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Analyses of a large-scale depositional clinoformal wedge along the Italian Adriatic coast

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Abstract

The processes controlling the formation of the late Holocene high-stand systems tract along the central Adriatic coast – a prograding clinoformal sediment wedge – have been diagnosed using a large-scale behavior-oriented numerical model. This model is based on time-averaged marine sediment dynamics, allowing it to represent processes acting over millennial time spans. River-derived sediment is redistributed by the combined action of littoral, shoreface and shelf processes. In this application the numerical model successfully simulates both the overall geometry of the deposits and the internal time-line stratigraphy.

The simulation of this prograding clinoform with the numerical model clearly shows that the growth of these deposits depends on the combined effect of a strong and persistent coast-parallel advection and cross-shelf dispersion related to a large number of sediment re-entrainment events. This means that this clinoform is in the process of forming a new shelf surface with an offshore profile that is in adjustment with the present wave and current climate along with the relative stability of sea level over the past six millennia.

Keywords: shelf stratigraphy; marine clinoforms; marine sediment dynamics; behavior-oriented; modeling; Adriatic sea; Dansgaard–Oeschger cycles

1. Introduction

An extensive subsea terrace stretches about 500 km along the central Italian Adriatic coast. This has been described in detail by Correggiari et al. (2001), Cattaneo et al. (2003) and Cattaneo et al. (2004). Fig. 1(a) shows a satellite view of the entire Italian Adriatic coast with a near-shore plume extending southward from the Po delta. This spectacular view illustrates several features of the sedimentary regime. The coast-wise transport shows a coherent pattern along the entire coastline. The suspended plume originates at the Po delta and is augmented by discharges from small rivers draining Apennine watersheds. The ob-

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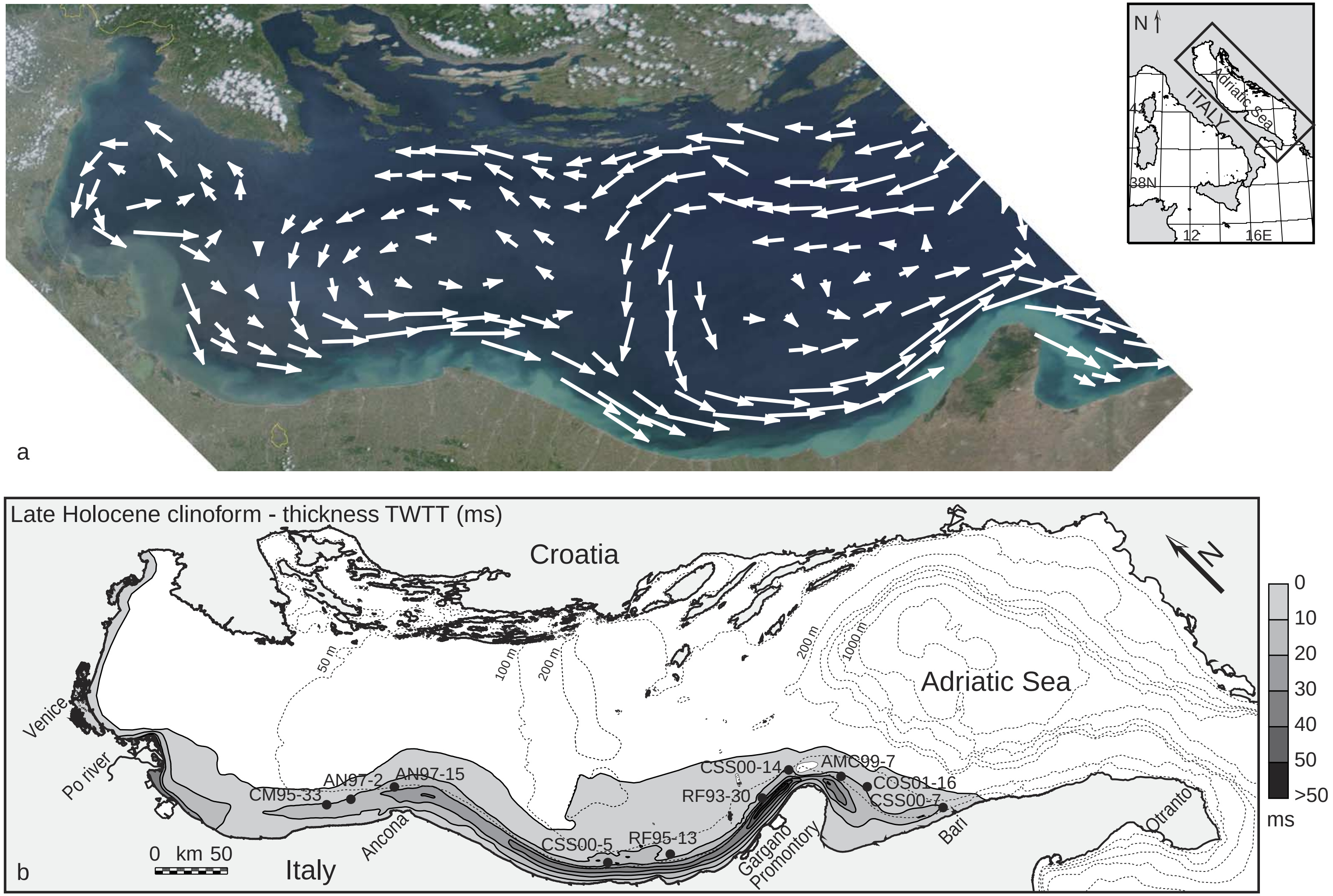

Fig. 1. (a) Satellite image of the Italian Adriatic coast with suspended sediment plume. White arrows show surface circulation from Poulain (2001). (b) The Holocene subsea clinoform of the Italian Adriatic coast (from Correggiari et al., 2001, as redrawn in Cattaneo et al., 2003). The thickness of the clinoform is represented on the western side of the basin by grey shading, from 0 to 50 ms of two-travel time (TWT) in the seismic data. Fifty milliseconds represents approximately 40 m. Bathymetric contours (white ovals) are in meters. The model domain extends 160 km from the Gargano Promontory to 70 km South of Ancona and 90 km offshore.

servable length of this coastal plume of suspended sediment corresponds to the length of the subsea terrace. From these observations it is tempting to draw the conclusion that the plume is the direct source of the terrace formation and the sedimentary wedge that supports it. However, the terrace is more extensive in the offshore direction than the coastal plume. This, and the composition of the sediments in the sedimentary wedge, suggests that the processes that have been forming the clinoformal wedge are more involved than simple settling from the suspended coastal plume. Although longshore sediment transport in the littoral and coastal plume systems are important, they mainly serve to distribute the sediment load along the coast without a net sediment export offshore. The redistribution of the sediment load over the entire clinoformal wedge is instead caused by the action of varying currents and wind waves, which resuspend and transport sediments in deeper water. When viewed in the long term it is not necessary to examine the details of each episode of resuspension. Instead, this is better viewed as large-scale diffusion of the sediments (Niedoroda et al., 1995). It is then the combined effect of longshore currents and wave–current resuspension that controls the shape of the submerged terrace and the internal geometry of the clinoformal deposits. Time-averaged advection contributes significantly to the alongshore shelf sediment flux while the cross-shore flux results primarily from large-scale diffusion.

It has been proposed (Niedoroda et al., 1995) that for most shelf environments there is a unique shore-normal depth profile that is controlled by the wave and current climate, rate of sediment supply, size and type of sediment and rate of sea-level rise. When this profile exists, the time-averaged cross-shelf sediment transport flux is uniform, resulting in a total bypassing condition between the coastline and the shelf edge. This equilibrium profile can be also seen as an extension of the shoreface equilibrium profile of Dean (1991) to the inner shelf topography.

It was demonstrated in the Niedoroda et al. (1995) paper and others (e.g., Stive and deVriend, 1995) that, in most shelf locations, the time scale for achieving this bypassing condition is long compared to the rates at which sea-level variations occur. Consequently, the modern shelf profiles often represent the results of processes that occurred as the shoreline migrated across them during the Pleistocene and Holocene epochs, with modifications introduced by more recent marine sediment dynamics. However, this situation is far from universal. There is a wide spectrum of scenarios, from coastlines where modern processes, acting over the past several millennia of relatively stable sea level, have had only minor effects to coastlines where these processes dominate the characteristics of the shelves.

The Holocene subsea clinoformal wedge that has formed along the Italian Adriatic coast over the past 5500 years (Cattaneo et al., 2003) appears to be a particularly good example of a virtual end-member in that spectrum, a shelf environment dominated by modern processes. This provides an example that can be simulated with the large-scale, behavior-oriented CST numerical model (Niedoroda et al., 2001, 2003).

2. Background

The central Adriatic Holocene subsea terrace extends more than 500 km from the Po River to the Gargano peninsula. It ranges from 40 km wide in the north near Ancona to about 25 km wide near the Gargano Promontory. It is up to 35 m thick and formed over the last 5500 years (Cattaneo et al., 2003). Fig. 1(b) shows the thickness distribution of these deposits. Fig. 2 shows that the associated clinoformal wedge lies above a maximum flooding surface that is readily identified as a low-angle downlap in the sub-bottom records (Correggiari et al., 2001). The sediment is derived from the Po River and a number of smaller streams draining the Apennine watershed. It is clear that these deposits have grown both southward and seaward. The seaward growth is indicated by a progressive offshore shift of the zone of maximum sedimentation over time. The mechanisms controlling these deposits have not yet been expressed quantitatively.

We have applied a numerical model to simulate the formation of this subsea clinoform and to diagnose the processes that caused its formation. The behavior-oriented CST model was used. It is based on the Coastal System Tract concept. As explained in Cowell et al. (2003a,b) the term Coastal System Tract is used to emphasize the continuum of sediment sharing systems in the nearshore marine environment in a manner

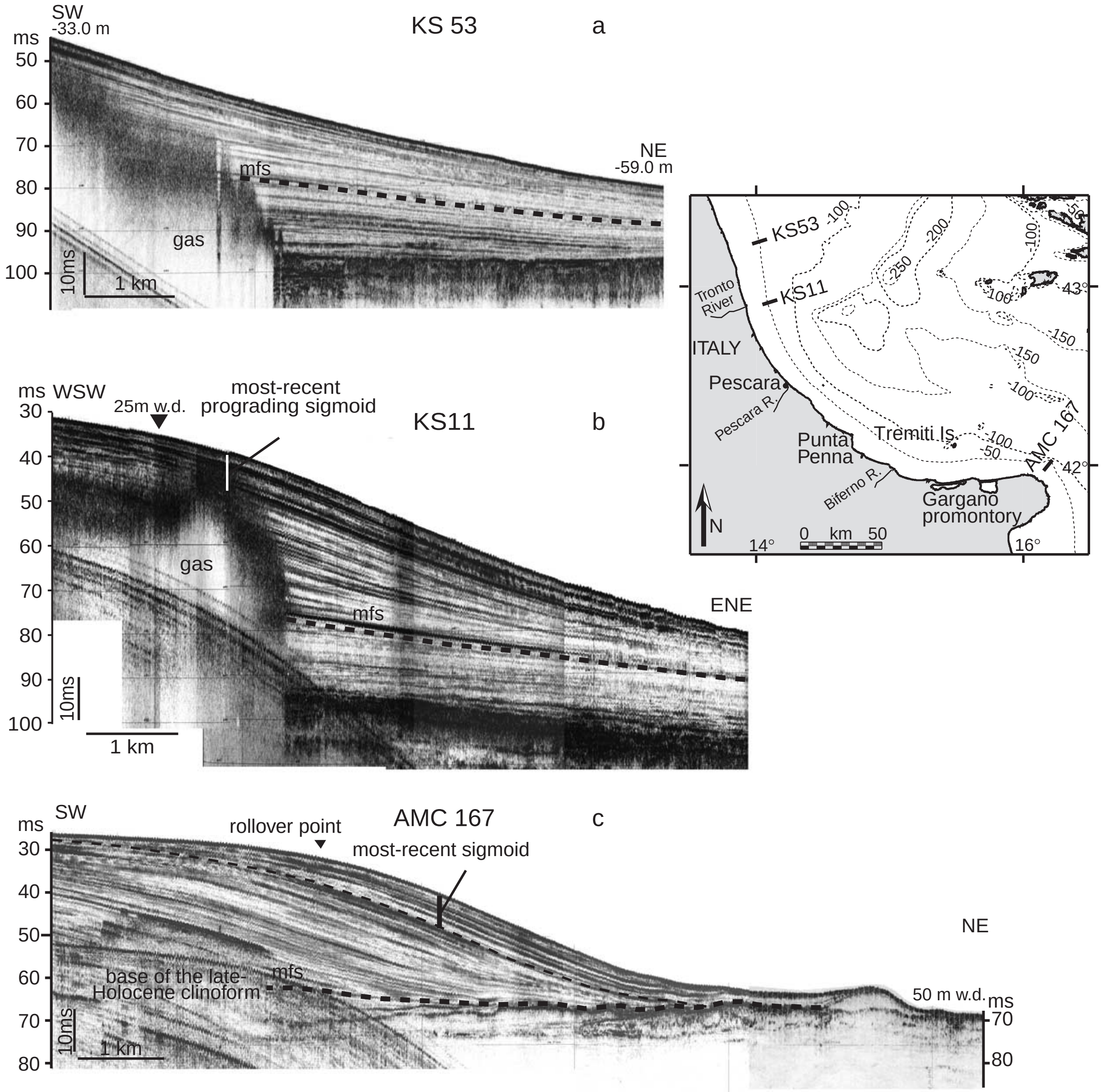

Fig. 2. Three high resolution 3.5-kHz sub-bottom records showing how the Holocene subsea clinoform has grown upward, seaward and along the coast. Although line AMC 167 is south of the area modeled, it shows a clinoform geometry similar to the other lines and extends well shoreward of the rollover point.

similar to the way the term "system tract" is used in stratigraphy to define depositional systems grouped together and ascribed to a particular interval of a relative sea level curve. In this concept, coastal systems are viewed as comprising discrete dynamic components. Examples of these components are the beach/surf zone, the shelf, and tidal inlet components. This long-term approach is particularly suitable for the study of depositional systems and for the coupling of coastal environments to terrestrial landscape models (Fagherazzi et al., 2004). Each dynamic component of the entire coastal sedimentary system shares the available sediment supply according to the dictates of the differing large-scale sediment dynamics. The model (Niedoroda et al., 2001, 2003) is a multi-line model with individual mathematical representations of the coastal system components. Sediment transport fluxes and gradients are computed within each of the dynamic components. The fluxes are transferred between components at their boundaries at each time-step so that the model fully represents the continuum of the combined systems. The components that were used to analyze the Adriatic deposits are briefly explained in the following text.

Surf zone sediment transport and wave-induced shelf sediment entrainment are modeled using a time-averaged, power-equivalent wave climate. That is, it is assumed that the actual wave climate of a region can be reduced to a single set of parameters that include the significant wave height, the wave period and the deep-water wave propagation direction parameters based on similarity of the power density equivalency to an annual average wave climate. These waves propagate across the model ocean domain and provide bottom fluid stress which, when combined with a time-averaged stress due to currents, entrain shelf-and shoreface sediments. This combined stress yields a time-averaged entrained sediment concentration across the shelf portion of the model domain. The waves are refracted and undergo shoaling transformations by the bathymetry in the model. The computed refraction is accomplished by a function that increases exponentially with decreasing depth and that tends to bring the initial wave propagation direction into alignment with the local slope normal. We have scaled this algorithm using the much more elaborate equivalents available from the U.S. Army Corps of Engineers (USCOE) and found reasonable agreement.

Surf zone sediment transport is computed as two components that represent both the time-averaged gross – and net littoral drift. That is, even if a given long-term wave climate produces zero time-averaged net transport, the day-to-day variability of wave conditions, especially with respect to the breaker angle, will serve to disperse sediment away from areas where time-averaged breakers are higher than the average due to convergence of wave orthogonals. On most ocean coasts, there is also a time-averaged net littoral drift, and this is modeled by using the time-averaged breaker conditions with a radiation stress-type transport equation (Komar, 1976). Thus the net transport is given by

$$Q_{\mathrm{LN}} = N E_{\mathrm{b}} \sin\alpha_{\mathrm{b}} \cos\alpha_{\mathrm{b}} \tag{1}$$

and the dispersive transport is given by

$$Q_{\mathrm{LG}} = M E_{\mathrm{b}} D_{\mathrm{SL}} \frac{\partial \bar{C}_{\mathrm{s}}}{\partial s} \tag{2}$$

where:

C_{s} the time-averaged entrained sediment volume concentration in the surf zone
Q_{LN} the time-averaged net littoral drift
Q_{LG} the time-averaged gross littoral drift
E_{b} the time-averaged power-equivalent breaker energy density
α_{b} the power-equivalent breaker angle
D_{SL} the littoral zone diffusion coefficient
s distance coordinate in the surf zone
M and N are scaling coefficients.

Spatial sediment transport gradients due to both gross and net longshore fluxes result in erosion or progradation of the shoreline. Because the waves undergo refraction and shoaling, the littoral transport is heavily influenced by the local time-averaged breaker angle. The shoreline position is tracked in a Lagrangian framework within the beach/surf zone cells to maintain realistic smooth curvature without the necessity of very small grid cells. A rigid equilibrium beach/surf zone and upper shoreface profile, similar to the approach of Cowell et al. (1995), is used in the cross-shore direction. The same approach has been successfully used to estimate the amount of coastal retreat due to sea level rise (Bruun, 1962) and to simulate the development and evolution of barrier islands (Fagherazzi et al., 2003). Thus, as the shoreline position changes, the surf zone and upper shoreface portion of the shore-normal profile moves in or out. Overall, this approach is similar to that used by the GENESIS model except that the regime extends beyond the closure depth (Hallermeier, 1978) used by coastal engineers.

Beyond the beach/surf zone domain, the CST model represents the shoreface, shelf and upper slope components with a depth-averaged two-dimensional grid. Sediment transport results from the combined action of waves and currents. This is an expansion of the earlier one-dimensional model described in Niedoroda et al. (1995).

The waves that are important in the transport processes occur during periods of strong wind-forcing and storm-generated waves. Even in the western Adriatic where there is a strong and persistent net current pattern (Poulain, 2001) the variable components of the flow that are associated with strong forcing events are much larger than the mean. This leads to a net translation of sediment particles after a transport event that has a random distance and a direction that is biased by the mean current. The entrained sediment concentration is scaled by the wave-derived boundary stress that is an inverse function of the water depth. The depth- and time-averaged entrained sediment concentration varies according to a depth-dependent function. Consequently, there is a tendency for a negative offshore gradient of the time- and depth-averaged entrained sediment concentration over the offshore domain.

In the CST model the total shelf sediment transport is taken as resulting from the sum of a large number of random events acting on the gradient of the time- and depth-averaged entrained sediment concentration. This transport has both a large-scale diffusion and mean advection component. The diffusion is represented in the model by individual eddy diffusivity coefficients in the along- and cross-shelf directions. The effects of the persistent mean currents of the western Adriatic are included in the sediment transport equation by a time-averaged advection term. Another term in the sediment transport equation decreases exponentially with depth and represents a weak net flux of bottom sediment in the direction of wave propagation. Also, beyond the seaward extent of the submerged terrace where the bottom slope rolls over to form a distinct slope that eventually exceeds a pre-set limiting slope in the model, the time-averaged down-slope sediment flux is enhanced by the tangential component of gravity.

Across most of the shoreface and shelf, the time-averaged sediment transport is modeled with the advection–diffusion equation given below. On the right side of Eq. (3), the first term represents the advective flux, the second is the wave-driven onshore flux, the third term is the flux due to the large-scale diffusion and the last term, which is set to zero when the bottom slope is less than a cut-off value (R), is the gravitationally controlled flux on the continental slope.

$$\bar{Q} = -\bar{U}\bar{C} - K_1\frac{\bar{P}}{\rho g h}\left[e^{-\beta h}e^{-d\theta}\right] - K_2\,\bar{D}_{\mathrm{H}}\nabla\bar{C} + G(\nabla h - R) \qquad (3)$$

where:

- $\bar{Q}$ time-averaged sediment volume flux on the shoreface and shelf
- $\bar{U}$ time- and depth-averaged shelf current
- $\bar{C}$ the time-averaged areal entrained sediment volume
- K_1 proportionality coefficient
- $\bar{P}$ wave bottom current areal power density
- ρ water density
- g earth's gravitational acceleration
- h local water depth
- β model scaling coefficient
- d model scaling coefficient
- K_2 proportionality coefficient
- $\bar{D}_{\mathrm{H}}$ time-averaged horizontal diffusion coefficient
- G scaling coefficient (set to zero shoreward of the continental slope)
- R threshold bottom gradient for downslope transport
- θ the local bottom slope.

In each time-step the sediment transport fluxes are computed within the individual domains and matched at the boundaries. The coupling between the model representations of the upper shoreface and the surf zone requires special treatment to keep changes from the initial conditions from bringing about unrealistic local bottom slopes. To avoid this, the shore-normal transport rate between the surf-zone cells and the upper shoreface cells is taken to be proportional to the difference between the slope computed at each time-step and a pre-set equilibrium slope. If the instantaneous slope is greater than the equilibrium value then an offshore sediment flux is imposed (and vice versa). A special consideration is also needed to represent sediment exchange between certain shoreface cells and the surf zone where the shoreline slants across more than one cell of the model grid. The surf zone transport is always taken to be one-dimensional, even when adjacent grid cells meet only at a corner. In this condition some of the sediment moving in the surf zone must exchange with the "new" row of shoreface cells necessitated by the "slanting" shoreline. This ad hoc adjustment is made based on sediment volume conservation.

An Exner equation is used to compute sedimentation and erosion. At pre-set intervals the depth of the sea floor is outputted. The time-sequence of these depth outputs is used to create the time-line stratigraphy where deposits form.

3. Approach

In the form of this model used to represent the Italian Adriatic coastal system tract, the sediment sources were taken to be the Po River and a series of smaller rivers that drain coastal Apennine watersheds. The model domain was selected to cover the area from south of Ancona to the Gargano peninsula (Figs. 1 and 2). This is a distance of about 300 km, and includes both a straight and a curved portion of the shoreline. At this time it was thought that representing the full transport system as it wraps around the Gargano promontory would be too ambitious, and that portion of the system was therefore not included. In this way, details of sediment dispersal in the region of the Adriatic near the Po delta were avoided. The model grid extended 90 km offshore to take it beyond the present offshore extent to the Holocene subsea clinoform.

Sub-bottom profile data from Correggiari et al. (2001) and Cattaneo et al. (2003) were used to estimate the depth to the bottom of the Holocene clinoformal wedge. These authors identified a maximum flooding surface related to the most recent marine transgression. We took this to represent the depth of the original sea floor in the CST model grid. The actual depths were smoothed to eliminate features considered to be too detailed to be of interest in this initial modeling work. Fig. 3 shows the model domain with the initial bottom contours.

Behavior-oriented models depend on fitting the major parameters to observed features of the regime that is represented. In this application we make the observation that the Holocene clinoform has grown both in length and width. The major cause of this is a persistent longshore gradient in the time-averaged sediment transport rate. The sub-bottom profiles show that the location of most rapid sedimentation

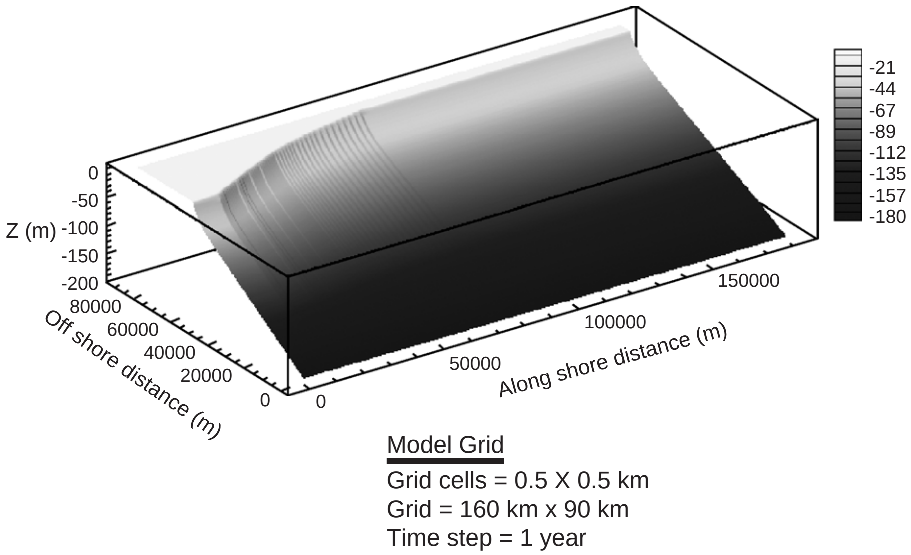

Fig. 3. Isometric view of the CST model grid absent the Holocene clinoform. The view is looking towards the southwest. Arrows show the sediment sources that include the Tronto (T), Pescara (P), and Biferno (B) rivers. Sediment moving longshore from the Po River enters the northern boundary (unlabelled arrow).

shifts progressively offshore as these deposits prograde. This clearly shows that the shallower portion of the profile tends towards a bypassing condition, while the deeper portions remain depositional and extend further offshore. We also observe that global sea level has been relatively constant over the last six millennia, based on a recent eustatic sea level record from the Red Sea (Siddall et al., 2003). From this we take the inner portion of the present surface of the Holocene subsea terrace to be at, or very close to, the idealized bypassing profile that was postulated in our earlier paper (Niedoroda et al., 1995).

The assumption that the shore-normal profile of the submerged terrace is dynamically adjusted to the present wave–current environment and a stable sea level allows the time- and depth-average entrained sediment concentration $C(h)$ to be determined from the measured local bottom slope, the rate of sediment supply and the fitted wave parameter W_o. The shore-parallel component of sediment transport is not considered in this portion of the analysis because it is considered to be undergoing long-term deposition. The approach is to fit a curve to a representative shore-normal depth profile over the top of the shelf terrace (Fig. 4). This can be used with Eq. (3) to establish the spatial distribution of the time-averaged entrained sediment that corresponds to the bypassing condition. To simplify this equation we note that the depth-averaged advection in the cross-shore direction must be zero, as is the last term, because of the small bottom slope in the shelf portion of the profile. Therefore, the local depth- and time-averaged sediment flux (q_o) is entirely controlled by a balance between the onshore wave-biased term and the large-scale cross-shore diffusion from Eq. (3) as given in the following:

$$\bar{Q} = W_0 e^{-\beta h} + D \frac{\partial C}{\partial h} \frac{\partial h}{\partial x} \tag{4}$$

which can be rewritten as:

$$\frac{\partial C}{\partial h} = \frac{\bar{Q} + W_0 e^{-\beta h}}{D \frac{\partial h}{\partial x}}. \tag{5}$$

In this equation the dependence of the cross-shelf wave-driven transport on the local bottom slope is neglected, as it is very small. Also:

$$W_0 = K_1 \left(\bar{P} / \rho g h \right) \tag{6}$$

Integration of this equation yields

$$C(h) = \int_0^h \left(\frac{\bar{Q} + W_0 e^{-\beta h}}{D \frac{\partial h}{\partial x}} \right) dh. \tag{7}$$

On a bypassing profile the depth- and time-averaged cross-shore sediment flux gradient is zero. Using

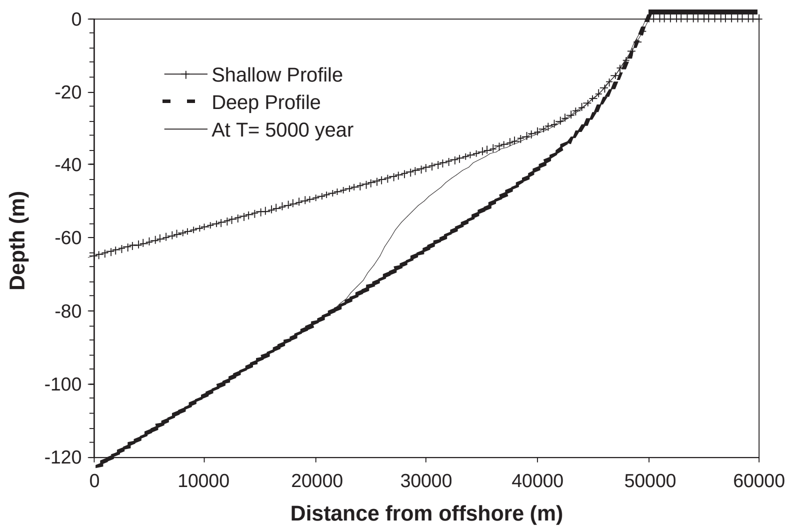

Fig. 4. Schematic representative profiles of the actual bottom shape, the bottom before deposition of the clinoform (deep profile) and the curve fitted to the top of the present profile. Horizontal coordinates relative to the offshore model boundary.

this, Eq. (7) can be solved using iteration. The resulting function is taken to describe the depth- and time-averaged entrained sediment concentration $C(h)$ as a function of depth. In the model this function is used across all of the profiles as they develop towards this equilibrium bypassing condition. Because all other profiles depart from this condition, this function serves to steer their development by causing local deposition or erosion.

In the absence of significant astronomical tides, the currents and waves of the Adriatic are strongly related to the varying winds. The strongest wind event are the southeast Scirocco events and the northeast Bora events (Furlan, 1977). Long-term data collected by the Italian Navy at Punta Penna show that the strongest winds are from the northeast to northwest which has the maximum fetch for the central Italian coast (Istituto Idrografico della Marina, 1994).

The net surface current pattern, based on averaging drifter trajectories over the period 1990–1999 that are given in Poulain (2001) and modeling results (Bergamasco et al., 2003) show a persistent cyclonic circulation in the Adriatic with a time-averaged southward flow along the coast of Italy from Ancona to Pescara (see also Orlic et al., 1992). We modeled this behavior with a function that yielded an individual mean current in each model cell. The speed was taken as zero at the shoreline, increasing linearly with distance offshore to 3 km. Beyond this offshore distance the flow was taken to be uniform in the cross-shore direction and increasing down-current. In some of the model runs an adjustment in the direction of this mean current was made to bring it into agreement with the results of recent ADCP measurements (Puig et al., in press). These measurements showed a tendency for the bottom currents to be turned about 20° to the left (i.e. offshore) with respect to the measured mid-depth flows. Because real sediment transport patterns are largely controlled by bottom currents, we adjusted the direction of the advective flow in the model accordingly.

Although the time–mean circulation provides a southward bias to all sediment transporting events, the overall sediment transport discharge is strongly controlled by the net effect of wave and current resuspension during strongly forced conditions (Scirocco and Bora). When viewed in a time-averaged sense, these events provide significant varying flows that can be regarded as a form of large-scale turbulence (Niedoroda et al., 1995). It would be possible to derive large-scale time-averaged diffusion coefficients from current records obtained with long-term moorings. Although data of this type have been taken in recent physical oceanographic programs in the Adriatic, we have not accessed these data. Instead, we have used an assumed a ramp-type profile with both the horizontal coefficients starting at zero on the shoreline and increasing at a prescribed linear rate to a preset maximum. The magnitude of these coefficients is adjusted according to the model time-step. The shape of the offshore profiles loosely mimics the observation given in Csanady (1973) that the horizontal eddy sizes are approximately proportional to the depths in large lakes and the coastal ocean.

The annual average sediment discharges for the Po and Apennine Rivers are given in Milliman and Syvitski (1992). Not all of the smaller river sources were included in the model to avoid excessive detail. The Po sediment source (total sediment load of 13×10^6 t yr^{-1}) was reduced by 21% to account for estimated sedimentation north of Ancona, outside the model boundaries. The remaining flux entered the model domain along the inshore third of its northern boundary. In this simulation we consider the three Appennine rivers with the higher discharge and sediment load south of Ancona: the Tronto river (with a total sediment load of 1.1×10^6 t yr^{-1}), the Pescara river (0.9×10^6 t yr^{-1}), and the Biferno river (2.2×10^6 t yr^{-1}). The sediment inputs from the representative coastal drainages are routed directly to the shoreface model cell opposite the river mouths. This expedient has little overall effect but permitted us to avoid the detailed model tuning that would be needed to have the river discharge enter the littoral transport stream.

4. Results

Sample model results are shown in Fig. 5. Here the growth in both the longshore and cross-shore directions is portrayed in a series of perspective views, shown in two stages. Initially the individual river sources develop clearly identified subsea clinoforms. The greater amount of sediment supplied from the Po River, which enters the model domain as a longshore

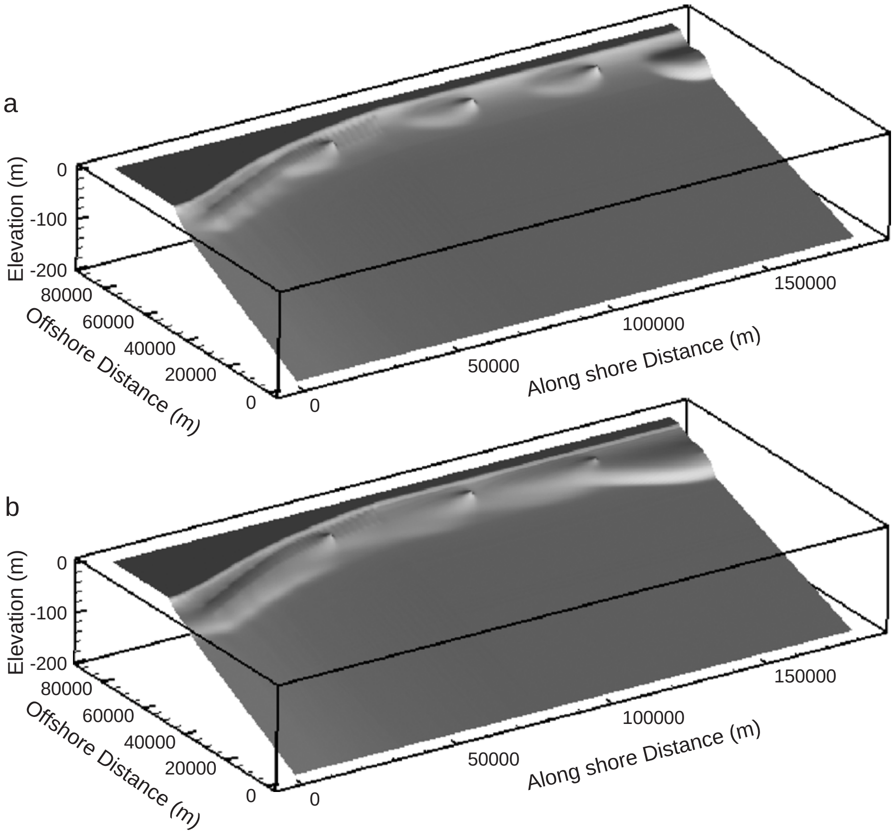

Fig. 5. Model results showing two stages in the development of the subsea clinoform. Upper panel: initial development of subsea clinoforms. Lower panel: after 5000 years of model progradation.

discharge through the northern boundary, produces a larger deposit that spreads faster in the longshore than the cross-shore direction. This causes the initial depot centers to coalesce. The actual degree that the model gives a true representation of the early history of the overall clinoformal wedge is hard to determine. For example, the initial small and distinct clinoforms, indicated in the present model results, would now be buried close to the shore where there are few seismic lines and significant blanking due to gas. It is possible that the earliest stages in the development of the basal deposits occurred while sea level was still rising. With additional field data to address these issues the model could be used to distinguish between these two alternatives.

The shoreline is relatively stable in position, while the clinoformal wedges (or prodeltas) extend seaward. In the second stage, representing about 5000 years of development, the individual deposits have coalesced and the individual shapes are obscured. These panels also show that the modeled central Adriatic shoreline remains relatively static in position, while there is some shoreline progradation as the Gargano peninsula is approached. From maps, the recent morphology of this portion of the coast shows indications of this type of localized progradation with depositional landforms behind the shoreline.

Fig. 6(a) shows the internal time-line stratigraphy that developed in the model. This model uses a post-processor that eliminates the portions of the deposits that are later eroded away. The general arrangement of these internal layers compares well with those from Correggiari et al. (2001) seismic data which are similar to those shown on Fig. 2. The effect of the offshore turning of the bottom currents that has been observed by Puig et al. (in press) was tested by doing model runs with and without this effect. It was found that both sets of runs (with and without this offshore

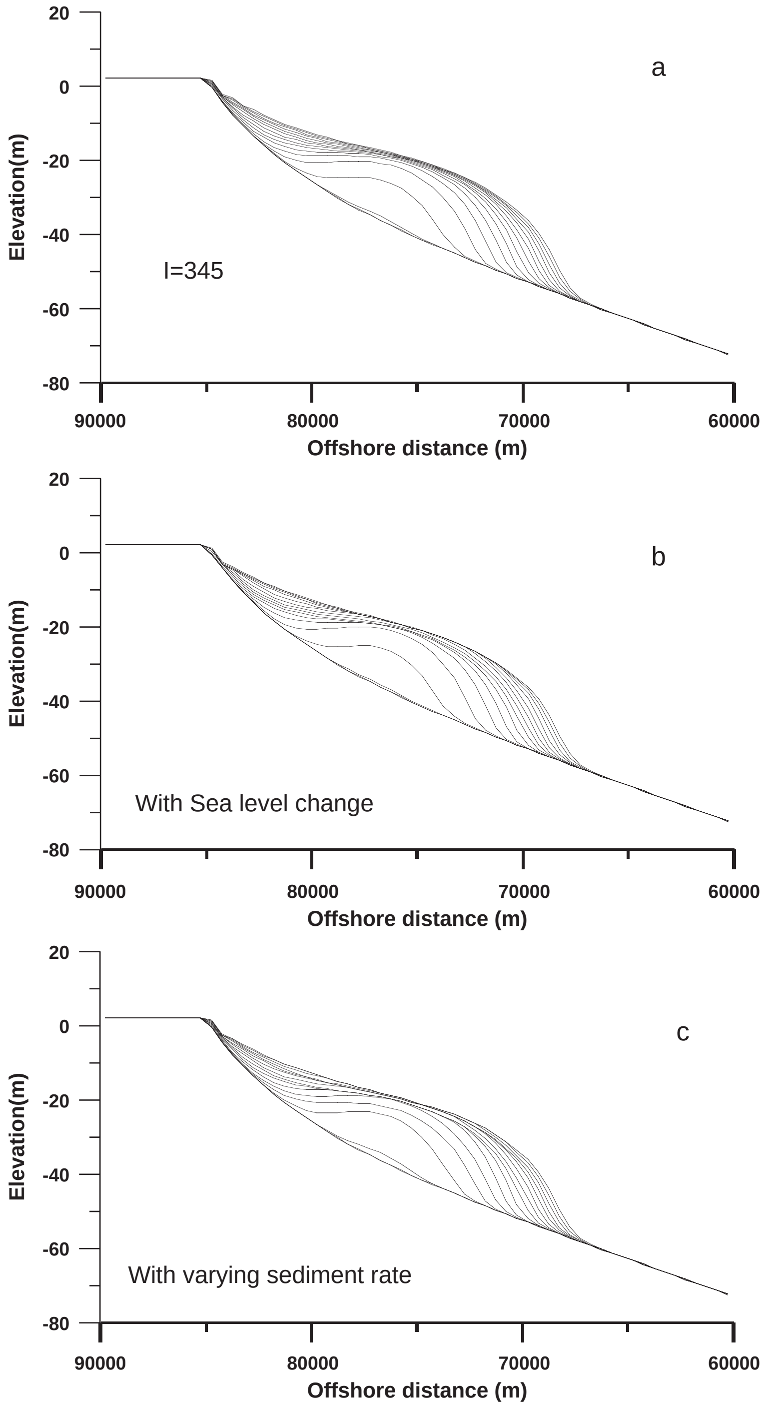

Fig. 6. (a) Modeled time-line stratigraphy on an idealised cross section in the study area. (b) Close-up of the time-line stratigraphy predicted for millennial-scale sea level variations. To produce the results shown, sea-level was varied over a 1 m range with a period of 1500 years. This approximately corresponds to the Dansgaard–Oeschger climate cycles. (c) Close-up of the time-line stratigraphy predicted for millennial-scale variations in the rate of sediment supply. For each run, sea level was kept constant and the rate of sediment supply was varied by 15%, approximating the climatic variations that would be associated with the Dansgaard–Oeschger cycles.

turning) gave the same general volume, shape and internal geometry of the deposits. However, in the runs that included the offshore turning of the current representing the net advection, the shape of the deposits at the toe of the clinoform was more realistic. It appears that this turning, in itself, is not an explanation for the overall development of the subsea clinoform. Instead, the overall shape of the profile (from the rollover point landward) is adjusted to the sediment bypassing brought about by the frequent resuspension and dispersal of the seafloor sediments. Seaward of the rollover point this effect diminishes rapidly and the effect of the mean bottom current predominates.

5. Discussion

The results indicate that the central Adriatic Holocene subsea clinoformal wedge can be explained by the concept of an equilibrium depth profile that is adjusted to the wave, current and sediment supply conditions of this area. The progressive seaward displacement of the zone of maximum accumulation strongly supports the concept that the present upper surface of this deposit, shoreward of the rollover point, is at, or close to, the idealized shelf sediment bypassing condition. From this it is clear that this subsea clinoform results primarily from the cumulative effects of a large number of individual sediment transport “events” (strongly forced flows with waves) that serve to redistribute the sediment in the cross-shore while adding to the longshore flux as well. The dominant direction of sediment transport and growth of the clinoform is to the south in response to the time-averaged current direction. The suspended sediment plume (Fig. 1a) contributes to, but does not dominate, these depositional processes as evidenced by both the width of the overall clinoformal wedge and the distance from the shore of the zone where the accumulation rate is greatest.

We have applied the CST model to diagnose this large-scale coastal sedimentary system. The numerical model is a way of placing these processes into a quantitative framework to demonstrate the credibility of this explanation. However, this model and other behavior-oriented models generally suffer from an inability to provide unambiguous proof that they are truly representing the development of the deposit. In this case we derive much of the action of the model from the assumptions regarding the equilibrium bypassing profile. It would be circular reasoning to take the apparently realistic results of the modeling as a proof of this assumption. It is simply possible to state that if this behavior is assumed, it can lead to large-scale deposits with the correct geometry and internal structure.

One of the major goals of the Eurostrataform project (and of the earlier Strataform project) was to develop scientific concepts and tools that can be used to understand the development of shallow stratigraphy on continental shelves. These are especially valuable where they offer the capability to either predict stratigraphic conditions in areas where there is very little data or to provide mechanisms to extrapolate between sparse data. The application of the CST model to represent the development of this subsea clinoform is an example of one of these developments. In its present form this modeling approach meets these objectives.

Now that the model framework has been used to represent the development of the entire clinoform, it can be used to explore some stratigraphic questions in a prognostic manner. To this end, we have posed the question of whether we can expect the effects of variations in the rate of sediment supply and in sea-level elevation to leave detectable and even unique signatures in the shallow stratigraphy. We elect millennial-scale variations because they are most likely to leave patterns in the deposits that are large enough to be later verified with high-resolution reflection profiling. Fig. 6(b) and (c) shows the results of these model runs. To produce the results shown in Fig. 6(b), sea level was varied over a 1-m range with a period of 1500 years. This approximately corresponds to the Dansgaard–Oeschger (D-O) climate cycles (Dansgaard et al., 1993). The patterns of shallow time-line stratigraphy shown in Fig. 6(c) come from runs where the sea level was kept constant and the rate of sediment supply was varied by 15%, which we estimate to approximate climatic variations that would be associated with the D-O cycles. These results show that there should be distinctive patterns in the shelf deposits related to these causes. Unfortunately, these are best exhibited in the shallower water depths where high-resolution sub-bottom data are currently not available.

A shortcoming of behavior-oriented modeling that is presently accepted is that there are no long-term data sets from which the controlling variables can be directly evaluated. In this absence “fitted” values are used. Reed et al. (1997) point out that having to produce meaningful results without data sets that would formally be considered to be complete is the fate of all modelers addressing large-scale sediment- and morphodynamic problems. These are ambitious undertakings, and complete data collection programs are simply too expensive. Therefore, a certain amount of “bridging” over data gaps must be accepted. DeVriend (1991) has shown that large-scale modeling depends on proper parameterizations of processes and using parameters that occur at spatial- and temporal scales that are significantly below the scale of the problem at hand. We are presently working to combine these ideas so that the independent variables in the CST model can be related to quantities that can be directly measured. In this undertaking we, with the help of others in the EuroStrataform project, are developing a series of large-scale models focused on different time-scales. With the completion of these it will be possible to make direct calculations of parameters like the time-averaged concentration of entrained sediment and the large-scale shelf diffusion coefficients.

6. Conclusions

The formation of the Holocene subsea clinoform of the central Adriatic coast has been successfully simulated with the large-scale behavior-oriented CST model. The model shows that this deposit forms as a result of sediment arriving from the Po River and a series of small rivers draining the eastern slopes of the Apennines. In this model the present upper surface of these deposits is assumed to have a shape that is adjusted to the wave and current climate and rates of sediment supply in such a way as to cause no time-averaged sediment transport gradients in the shore-normal direction. This is called the shelf sediment bypassing condition. The deposits grow seaward due to deposition beyond the offshore limit of the bypassing profile. The major growth of this deposit has been in the longshore direction due to the strong advective flux associated with a dominant wind-driven circulation pattern in the Adriatic. The model demonstrates a capability to predict the morphology and internal time-line stratigraphy of shelf deposits with relatively small amounts of data.

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