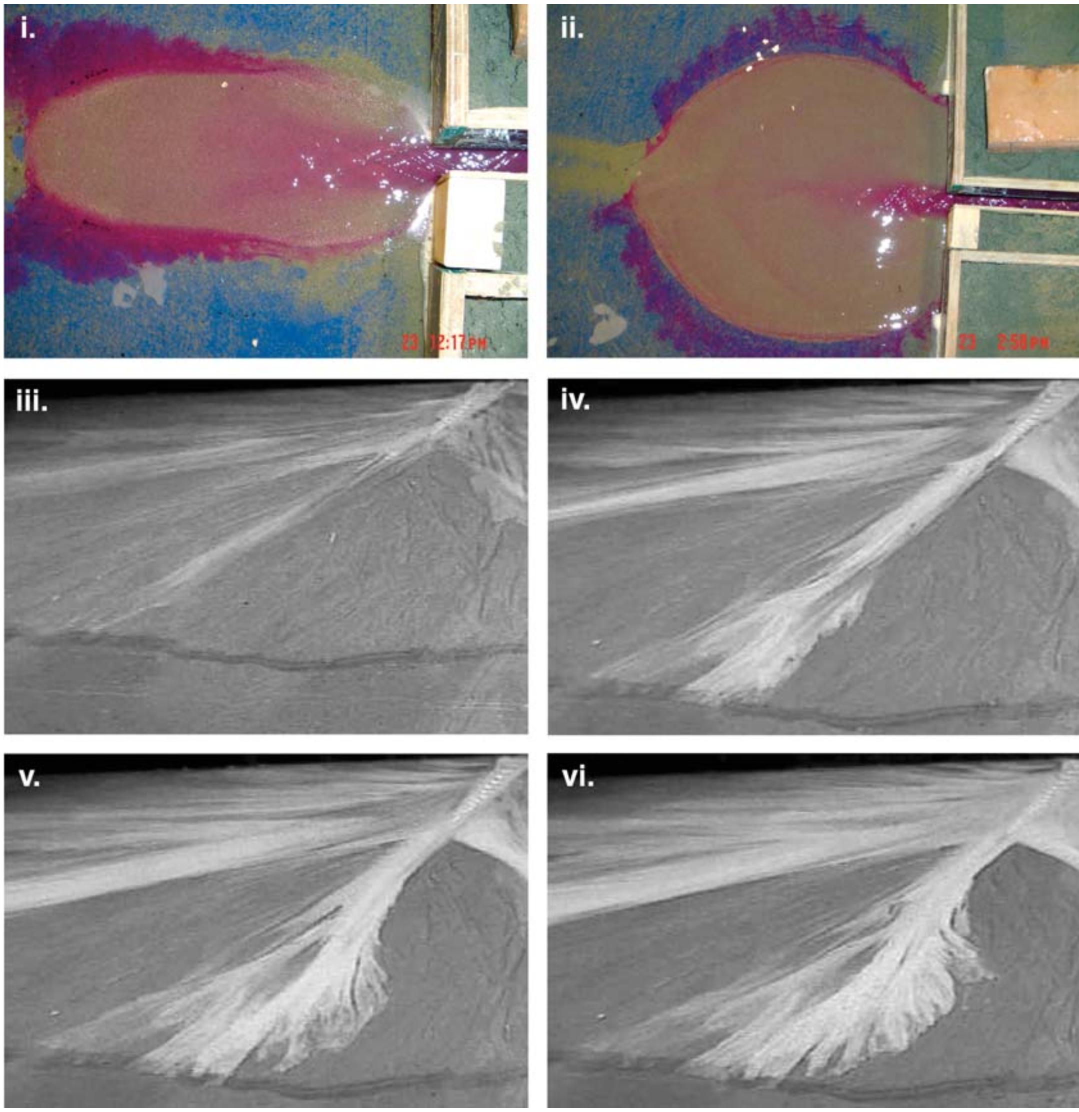


Figure 1. Simulations of size distributions of sediments delivered to the coast or left behind in river channels and flood plains when flooded by a sea-level rise. (A) Downstream fining of sediment grain sizes in a river channel by hydraulic sorting. $\bar{D}^*$ is normalized variation in mean grain size, and σ* is standard deviation in grain size, both of which vary as a function of normalized distance *x** from the point of sediment input. (B) Downstream variation in the fraction of a river basin cross section occupied by sandy channel-belt deposits for constant and exponentially decreasing rates of sediment deposition with distance from the point of sediment input.

A



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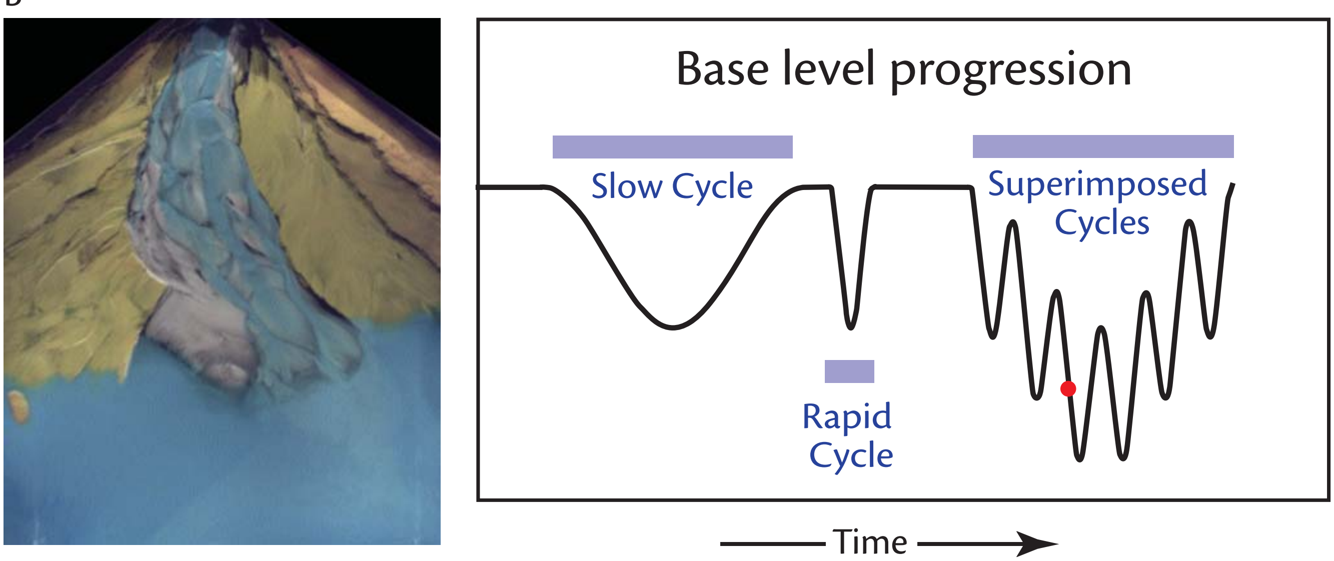


Figure 2. Laboratory experiments of delta formation and river channeling during shoreline regressions. (A) Evolution of experimental delta created at the Utrecht University: (i) initial jet deposit; (ii) deposition beginning to interact with flow to form a bar or "leaf"-like deposit (purple color of water due to dye); channel cutting (iii and iv), followed by backfilling of the channel as indicated by back stepping splays (v and vi) that finally leads to a new avulsion. (B) (left) Incised valleys and unpaired terraces formed in the XES Basin, University of Minnesota. (right) Plot of experimental "sea-level" curve; red circle indicates time when photo (left) was taken.

shift position are measured from digital time-lapse video.

In the experiments, delta evolution begins similarly. The inflow jets straight into the basin and then disperses in a sheet flow-like fashion to form an initial delta that is lobate in shape. As the delta grows, though, it reaches a size that the sheet flow cannot completely cover and the flow breaks up into a distributary drainage system. Through channel splitting and avulsions, the flow continues to enlarge the lobate form of the delta (Figure 2A). Preliminary results suggest that the larger the water discharge to the delta, the more frequent the channel shifting and the less parabolic the curved edge of the delta.

A second experimental study being done at St. Anthony Falls Laboratory (University of Minnesota) is examining fluvial channel evolution over the course of changes in base level. The study is being carried out in the eXpermintal EarthScape (XES) subsiding-floor laboratory basin (Paola, 2000; Paola et al., 2001). An experiment has been run in which sediment and water inflow to the basin were held constant, and subsidence rates were constant in time but increased linearly downstream from the basin inflow. The only controlling variable that was adjusted with time was base level, which was made to undergo a single slow cycle followed by a single rapid cycle and then a series of short cycles superimposed on a single long cycle.

The experiment produced a series of stacked deltas with complex channel morphologies. Incised channels formed only during the rapid base level cycles and did so through a combination of incision triggered by the base-level fall and incision associated with channel avulsions as a delta prograded basinward in response to the fall (Figure 2B). The incised channels were narrow upstream, but widened downstream due to increasing deposition rates in that direction. The result was a tapered planform comparable to those found in natural estuaries. During rises in base level, further channel widening occurred as the channels flooded. However, the drowned channels never completely infilled with sediments during these times, suggesting that in the absence of wave and current reworking of the bed, the shelf will retain a topographic imprint of fluvial channels formed when the shelf was last subaerially exposed.

SUBMARINE STRATA FORMATION

Once sediments are carried past the shoreline, they have the potential of being moved even farther seaward by a combination of marine processes. These range from river plumes, waves, and currents to submarine gravity flows. All of these processes are active in the Adriatic Sea and modeling predicts that all have left discernible imprints on the shelf morphology and strata.

The impact of plume sedimentation depends on the river discharge and the size of the river's drainage basin with respect to flood-generating storms. This is re-enforced in a study by Pratson et al. (2003) using *PLUME*, a numerical model that simulates river plume spreading and sedimentation (Moorehead et al., 1999). The stratigraphic record produced by the process is modeled for two rivers. One is the Po, which has a drainage basin that extends over much of northern Italy and is subject to relatively infrequent but large, sustained floods. The other, the Pescara River, drains a much smaller area in the Apennine Mountains of south central Italy and its floods are smaller, shorter, and more frequent. Two past-versus-present simulations of plume sedimentation were generated for each river. The Po simulations contrast the past 100 years of sedimentation with a 100-year interval during the LGM, while the Pescara simulations contrast 100 years of sedimentation before and after the emplacement of dams. Due to a lack of hydrologic data, the discharges for all of these scenarios were modeled using *HydroTrend* (Kettner and Syvitski, in press; Syvitski and Kettner, in press).

In the simulations for each river, which total 200 years, deltas form off of the river mouths (Figure 3A). Due to its order of magnitude greater discharge, the Po Delta progrades more than three times farther than the Pescara (~15 km vs. <5 km). Outbuilding of both deltas, however, is slowed by the reduction and fining of sedimentation during the second 100 years of the simulations. In the case of the Po, this reduction is caused by the drop in discharge since the LGM (see previous section), while for the Pescara, it is due to the damming of the river. The changes in grain size lead to corresponding changes in the acoustic reflectivity of the seabed, suggesting the changes may be discernible in seismic reflection data. Mean variations in reflectivity likely diminished gradually since the LGM, but damming of the rivers should have caused an abrupt decrease (Figure 3B).

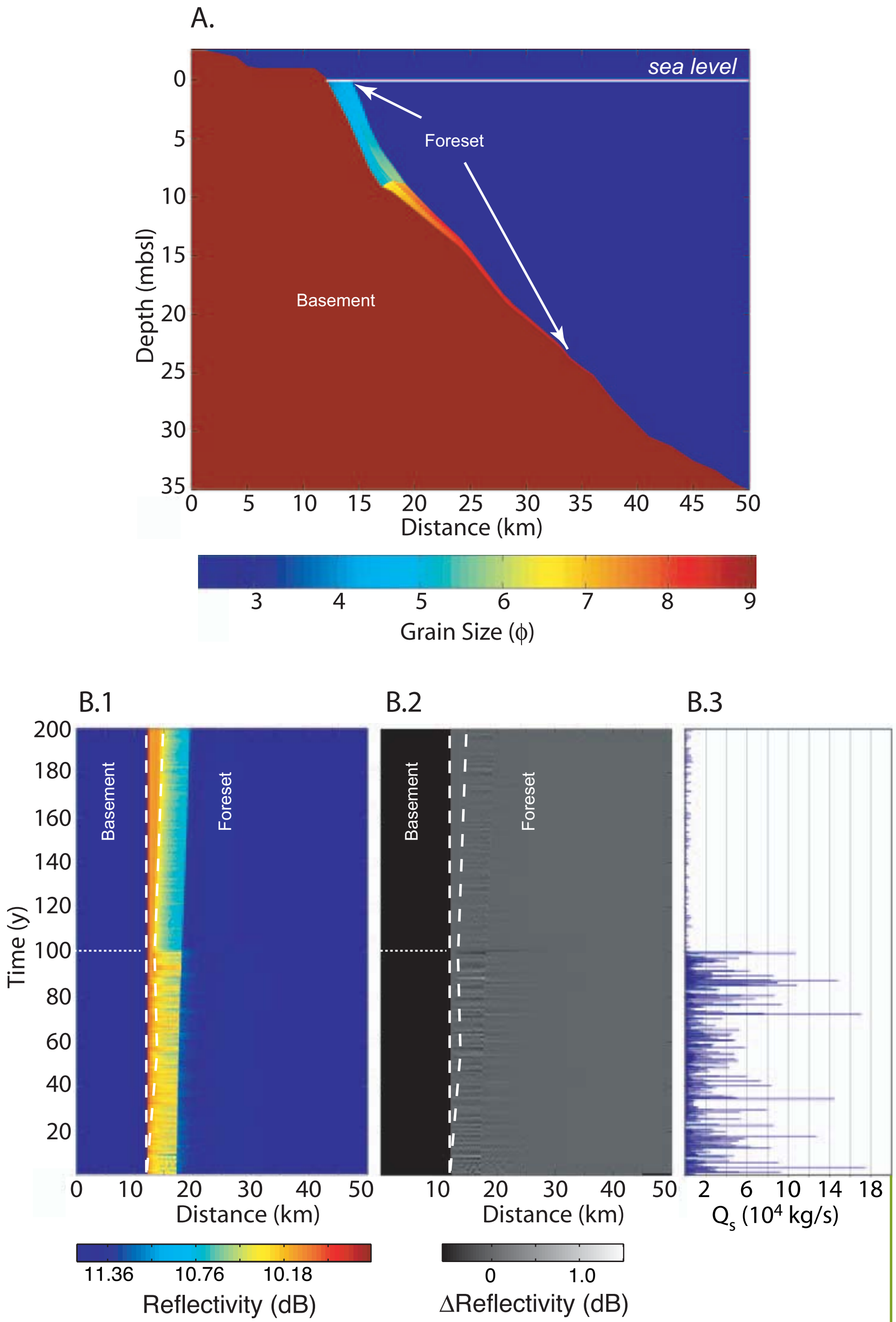


Figure 3. Simulation of changes in seabed reflectivity on the inner shelf as caused by episodic deposition from river floods. (A) Delta modeled from *HydroTrend* simulation of 100 years (y) of sediment discharge before the emplacement of dams along the river and 100 y of sediment discharge afterwards. (B) Annual change in seabed reflectivity with distance from the left side of the model: (1) absolute reflectivity, (2) annual change in reflectivity, (3) *HydroTrend* discharge simulation.

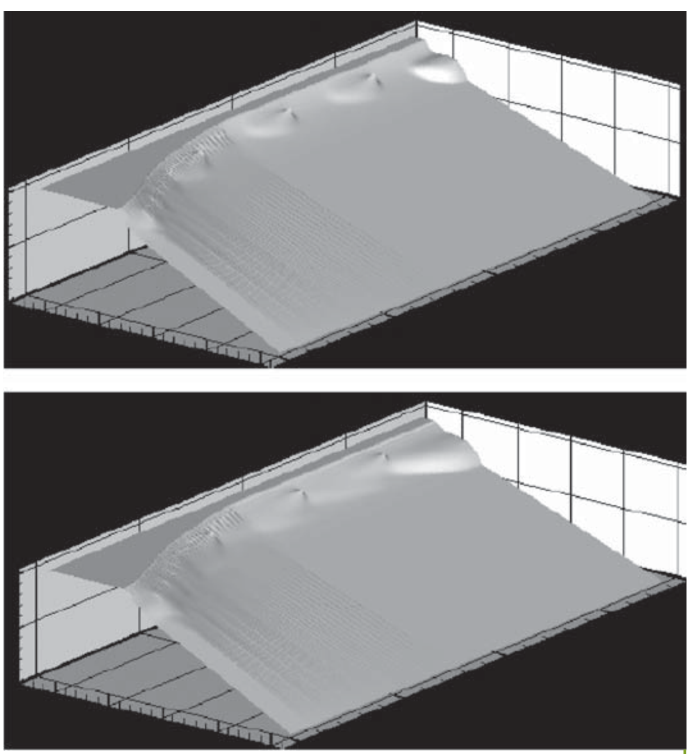
Individual flood events, however, should still produce the greatest change in seabed reflectivity, a change that preliminary estimates suggest will be ~10 percent (Figure 3B) (Pratson et al., 2003). This is a drop in signal strength of the seabed bottom echo approaching 1 dB (decibel), which by acoustic standards is significant.

In the western Adriatic, river plumes are turned to move southeastwards parallel to shore by the Sea's cyclonic currents (Cattaneo et al., 2003). Individual river plumes combine into a single, long coastal jet that extends the length of a 500-km-long actively prograding clinoform, which also parallels the Italian Adriatic Coast. The correspondence suggests that the clinoform is the product of sedimentation from the coastal plume. However, the clinoform is wider than the plume in the offshore direction, and the deposit volume is much larger than can be attributed to this sediment source. All of this indicates that other marine processes are important in the clinoform formation. The combined roles of two of these, waves and currents (including tides, wind-driven, and geostropic currents), have been explored using a large-scale, behavior-oriented numerical model referred to as the Coastal Systems Tract (CST) model (Niedoroda et al. 2001, 2003; Niedoroda et al., in press). The CST model simulates the time-averaged impact of waves and currents in re-entraining and moving sediments about the littoral, shoreface, and shelf environments over periods of thousands of years. The shoreline and upper shoreface positions move in response to longshore transport gradients. The output shows the three-dimensional morphology and stratigraphy.

Behavior-oriented models depend on fitting major model parameters to observed features in the regimes being represented. The feature used in this study was the shore-normal profile of the shelf depositional terrace or clinoform. Seismic reflection data suggest that the shallower portion of this profile has become a bypassing surface as the clinoform has widened into deeper water. By assuming this to be the case, the profile can be used to invert for the local depth- and time-averaged wave-biased variables in the model that yield sediment entrainment. Entrained sediments, along with those introduced by rivers, are then moved and re-deposited according to observed current patterns.

Repeating this process over time, the CST model generates a series of subaqueous deltas that build out and downcurrent from the mouths of the Po and Appenine Rivers. The biggest and fastest growing of these forms offshore of the Po, but after 5000 years of progradation, all of the subaqueous deltas have coalesced into single, large-scale clinoform and their individual shapes are obscured. The final model clinoform approaches the size and shape of the present inner shelf depocenter (Figure 4A). Successive surfaces of the model clinoform as

A



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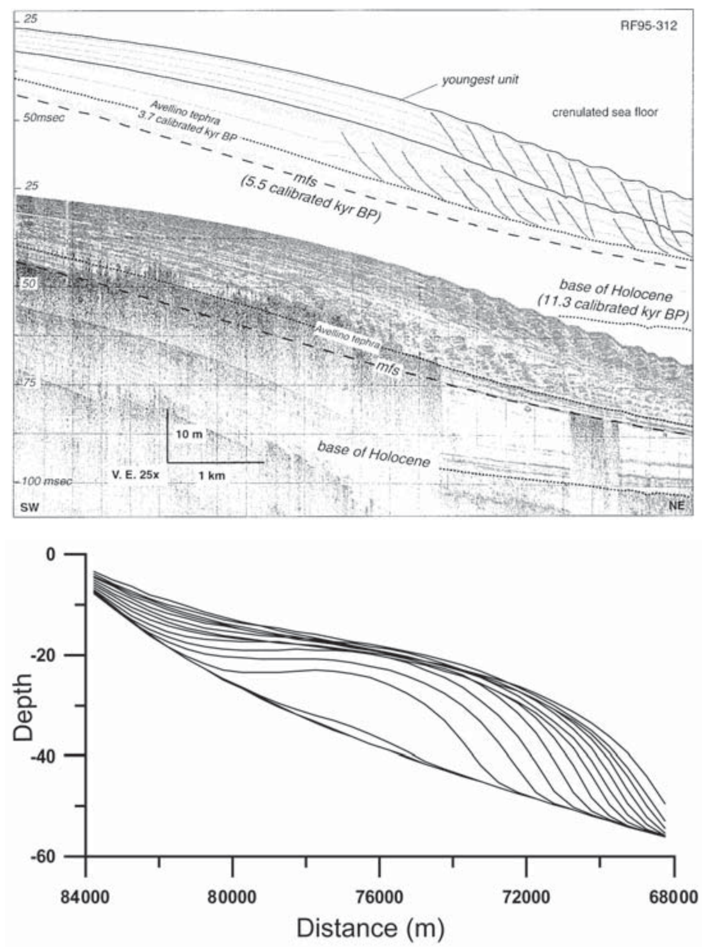

Figure 4. Simulation of the morphologic and stratigraphic evolution of the continental shelf in the western Adriatic offshore of the Appenine Coast, Italy. (A) Two stages in the development of the inner shelf depositional wedge or subaqueous clinoform. Top: initial development. Bottom: after 5,000 years of model progradation. Bathymetric highs along shoreline are formed by the sediment input at the mouths of the Appenine Rivers. (B) (top) seismic profile across the subaqueous clinoform (from Correggiari et al., 2001) versus (bottom) the buildup of successive model surfaces predicted for millennial-scale variations in the rate of sediment supply.

it evolved also show a first-order resemblance to the stratal geometry of the real clinoform as imaged in seismic reflection data (Figure 4B).

As clinoforms grow (Figure 4B), their tops become a surface of bypass and growth becomes focused at their fronts or along the foreset region. The assumption that the shelf is a bypass surface and thus in equilibrium with the processes moving sediments across it is being further explored in a modeling study of shelf evolution under the influence of wave-induced turbulent gravity flows (Friedrichs and Wright, 2004). Like the turbidity currents they can devolve into, these are high concentration sediment-laden bottom flows, but the sediments in them are partially to wholly kept in suspension by wave-generated turbulence. Such wave-induced turbulent gravity flows are increasingly being observed on the continental shelf particularly offshore of muddy rivers with high sediment yields (Ogsten et al., 2000; Traykovski et al., 2000; Wright et al., 2002). Waves coincident with river floods initiate these events, and waves help keep sediments in suspension once these currents are underway. A time-averaged, depth-integrated analytical model has been derived for a wave-supported gravity flow (Friedrichs and Wright, 2004). The model solves for the equilibrium shelf profile across which there is a balance between the supply of sediments from a river at the coast and the downslope bypassing of the sediments to deep water by the coupled wave-turbidity current transport. The resulting equilibrium profile is convex, with bottom slope increasing seaward such that the attenuation of wave agitation with water depth is compensated for by an increase in the downslope pull of gravity, which takes over as the main turbidity-current driver (Figure 5A).

The two model inputs that govern the convexity of the equilibrium shelf profile are root-mean-square (RMS) wave height, and river sediment discharge per unit length along-shelf during floods. Values for these parameters have been compiled for different shelves offshore of major rivers from around the world. When input to the model, these values yield equilibrium profiles that approximate to first order the convex portion of the shelves. The general relationship is that as wave height increases and/or sediment supply decreases, the equilibrium profile deepens and broadens (Figure 5B).

COUPLED SUBAERIAL-SUBMARINE STRATA FORMATION

Subaerial and submarine strata formation are linked by the shoreline, which moves in response to sea-level fluctuations, climate change, and human activities. Shifts in the shoreline change the distribution and activity of sediment-transport processes across a continental margin while also triggering behavioral changes in the transport processes that propagate away from the shoreline in both landward and seaward directions. These changes include adjustments in river gradients, fluvial sediment loads, and the sediment trapping and transport efficiencies of shallow-water environments. The adjustments can alter the flux of sediments across the shoreline such that it moves opposite to the direction it would if driven by changes in sea level alone. Consequently, the stratigraphic record of the shoreline is a sensitive but complex history of environmental change. Insights into the forces that drive shoreline movement are being gained through modeling of the coupled subaerial-submarine evolution of continental margins.

One such modeling effort uses a morphodynamic approach to simulate the joint evolution of the coastal plain and continental shelf. The fluvial development of the coastal plain is modeled using the diffusion formulation developed by Paola et al. (1992), while a depth-dependent advection-diffusion equation governs the long-term behavior of the

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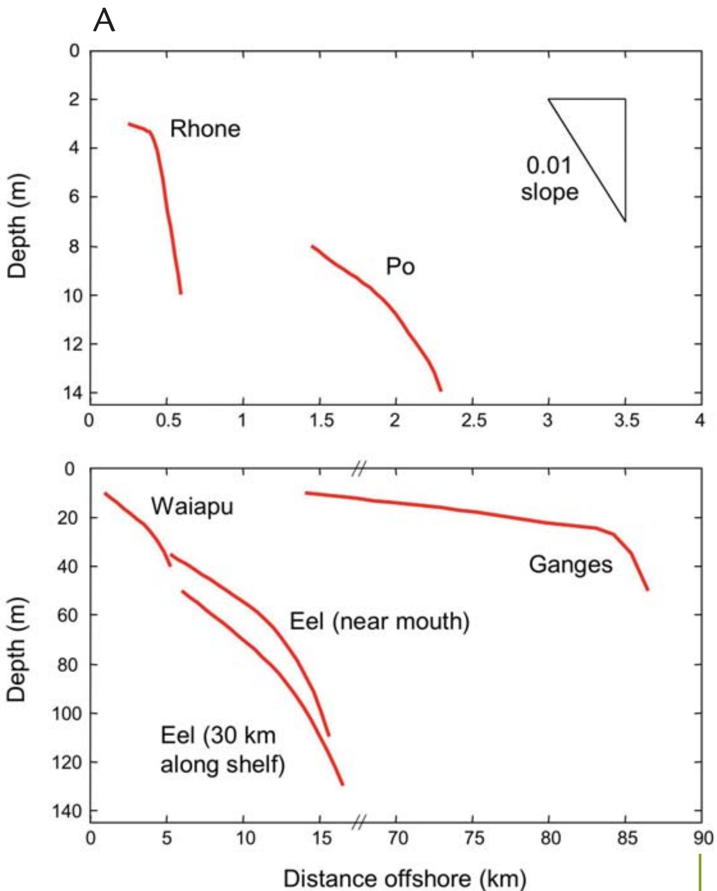

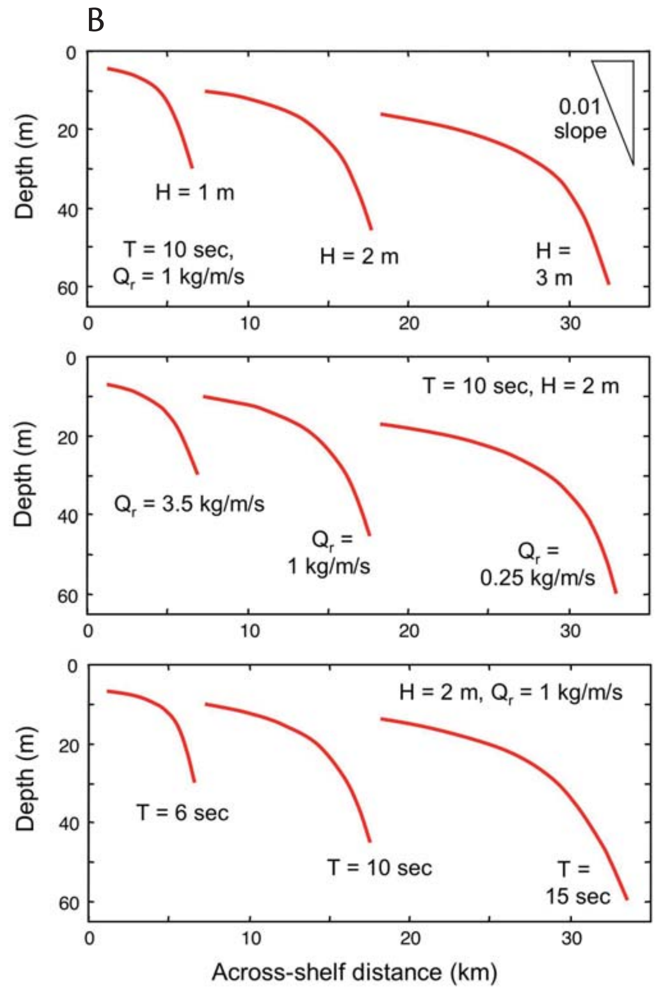

Figure 5. (A) Bathymetric profiles across well-resolved, convex upward portions of subaqueous deltas/clinoforms located on the inner shelf offshore of major rivers. (B) Inner shelf profiles modeled to be in equilibrium with wave climate and sediment input based on realistic ranges of river sediment discharge per unit length along-shelf, *Qr*, wave height, *H*, and wave period, *T*.

shelf. To maintain the same generality and uniform time scale over the whole model domain, a linear sloping shoreface is prescribed to form a shock condition for coupling the two equations. As in nature, the shoreline is not fixed, but is instead a dynamic moving boundary that responds to specified time-averages of fluvial discharge, wave height, and current strength.

The morphodynamic model has been used to generate both two-dimensional and three-dimensional simulations of shelf-coastal plain development. The two-dimensional simulations predict general environmental conditions under which simple versus compound shelf surfaces will evolve (Swenson et al., 2003a). If wave heights and ocean currents are on average low, as in a protected basin, fluvial transport processes will dominate to form a subaerial delta and a narrow shelf (Figure 6A). But if waves and currents are more energetic due to greater storminess, a complex shelf forms, one in which the subaerial delta links to a wide subaqueous delta (Figure 6B). When sea level varies, relatively small changes in fluvial sediment supply and ocean activity can generate significantly different stratigraphy. Where fluvial input overwhelms marine sediment movement, sea-level cycles will produce spatially restricted erosional surfaces during sea-level falls and deposits dominated by fluvial sediments when sea level rises back up again (Figure 6A). In contrast, heightened marine sediment transport can create wide subaqueous deltas that will lead to an extensive erosion surfaces when exposed by a sea-level fall (Figure 6B). As sea level then rises, the same region is eroded by waves, and a broad overlying deposit of shallow-marine strata forms (Figure 6B).

The simulation addresses the added complexity of sediments being sourced from multiple rivers of varying discharge during the course of a single, high-amplitude sea-level cycle superimposed on slower, background subsidence (Swenson et al., 2003b). The most notable outcome of the simulation is the development of paired subaerial and subaqueous deltas (the latter being completely submerged and of submarine origin). During rapid sea-level rise, the tops of existing subaqueous deltas are starved of sediment (Figure 7A). But as the rise slows and ends, the river mouths develop new sub-

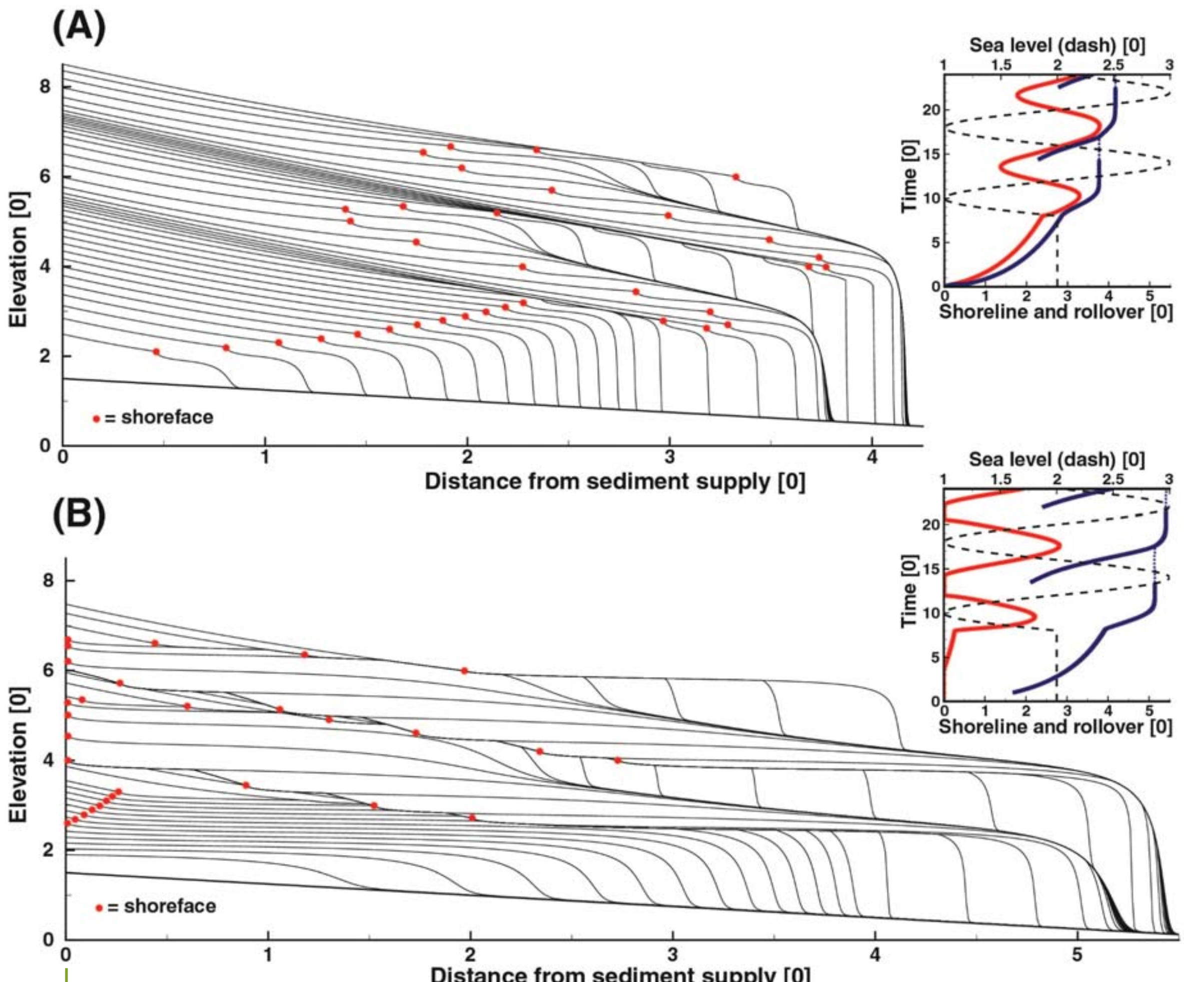

Figure 6. Offshore-oriented cross-sectional simulations of shelf evolution for cases in which (A) river input dominates and (B) wave/current activity dominates. In insets, dashed lines are sea-level change, red lines are shoreline position, and blue lines are position of clinoform rollover (i.e., slope transition from top to front of delta). Note how vigorous wave/current activity produces broader shelves (i.e., longer distances between shoreline [red dots] and shelf edge).

aerial-subaqueous deltas that prograde over the abandoned ones (Figs. 7B and 7C). Falling sea level drives rapid expansion of the fluvial systems, which in the simulation fuels the advance of the subaerial-subaqueous deltas. Eventually the subaqueous deltas reach the relict shelf edge, rejuvenating its progradation. (Figure 7D). Not unexpectedly, subaerial-subaqueous delta interference is strongest during sea-level fall and lowstand. In the simulation, this interaction renders the morphology of the margin largely two-dimensional. In contrast, margin morphology is strongly three-dimensional during sea-level highstands. Based on the choice of terrestrial-flood and coastal-storm parameters used in this simulation, the timing of overall margin growth (progradation) corresponds to the late fall and lowstand of eustatic sea level.

The morphodynamic modeling is significantly clarifying the timing relationships between strata formation and relative sea-level change conceptualized in sequence stratigraphy. However, a second modeling study of shelf-coastal plain evolution is showing that in the case of epeiric seas like the Adriatic, strata formation as a function of sea-level change may not fit the standard sequence stratigraphic model. The study is using *Sequence4*, an interactive, two-dimensional stratigraphic modeling program (Steckler, 1999; Steckler et al., 2001). For its application in the Adriatic, the model has been modified to include along-strike transport of offshore sediments. The focus of the study is the Gargano Peninsula region where a succession of four depositional sequences mainly composed of regressive deposits have been mapped by Ridente and Trincardi (2002). The sediments that comprise these sequences have primarily been transported along the Adriatic margin from the Po and other Apennine Rivers by the strong along-strike current system. The sequences exhibit along strike variations in thickness and morphology due to the local tectonics. These are being reproduced

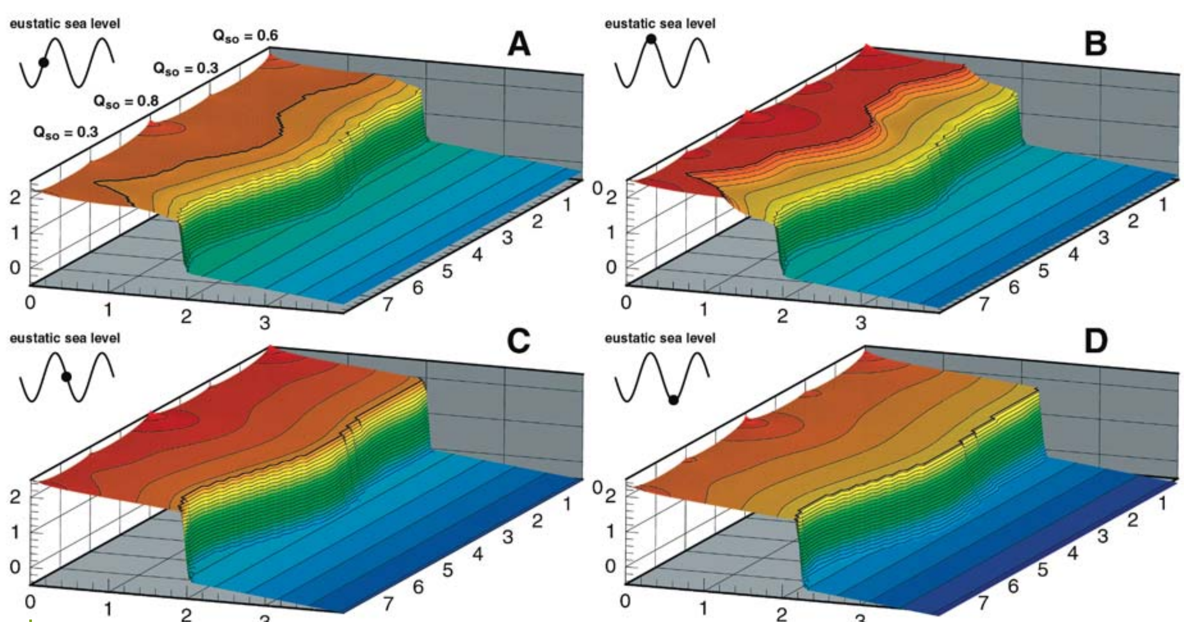

Figure 7. Morphologic evolution of the coastal plain and continental shelf in the vicinity of four rivers in response to changes in global (eustatic) sea level. Panels shows successive changes by the times of (A) rising sea level, (B) maximum sea level, (C) falling sea level, and (D) minimum sea level.

The achievements in modeling shelf evolution during the first half of EuroSTRATAFORM program have been significant.

with *Sequence4* by varying the sediment supply and uplift along the Peninsula.

Initial results of the modeling contradict typical assumptions about the evolution of continental shelf strata during sea-level changes. Sediment supply is commonly assumed to increase during sea-level falls when a larger area is subareally exposed and decrease during sea-level rises as surface area is flooded and sediments are trapped in estuaries. The modeling, however, is finding that along the Adriatic coast the opposite effect occurs due to a combination of the mainly marine, along-strike source of the sediments and the changes in its transport pathways associated with sea level. Little sediment is supplied from land at the Gargano Peninsula during either high or low sea level. Instead, the main sediment source to the shelf in this region is an along-strike current, which carries in sediments from the Po and Appenine Rivers to the north. Furthermore, this coastal flow operates only during highstands in relative sea level. During lowstands, the shelf is exposed and the enlarged Po River discharges directly over the shelf edge into the Mid-Adriatic Deep. This alternative sediment-supply pattern may be common along margins where sediment transport often has a large along-strike component, such as basins along active plate margins (i.e., foreland basins).

FUTURE WORK

The achievements in modeling shelf evolution during the first half of EuroSTRATAFORM program have been significant. Process-based models developed during the STRATAFORM program and validated in simulations of the New Jersey and northern California continental shelves have proven equally adept at simulating shelf evolution in the Adriatic. New morphodynamic models have also successfully reproduced fundamental elements of the Adriatic shelf while advancing a potent time-averaged approach for extending model simulations to three dimensions and for gaining first-order insights into shelf evolution in general. Similar insights are also gained using new laboratory facilities that offer an unprecedented means for studying how shelves and continental margins as a whole evolve in three dimensions under controlled environmental forcing.

Studies of shelf evolution during the second half of EuroSTRATAFORM program will focus on testing model predictions. Major comparisons of model simulations with field data will be conducted for both the Adriatic and the Gulf of Lions, the main subject of future modeling efforts. Simulations of shelf strata formation from the late Pleistocene to today will be compared against age and facies measurements from long cores now being collected in the Adriatic and Gulf of Lions by the PROMESS program. The comparisons will offer an opportunity to evaluate how the models used in EuroSTRATAFORM scale strata formation by event-based sedimentation up to millions of years. At the same time, the 2003 flood of the Rhône River will be used to further test the ability of the models to simulate a single event. Modeling of the flood deposit is underway in advance of sampling that will occur during a field campaign in the Gulf of Lions. Model results will be used in determining sampling locations, while cores from these locations will test model predictions of such deposit attributes as thickness, grain sizes, and acoustic properties.

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