Computers & Geosciences 34 (2008) 1381–1393
COMPUTERS & GEOSCIENCES
www.elsevier.com/locate/cageo

Controls on the degree of fluvial incision of continental shelves

Sergio Fagherazzi[a,*], Alan D. Howard[b], Alan Wm. Niedoroda[c], Patricia L. Wiberg[b]

[a]Department of Earth Sciences and Center for Computational Science, Boston University, Boston, MA 02215, USA
[b]Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904-4123, USA
[c]URS Corp, 1625 Summit Lake Drive, Tallahassee, FL 32312, USA

Received 10 September 2006

Abstract

During sea-level low stands continental shelves were dissected by a network of channels somewhat resembling today's coastal plain streams. The network was subsequently buried or erased by marine processes during sea-level transgression, so that only some tracts are still conserved in the geological record. Herein we use a numerical model to study the effect of base level change by sea-level fall on the total channel incision. We find that four factors control the total incision on the shelf: (i) the presence of convex deposits; (ii) the evolution of the rivers towards equilibrium (graded) conditions; (iii) geometrical differences between coastal plain and shelf; and (iv) the exposure of the continental slope. The conceptual model is then applied to the Adriatic Sea, Italy. Simulations show that incisions in the Adriatic shelf develop in high stand fluvial deposits in the early stages of sea-level fall. At lower sea level, fluvial incision occurs in the mid-Adriatic due to the regrading of the Po River after the capture of the Apennine streams in its drainage system.

Keywords: Fluvial incisions; Continental shelf; Sea-level oscillations; Numerical modeling

1. Introduction

In contrast to terrestrial landscapes, few valleys dissect the inner-, and mid-shelf. Those that do are limited to areas where large rivers scoured wide paleo-valleys during sea-level low stands, and were then able to survive subsequent reworking and partial filling by coastal and marine processes. Examples are the Delaware shelf valley in front of the Delaware River (Swift, 1973), the shelf along the east coast of Brazil, and the Hudson shelf valley in front of the Hudson River on the US East Coast shelf (Uchupi et al., 2001). Despite the fact that modern shelf surfaces bear the signs of only a few major rivers, there is evidence that during sea-level low stands exposed shelf surfaces were dissected by intricate networks of channels somewhat resembling today's coastal plain streams (Fagherazzi et al., 2004). These networks were subsequently buried or erased by marine processes during sea-level transgression, so that only some tracts are preserved in the geological record and can be detected through cores or seismic profiles. Duncan et al. (2000) and Davies and Austin (1997) found an erosional surface characterized by the presence of numerous paleo-channels in the stratigraphy of the New Jersey continental shelf. They interpreted these to be the result of fluvial incision during a subaerial period corresponding to the Wisconsin glacial maximum.

*Corresponding author.
E-mail address: sergio@bu.edu (S. Fagherazzi).

0098-3004/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cageo.2008.02.004

Some of the streams that form on the shelf are the continuation of upland rivers, while others were locally formed by the routing of direct rainfall on the shelf surface. For example, sub-bottom seismic profiling data collected offshore of the Florida Panhandle indicate that the river systems of north Florida extended well beyond their present mouths during sea-level low stands, creating extensive networks of fluvial features on what is now the inner and mid-shelf (Locker and Doyle, 1992; Donoghue, 1993; McKeown et al., 2004). Furthermore, the data show that many of the smaller rivers, which presently terminate at the modern coast were tributaries of the larger rivers during low stands.

Despite their lack of bathymetric expression on the modern shelf surfaces, past fluvial incisions must have been important for shelf morphological evolution. Sediment redistribution was governed by incoming rivers, their location and geometry. As such it is impossible to understand the evolution of shelf morphology during the last glacioeustatic cycle without determining the characteristics of the streams that were dissecting the shelf and the modality in which they provided sediments to the nearshore area.

An important aspect of shelf dissection by fluvial streams is the degree of incision related to a particular stream. The total incision controls the total volume of sediment eroded from the shelf and determines the possible preservation of the channel in the geological record. Several mechanisms control channel incision. Here we describe three main factors that are the focus of our research: (i) the presence of convex deposits on the shelf; (ii) the evolution of the rivers towards equilibrium (graded) conditions; and (iii) geometrical differences (slope) between coastal plain and shelf.

Talling (1998) points out that, where present, the shape and location of deltaic deposits are a key control for channel incision during low stands, with the thickness of high stand deposits (i.e. the coastal prism) determining the total incision. He assumed that if sea level does not fall below the shelf-slope break, the major valley incision will occur where convex coastal prisms are deposited during high stand. This framework requires that the river preserves its profile without major modifications, thus cutting through deposits accumulated during high sea-level periods.

In reality, the river can be out of grade during a decrease in sea level, and therefore it can erode the shelf bottom in trying to recover its equilibrium profile even without the presence of convex deltaic deposits on the shelf. Incision and aggradation are then a consequence of the fact that rivers tend toward an equilibrium longitudinal profile (graded condition, Mackin, 1948; Schumm and Lichty, 1965) that depends on water discharge, sediment load, and bottom slope. If the river is not at grade on the continental shelf, adjustments of the river longitudinal profile might be the leading cause of incision, rather than the shape and location of convex deltaic deposits. For example, if the graded conditions lead to a convex profile, this is likely a location of net erosion because convexity implies a downstream increase in slope, which produces a downstream increase in sediment transport capacity and therefore erosion.

Schumm (1993) recognized that a change in base level can produce not only a variation of stream gradient and related channel bottom incision or aggradation, but also an adjustment of channel sinuosity, shape and roughness. This notwithstanding, it is clear that adjustments in slope are always present when a river evolves toward graded conditions, and these changes in slope dictate the degree of incision in the shelf.

Changes in the geometry of contiguous coastal plains and shelves can also influence channel extension and incision during sea-level fall. A coastal plain slope greater than the shelf slope can lead to channel extension with progradation and aggradation, whereas a coastal plain slope smaller than the shelf slope causes a channel extension with deep incision during sea-level fall (Summerfield, 1985).

In recent years, several numerical models have been used to study the evolution of fluvial–deltaic systems on the shelf during glacioeustatic cycles. Meijer (2002) presented a cellular model for coupled river-shelf evolution during sea-level oscillations. The model is based on both a diffusive transport and a directional stream transport applied to a squared mesh, and favors the formation of a diffuse channel system, with several deltaic distributaries, during sea-level fall. The model well reproduces river avulsion, delta–lobe switching, incision and knickpoint migration during glacioeustatic cycles. More importantly, the model results show a direct link between the drainage basin and the fluvial deposition at the shelf edge. When the river attains equilibrium, in which neither erosion nor deposition occurs along the stream, sediment is directly deposited at the coastline, thus bypassing the entire exposed shelf. Moreover, Meijer (2002) finds that the timing of this drainage connection (i.e. when equilibrium conditions are reached) is highly variable and depends on the shelf initial conditions.

A similar approach is utilized in Clevis et al. (2003, 2004), where the fluvial drainage model GOLEM (Tucker and Slingerland, 1997) is coupled to a simplified, diffusion-based, marine module. This framework is applied to the hierarchical organization of foreland basins in the stacking of sequences deposited by transverse (alluvial fans) and axial (the major river forming the delta) systems.

Whereas Meijer (2002) focuses on one river and its coupling with the shelf system, and Clevis et al. (2003, 2004) emphasize the stratigraphy of the drainage basin, neither of their models are applied to large-scale coastal plain–shelf systems. In Fagherazzi et al. (2004), we presented a coupled continental shelf–coastal plain model for simulating fluvial incision and deposition on the continental shelf during sea-level cycles. The model utilizes the DELIM morphological model (Howard, 1994) for the development of fluvial drainage networks coupled to sea-level oscillations and nearshore processes. The regular grid and the simplified description of the processes utilized in the model allow us to simulate the evolution of large shelf areas through time with little computational effort. The model is able to predict the location of incised channels during sea-level low stands and the related degree of incision. Simulation results reported in Fagherazzi et al. (2004) show the strong influence of shelf morphology on establishing channel networks during sea-level low stands. The model also indicates that the detailed structure of sea-level oscillations has a strong influence upon sediment redistribution and channel development on the shelf.

Herein we present a series of simulations with the model of Fagherazzi et al. (2004) that explore the role of river-graded conditions, convex deposits (i.e. coastal prisms) and changes in slope between coastal plain and shelf on total channel incision. The conceptual model is then applied to the Adriatic Sea, Italy.

2. The model

We use the numerical model developed in Fagherazzi et al. (2004) to predict the evolution and the degree of incision versus deposition by fluvial channels on the continental shelf during sea-level cycles. The model accounts for mass-wasting processes, fluvial sediment entrainment and transport. These processes are simulated using the framework delineated in the DELIM model of Howard (1994) on a grid that represents the morphology of the continental shelf and corresponding coastal plain. The model is coupled with a deltaic module for sediment deposition in the ocean and a fluctuating sea level that mimics climatic changes on a $\sim 10^4$ yr time scale (see Table 1).

The process implementation is reported in Table 1 (see also Fagherazzi et al., 2004). The model runs with a time step of 10 yr, so that every parameter of the equations reported in Table 1 was calculated for this time step (see Fagherazzi et al., 2004 for the parameter determination).

Fluvial incision occurs in two different ways: in transport-limited conditions, when there is enough sediment in the shelf, incision is produced by the divergence of the sediment fluxes, and in particular it occurs when the sediment supply is less than the river carrying capacity. In detachment-limited conditions, when there is no loose sediment and the river has reached the underlying resistant substrate, incision is produced by a bottom shear stress higher than the critical shear stress for erosion. The two incision styles have different timescales that strongly dictate the evolution of the system. The timescale for transport-limited incision is relatively fast, so that the rivers rapidly adjust to variations in sediment supply. On the contrary, the timescale for detachment-limited incision is of the same order of the timescale of sea-level oscillations, so that the total incision is a function of the period during which the shelf or the continental slope are exposed.

3. Fluvial incision and graded river conditions

The model simulations described herein start from a strongly simplified shelf-coastal plain configuration; more realistic conditions are then discussed. In the first simulation, the continental shelf and the upper part of the continental slope are idealized as two flat tilted plains intersecting each other (Fig. 1a). The slope of the continental shelf ($\sim$0.0008) and its width ($\sim$100 km) are similar to those of the Atlantic shelf offshore Virginia. Only the upper part of the continental slope is considered (Fig. 1a). To produce a realistic fluvial path we have added a random elevation uniformly distributed between 0 and 1 m to the initial topography.

Table 1
Model components

Processes	Implementation
Weathering	Because of the intrinsically weak nature and high erodibility of continental shelf sediments (e.g., Howard and Kerby, 1983), we assume that reduction in erosive properties by weathering are inconsequential
Mass wasting $\frac{\partial z}{\partial t}=K_S\left(\frac{\partial^2 z}{\partial x^2}+\frac{\partial^2 z}{\partial y^2}\right)$	In steep, mantled landscapes the sediment flux most likely increases for slopes near the failure slope and the diffusion equation should be modified to account for this nonlinear mechanism (Howard, 1994; Roering et al., 1999). However, the gentle slopes of continental shelves and coastal plains suggest that near-failure mass wasting is a negligible process
Fluvial aggregation	In the model each square element of the computational grid drains into one of the eight neighboring elements following the steepest descent direction; we then calculate the drainage area as the sum of the areas of the elements that are connected upstream to the considered point
Detachment limited fluvial erosion $\frac{\partial z}{\partial t}=-K_T(\tau-\tau_c)\quad \tau\geqslant\tau_c$ $\tau=K_zA^{0.6e(1-b)}S^{0.7}$	Detachment-limited conditions are used when the regolith thickness (a) and the channel bottom is zero. The detachment capacity is assumed to be proportional to the difference between shear stress that the flow exerts on the bed and critical shear stress for erosion
Transport limited fluvial erosion $\frac{\partial z}{\partial t}=\frac{1}{\alpha}(Q_{sb}^{in}-Q_{sb}^{out})$ $Q_{sb}=K_qA^eS^p$	Transport-limited conditions apply when there is regolith above the bedrock at the channel bottom. In this case, changes in channel elevation depend on the divergence of the sediment discharge
Channel geometry $D=K_D\,Q^a$; $W=K_wQ^b$;	River dimensions vary downstream following the rules of hydraulic geometry (Leopold and Maddock, 1953)
Deltaic deposition	The foreset slope is provided as an input parameter, whereas the terminal topset slope is set equal to the equilibrium slope (at grade) of the river from the given drainage area and sediment discharge. Sediments are deposited at the delta forset maintaining constant topset and forset slopes

The model is divided in several modules that include the main processes acting on the coastal plains and inner shelf.
Notation: z, shelf bottom, t, time; x and y, spatial coordinates; Q, river discharge; Q_{sb}, total sediment load; D, channel depth; W, channel width; τ, shear stress exerted by the flow at the bottom; τ_c, critical shear stress for bottom erosion; A drainage area and S bottom slope of the river. K_S, K_T, α, K_D, K_W, a, b, e, *and* p are constants whose value is reported in the parametrization presented in Fagherazzi et al. (2004).

Furthermore, we assume a uniform sediment thickness of 15 m on the shelf. At the top edge of the simulation domain an incoming river having a drainage area of the same magnitude of the modern Delaware river is considered (drainage area $=0.017\times10^6\,km^2$; from Milliman and Syvitski, 1992). Furthermore, it is supposed that the river is at grade, so its sediment load is derived from the total sediment load equation (see Table 1), given the basin area and the shelf slope. With a total sediment load $Q_{sb}=800{,}000\,m^3/yr$ no aggradation or incision occurs on the shelf (Fig. 1a).

In the first two simulations, sea-level oscillations are simplified to a high stand period of 5000 yr with elevation of 0 m (present sea level), followed by a low stand period of 5000 yr at -60 m (Fig. 1d). The initial high stand period allows an alluvial delta to deposit at the coastline (Fig. 1b) and the fast drop in sea-level facilitates the investigation of its subsequent incision. Similar conditions can occur during pauses of sea-level regression. The almost flat delta topset extends inland whereas the steep forest (with slope $\sim5^\circ$) is submerged. After sea-level drops, a second delta forms at an elevation of -60 m (Fig. 1c) and erosion occurs at the location of the high stand alluvial deposits (Fig. 1c and e) as envisioned by Talling (1998). Since the river is at grade, the location of maximum incision occurs at the point of maximum convexity in the first coastal prism deposit. This configuration led Talling (1998) to conclude that valley incision is maximum in areas where convex deposits formed during high stands.

In the simulation, several channels develop next to the major channel (Fig. 1c). The watersheds of these channels are entirely located on the shelf and the sediment transported in them has a local origin. In simulations where the shelf is modeled as a gently sloping plane the minor channels are almost parallel and seldom discharge into the principal river under study (Fig. 1c).

If sea level drops below the shelf-slope break, a knickpoint forms at the break and migrates upstream (Fig. 2a–c). Again the high stand deposits will be cut by the river but now the incision caused by the migrating knickpoint is larger, being of the order of 20 m (Fig. 2f). The river thus scours the entire sediment thickness and part of the bedrock, forming a knickpoint that propagates upstream. On the contrary, if the incision is limited to the shelf sediments without exposing the bedrock, then the knickpoint will get rapidly smeared. The time scale of the knickpoint migration becomes crucial for

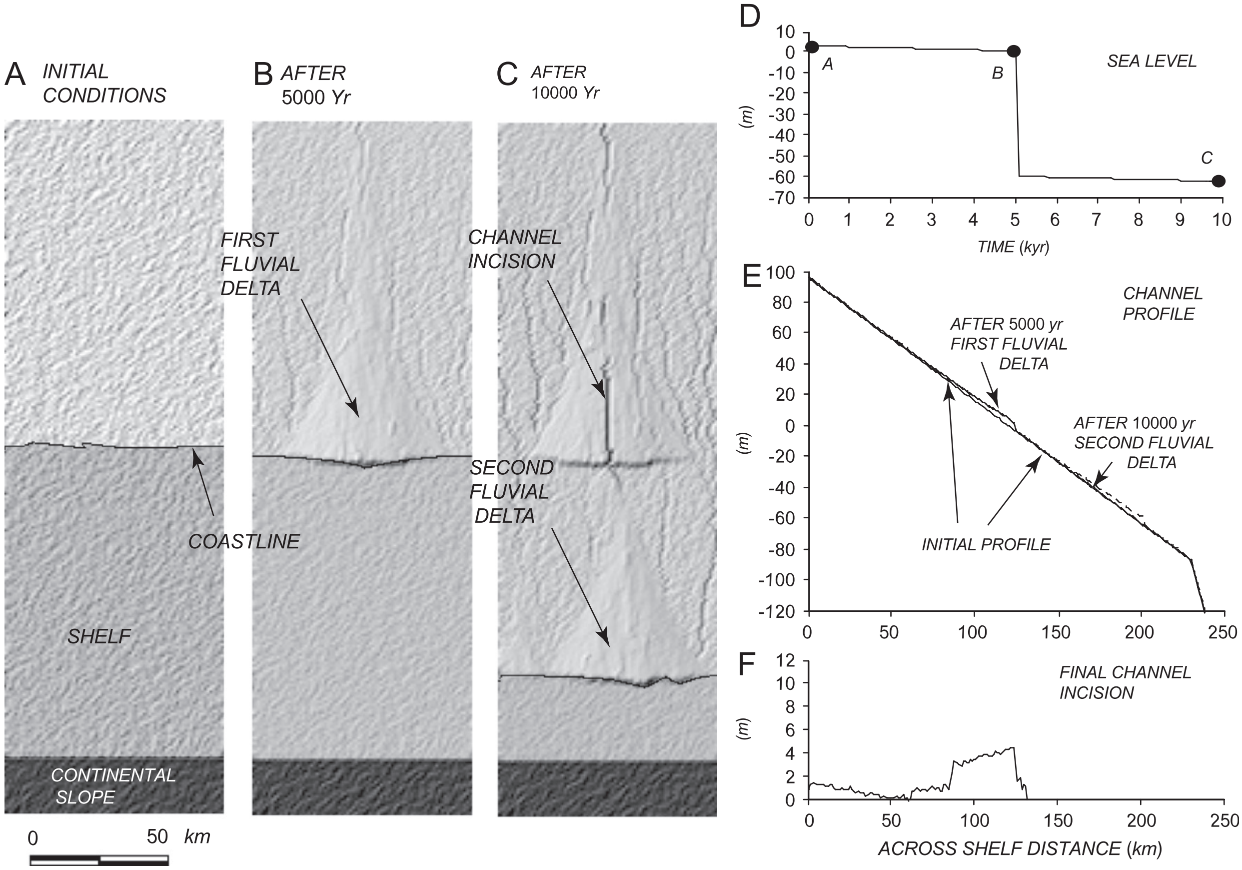

Fig. 1. Establishment of fluvial channels in the continental shelf after sea-level regression when the river slope is in equilibrium with the shelf and coastal plain gradients. The shelf and the upper part of the continental slope are schematized as two flat tilted planes. A river at grade for the given shelf slope flows in the middle of the simulation domain. (A) Initial conditions; (B) after 5000 yr a deltaic deposit forms at the coastline; (C) after 10,000 yr following a sudden drop in sea level a second delta forms at the new coastline location whereas the first delta is incised by the river. Note the establishment of secondary channels in the entire shelf surface; (D) sea-level curve; (E) channel profile; and (F) channel incision after 10,000 yr.

assessing the degree of incision. If the period during which the entire shelf is exposed is limited, the knickpoint will migrate for a short distance upstream and the river will not be able to reach a new equilibrium configuration.

So far we have considered rivers in equilibrium (graded) on the continental shelf. This condition is probably valid for few rivers, since changes in tectonic settings and climate may cause variations in sediment delivery to the coast. For the coastal plain rivers in Virginia, for example, it is plausible that the erosion of the Appalachians and the lack of tectonic uplift have resulted in a long-term reduction of the sediment volume delivered to the coast.

Even greater are the consequences of the succession of glacial and inter-glacial periods to river discharge and sediment load (Bull, 1991; Starkel et al., 1991). Changes of river regime (both in terms of discharge and sediment load) at the geological time scale suggest that rivers rapidly switch between different grading conditions through aggradation or incision. Furthermore, water is transported from the continent interior to the coastal plains through different rivers having a wide range of water discharges. Even if a river is in equilibrium with the shelf slope, a similar condition for a nearby one with different discharge or sediment transport is likely not.

Consider for example the US Atlantic coast where rivers flow from the Piedmont to the coastal plain and then, in former times, out across the shelf. In the initial configuration, we let the slope of the three units (piedmont, coastal plain and shelf) be identical, forming a tilted plain (Fig. 3a). We further consider a river not at grade in the sense that the sediment load is less than the expected given the

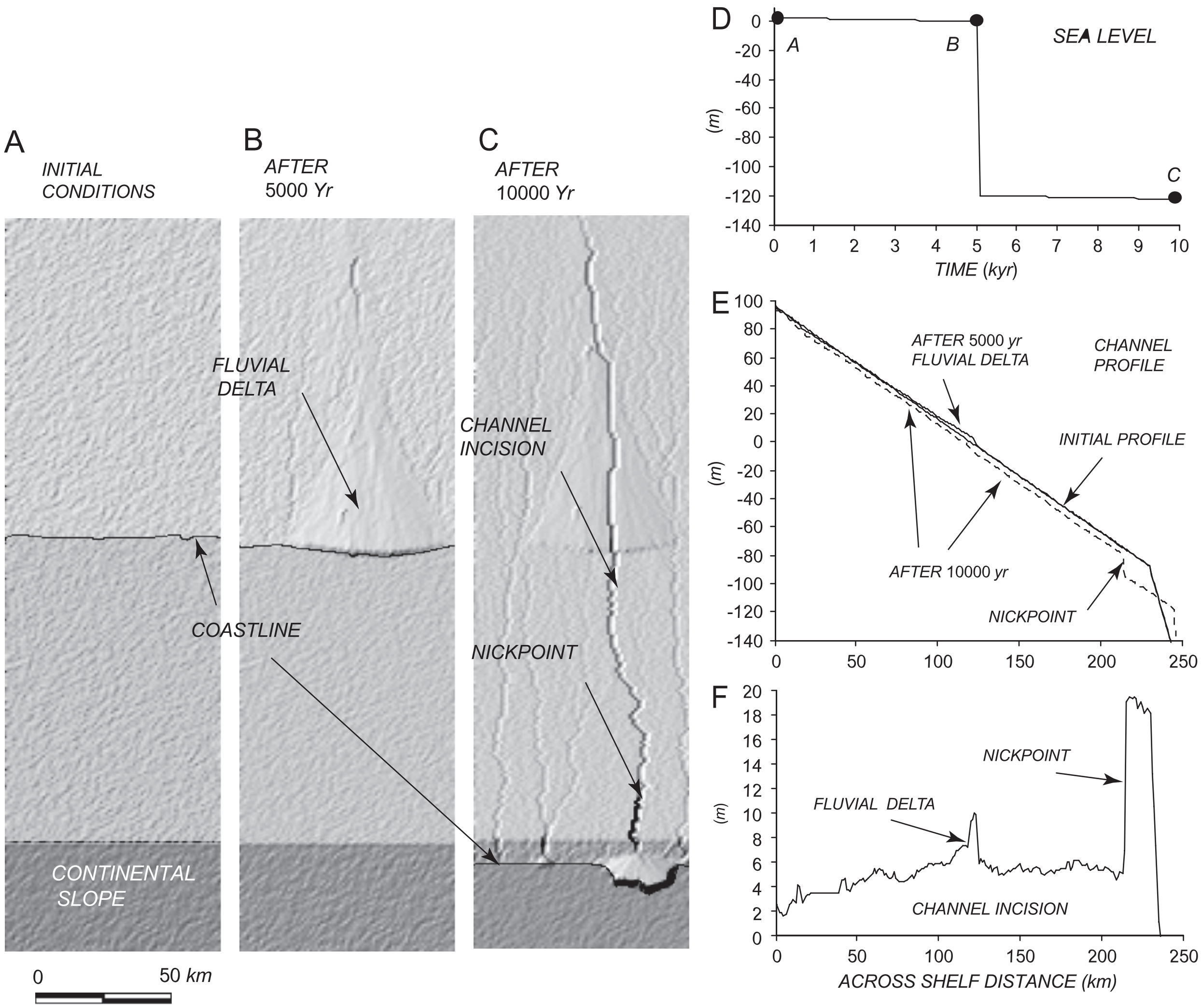

Fig. 2. Establishment of fluvial channels in the continental shelf after sea-level regression to below the shelf break. A river at grade with the shelf slope flows in the middle of the simulation domain. (A) Initial conditions; (B) after 5000 yr a deltaic deposit forms at the coastline; (C) after 10,000 yr the sea level is below the shelf slope, producing extensive downcutting along the river profile and the formation of a migrating nickpoint; (D) sea-level curve; (E) channel profile; and (F) channel incision after 10,000 yr.

discharge and the coastal plain slope. The flow will then erode the valley bottom trying to reduce the gradient and return to an equilibrium configuration. In our simulation, the top part of our domain is composed of resistant material (no erosion is allowed) that mimics the Piedmont bedrock. We consider a smooth drop in sea level that does not expose the entire shelf. After 7000 yr the river has already deeply incised the coastal plain surface (Fig. 3b and e). Because sea level is constantly decreasing, the river has to keep regrading in order to counteract these changes. After 14,000 yr the river incision will thus be higher (Fig. 3c and e).

Since incision is defined as the difference between the river bottom and the shelf surface, the high frequency ondulations in Fig. 3f are due to the ragged initial topography.

Because of the two boundary conditions of resistant material on the Piedmont and low gradient at the topset delta, the regrading of the river gives rise to a knickpoint at the Piedmont boundary. The longitudinal profile of the Rappahannock River in Virginia is reminiscent of this situation with a flat incised valley in the coastal plain and abrupt elevation change at the border with the Piedmont (fall line) (Fig. 4). Channel incision below the fall

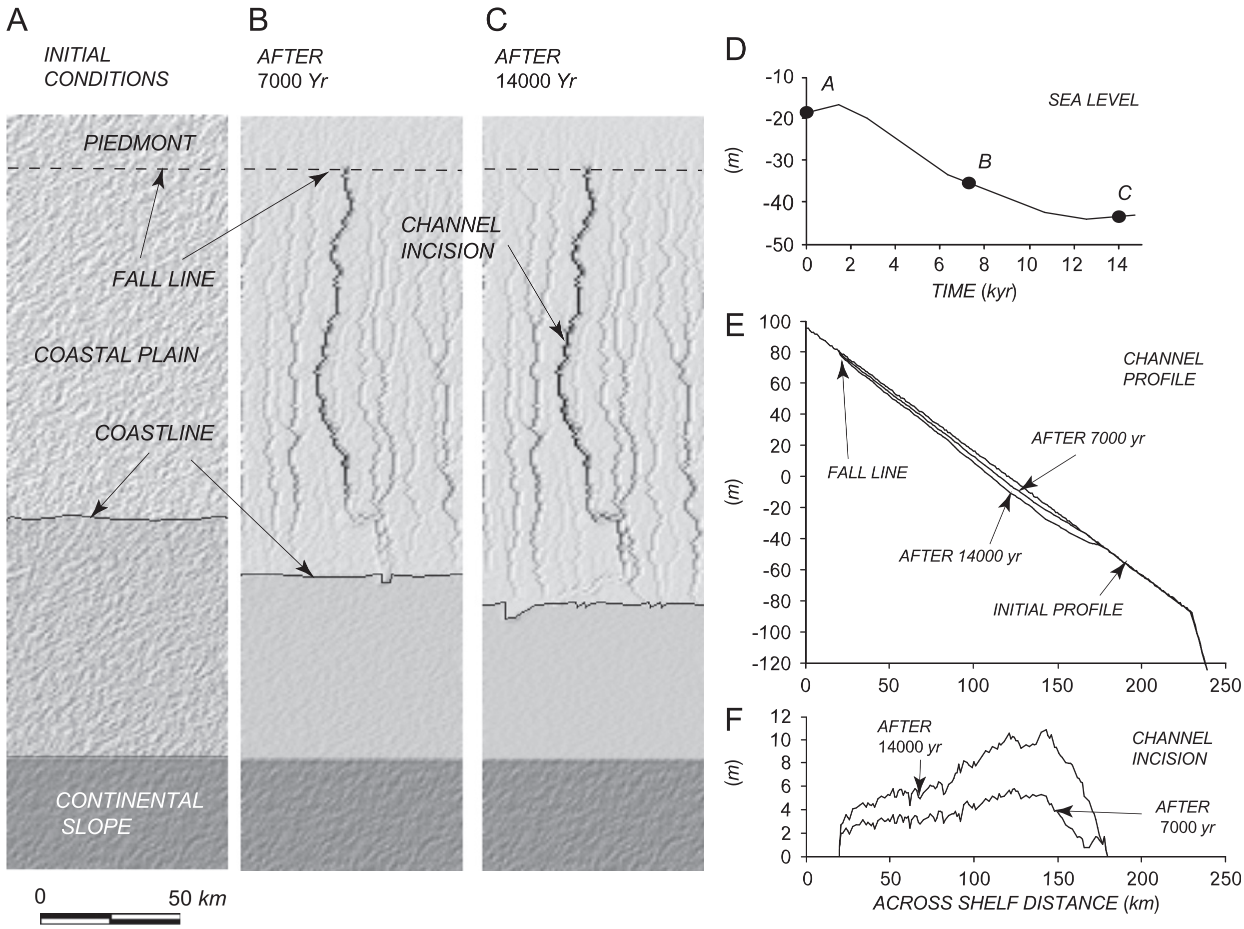

Fig. 3. Establishment of fluvial channels in the continental shelf after sea-level regression when the river grade is less than that of the shelf and coastal plain. An out-of-grade river flows in the middle of the simulation domain. The sediment discharge becomes less than the equilibrium value used in the simulations of Figs. 1 and 2, therefore the river tries to reduce its slope by downcutting. (A) Initial conditions; (B) after 7000 yr the river eroded the coastal plains surface forming a knickpoint at the border between coastal plain and piedmont; (C) after 14,000 yr channel incision is remarkable despite having the coastline still above the shelf slope; (D) sea-level curve; (E) channel profile; and (F) channel incision.

line is significant even if sea level does not fall below the shelf break and it is due to the fact that the river is out of grade. The role of sediment deposits in modifying the total incision is negligible, but they are instead important in setting the channel path (Fig. 3b and c).

4. Fluvial incision and the transition between shelf and coastal plains

Analysis of coastal topography shows that the shelf slope often differs from the average slope of the adjacent costal plains, with fundamental consequences for channel formation on the shelf. When the shelf slope is higher than the coastal plain slope (Fig. 5) the river, initially at equilibrium with the coastal plain, readjusts its profile continuously during marine regression, leading to uniform erosion along its course (Fig. 5c–e). When instead the shelf slope is less than the coastal plain slope, a sea-level drop produces the formation of thick deltaic deposits at the change in slope, where the river reduces its sediment load to adjust to the new gradient. Deposition still takes place at the change in slope even if the coastline has already regressed across the shelf. The deltaic deposits thus become fluvial fans, and the outgoing river is at grade so that neither aggradation nor erosion takes place on the continental shelf (Fig. 6).

We can thus summarize the different styles of fluvial incision in continental shelves in four

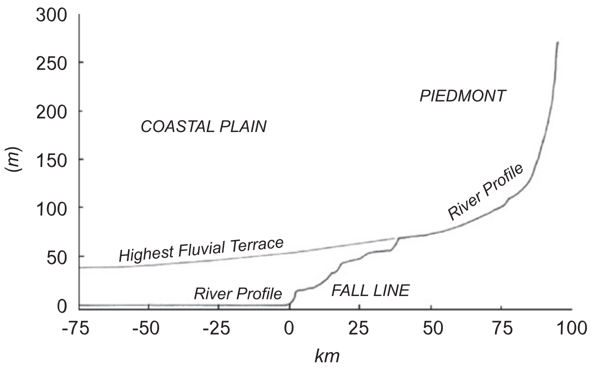

Fig. 4. Longitudinal profile of the Rappahannock River, Virginia. The fall line represents a past sea level high stand. During subsequent periods of lower sea level the river incised into the coastal plain sediments to recover its equilibrium (graded) configuration (modified after Howard et al., 1994).

categories (Fig. 7). Fluvial deposits or, in general, shelf convexities produce an incision that is localized and developed in a short timescale (Fig. 7a). A river out of grade with sediment supply less than its carrying capacity reworks its profile producing an incision that is maximum for some intermediate location along the river profile, but reduced at the river mouth. These incisions will have a knickpoint at the border with the erosion-resistant piedmont (Fig. 7b). An increase in slope in the shelf produces instead a uniform downcutting, with the river maintaining its equilibrium slope (Fig. 7c). Finally, the exposure of the shelf break gives rise to a knickpoint that propagates upstream (Fig. 7d). It is important to notice that an increase in the slope of the shelf or the exposure of the shelf-slope break

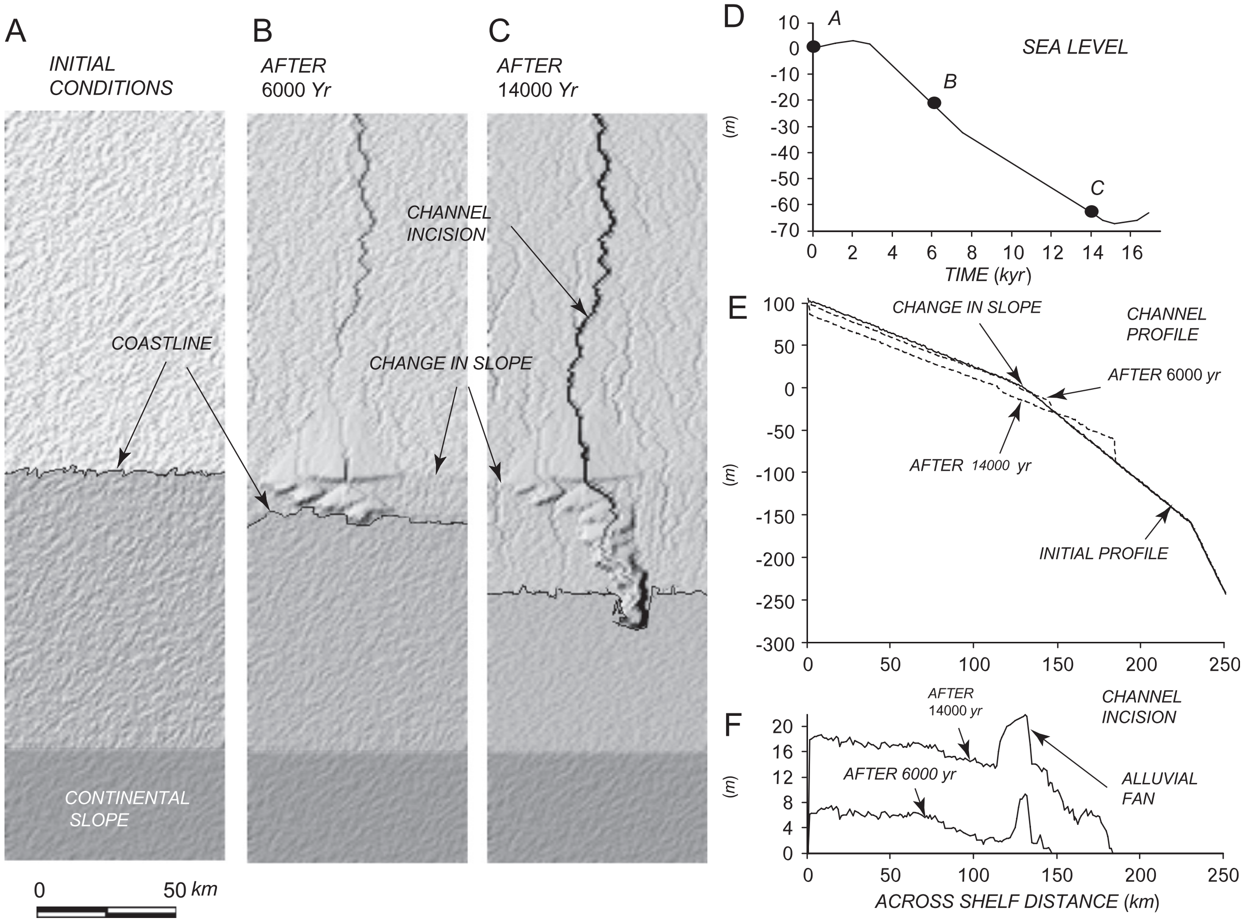

Fig. 5. Establishment of fluvial channels in the continental shelf after sea-level regression when the shelf gradient is steeper than the coastal plain and the grade of the inflowing river. The river profile is forced to translate following the decrease in base level, thus yielding uniform incision. (A) Initial conditions; (B) after 6000 yr the shelf is progressively exposed to rainfall action; (C) after 14,000 yr channel incision is uniform, and a series of deltaic deposits form along the river planform; (D) sea-level curve (interval A in Fig. 3); (E) channel profile; and (F) channel incision.

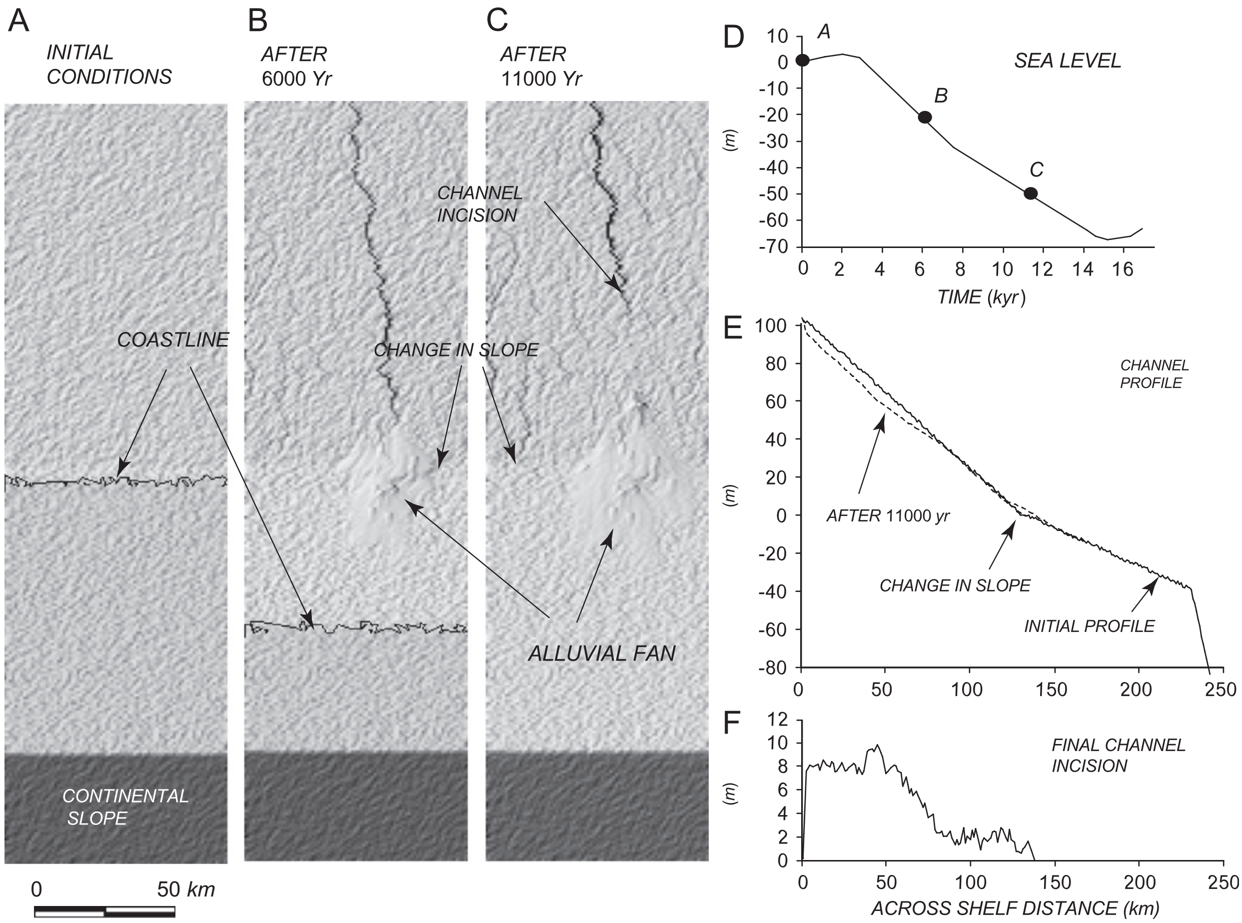

Fig. 6. Establishment of fluvial channels in the continental shelf after sea-level regression where the shelf gradient is more gentle than the equilibrium gradient of the inflowing river. In this case, the river deposits the extra amount of sediment load at the slope break, forming alluvial fans that increase in volume during regression. The outgoing river flowing in the shelf is at grade producing neither incision nor aggradation. (A) Initial conditions; (B) after 6000 yrs the shelf is progressively exposed to rainfall action; (C) after 11,000 yr alluvial fans form a the slope break, the river flowing out from the fans is at grade; (D) sea-level curve; (E) channel profile; and (F) channel incision after 11,000 yr.

reflect in reality the same geometrical configuration, but with different sediment transport regimes. Changes in the slope of the shelf are relatively mild producing a limited incision without exposing the underlying bedrock. The incised sediments are relatively unconsolidated so that the river still tends to be in transport-limited (as opposed to detachment-limited) conditions. The timescale of propagation of the incision is relatively fast and the river downcuts almost uniformly into the shelf. On the contrary, if sea level drops below the shelf-slope break, a deeper incision is produced that erodes into the underlying bedrock. The high resistance of bedrock to erosion produces a knickpoint that propagates slowly upstream. Different styles of incision can coexist and overlap depending on the evolution of the river during sea-level oscillations. As an example, we study the modality of incision of the Po River and adjacent Adriatic Sea during a drop in sea level.

5. Test case: the Po and the Apennine rivers, Italy

We apply our model to the Adriatic Sea to simulate the development of rivers and related incisions during a sea-level regression. The Adriatic Sea is an epicontinental basin of elongated shape connected southeast to the Mediterranean Sea (Fig. 8a). Bottom gradients range from 0.02° in the northern Adriatic to 0.5° along the central Adriatic, where a remnant basin (Meso-Adriatic depression) is located with a maximum depth of

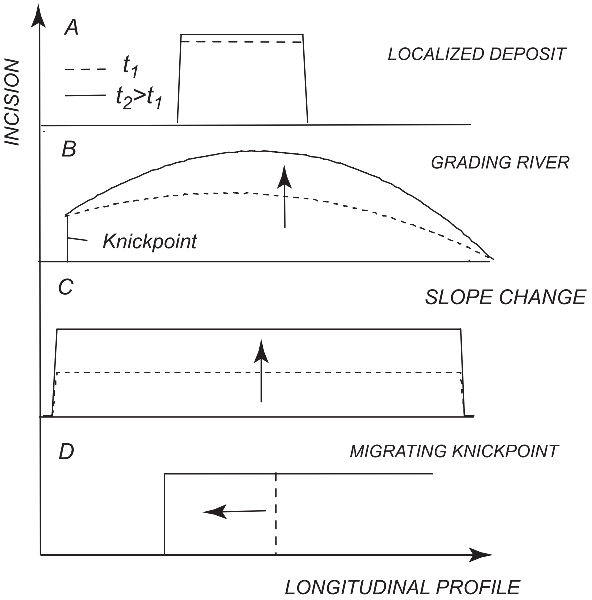

Fig. 7. Styles of fluvial incision of continental shelves. (A) High-stand deposits lead to a localized incision that is proportional to the deposit thickness. (B) A river out of equilibrium produces an incision that is maximum for an intermediate location along the river course; (C) an increase in slope in the shelf relative to the river produces an uniform incision; (D) a sea level below the shelf break triggers the formation of migrating knickpoints.

260 m (Cattaneo et al., 2003; Niedoroda et al., 2005).

During the Last Glacial Maximum large areas of the shelf were subaerial and dissected by rivers, and then progressively drowned by sea-level transgression. Contrary to pericontinental margins, epicontinental seas are characterized by large variations in both basin size and coastline length during variations in sea level. For example, the northern Adriatic experienced an eight-fold widening in submerged area during the Late Pleistocene–Holocene relative sea-level rise (Cattaneo and Trincardi, 1999). The enclosed, narrow shape of the Adriatic Sea dictates the evolution and degree of incision of fluvial channels in the shelf.

Herein we simulate a constant rate of sea-level drop of 6 mm/yr and we explore the consequences for the development of the drainage network and channel incision. The discharge and sediment load of the Po River and Apennine tributaries is maintained constant, for sake of simplicity, and equal to the values reported in Milliman and Syvitski (1992).

After a decrease in sea level of 120 m, the Po River dissects the Adriatic basin floor, flowing into the Mediterranean Sea 500 km away from the actual delta (Fig. 8d). Its narrow epicontinental basin prevents the distribution of fluvial sediments over large areas. Moreover, the Apennine rivers flowing into the Adriatic Sea along the west coast of Italy are easily captured by the Po River during sea-level low stands. The capture is critical for channel incision and sediment deposition in the shelf.

From the model results we can infer the presence of three distinct phases in the evolution of the fluvial system. In a first phase of regression (Fig. 8b) the Po River produces a prograding delta that extends from the actual delta into the Adriatic Sea. During this phase, large volumes of sediment are deposited at the river mouth forming convex deposits that can be easily downcut during the subsequent drop in sea level. When sea level decreases below the average depth of the Northern Adriatic Sea, large shelf areas become subaerial, affecting the river path toward the ocean (Fig. 8c). This second phase is similar to the situation reported in Fig. 6. The Po River extends in a shelf tract that is relatively flat with respect to the coastal plains in northern Italy, therefore the river dumps sediment at the boundary between the shelf and the coastal plain and continues its flow to the ocean in graded conditions. The flatness of the basin floor and the river equilibrium give rise to a landscape with negligible relief and probably dominated by wetlands and shallow lakes. Fluvial incisions are only present in the old high stand deposits, as indicated in Fig. 1 (Fig. 8c). Dissection is limited to the river depth and the river bypasses all its sediments to the Mediterranean Sea. Similarly, the Apennine rivers flow in the flat Adriatic shelf, discharging large volumes of sediments as soon as the shelf slope decreases (e.g. Fig. 6). These sediments form a uniform deltaic prism that extends to the entire eastern coast of Italy. After discharging the excess sediment load, the Apennine rivers are at grade, and neither erosion nor deposition occurs.

In a third phase, all the Apennine rivers become tributaries of the Po River, since its path extends to the entire Adriatic shelf. The massive increase in discharge of the paleo-Po River alters the equilibrium of the system, leading to river downcutting. In fact in our model the equilibrium sediment discharge is proportional to the water discharge to the power of 1.1 (see Fagherazzi et al., 2004), reflecting the fact that a higher discharge carries proportionally more sediments than a lower one. The sediment supply is then less than the carrying

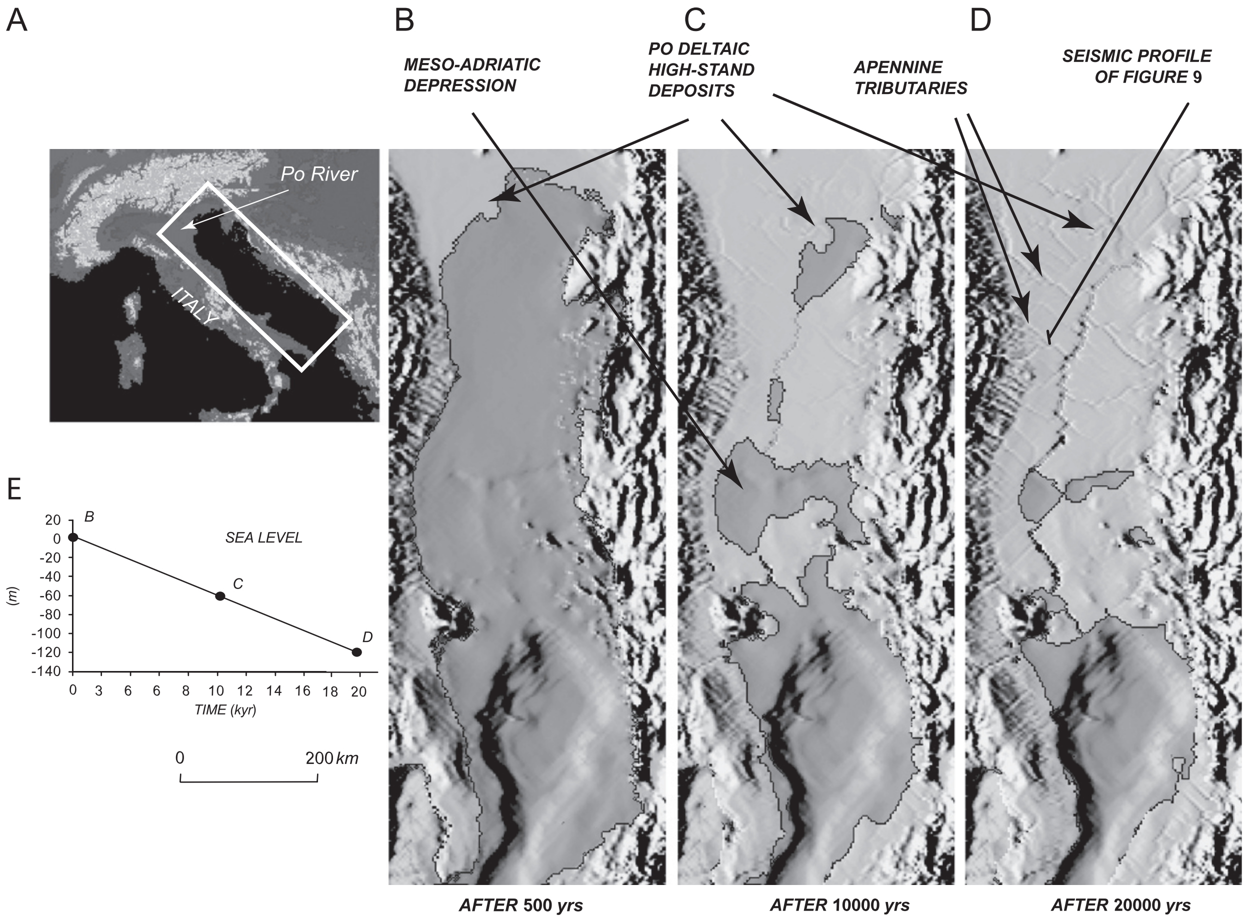

Fig. 8. Dissection of the Adriatic shelf during sea-level regression. (A) Location of the Adriatic Sea and Po River; (B) shelf topography after 500 yr of simulation; (C) shelf topography after 10 kyr of simulation; (D) shelf topography after 20 kyr of simulation; and (E) sea-level curve utilized in the simulation. The rate of sea-level decrease is constant and equal to 6 mm/yr.

capacity leading to bottom erosion and incision. This phase is similar to the configuration of Fig. 3, with a bell-shaped distribution of incisions that affects the entire river profile.

Simultaneously, all the Apennine tributaries entrench in steep valleys to follow the regrading of the paleo-Po. The landscape is completely transformed with a wide and deep paleovalley produced by the Po River and a series of parallel deep valleys corresponding to the Apennine tributaries. These conceptual results are in agreement with seismic data collected in the Adriatic. Buried paleovalleys typically 20 m deep and several kilometers wide are mostly found between 60 and 110 m of water depth (Trincardi et al., 1994; Ferretti et al., 1986).

We propose that the large erosional channels observed in the stratigraphic record were produced by the integration of the Apennine rivers in the Po drainage system in the geological past. The massive increase in discharge moved the system out of grade thus promoting downcutting. The style of incision is similar to the grading river of Figs. 3 and 7b, with maximum incision for intermediate depths, as shown in the seismic profiles. Finally, the paleo-Po flows in the Meso-Adriatic depression during sea-level low stand (Fig. 8d), forming progradational wedges that are found in the stratigraphic record (Trincardi et al., 1994).

For comparison, in Fig. 9 we report the interpretation of a seismic profile derived from Trincardi et al. (1994) in which fluvial incisions are present in the stratigraphic record. At the same location our model simulation shows the presence of several Apennine tributaries that dissect the Adriatic floor during sea-level low stand (Fig. 8d). Unfortunately, the limited length of the seismic

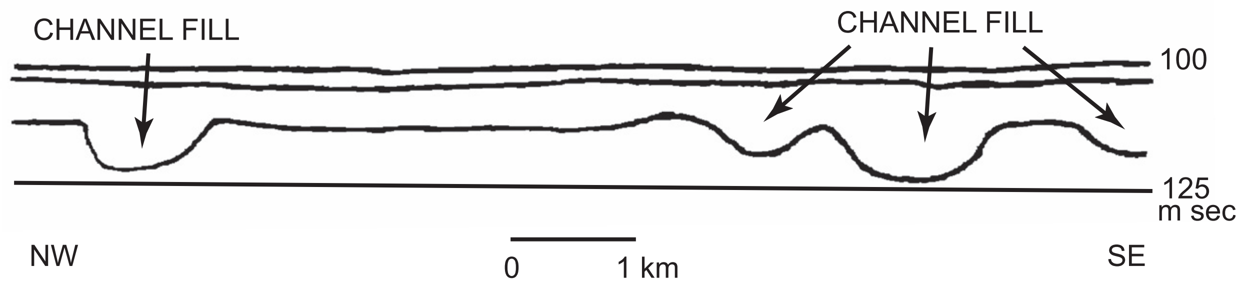

Fig. 9. Interpretation of the seismic profile reported in Trincardi et al. (1994). The fluvial channels are located in the top set of low stand deltas and correlate seaward to progradational foresets. The location of the seismic profile is reported in Fig. 8.

profile does not allow the identification of the specific Apennine river dissecting this location, and the presence of channel fills closely spaced suggests the repeated avulsion of a single stream. More stratigraphic data at a larger spatial scale are needed to correctly understand the evolution of fluvial incisions during sea-level cycles in the Adriatic Sea.

The semi-enclosed characteristics of the Adriatic basin and its low bottom gradients have been found to be determinant for the depositional sequence during sea-level transgression, favoring significant landward shifts of depositional environments and thin transgressive deposits not covered by high stand sediments (Trincardi et al., 1994). Here we show that the same factors influence the development of fluvial incisions during sea-level fall, with a phase of sediment bypassing and limited incision when large parts of the shelf are initially exposed, and a phase of rapid incision when the Apennine rivers are merged to the paleo-Po river.

6. Conclusions

Through numerical simulations we have highlighted four different styles of fluvial incisions of continental shelves:

- Convex deltaic deposits emplaced during sea-level high stands favor a localized incision during sea-level low stand, with the extending river cutting through the sediment prism (Figs. 1 and 7a).
- A river out of equilibrium with a sediment supply less than its carrying capacity re-grades by downcutting the shelf sediments, thus producing incision that is distributed along the river profile and is maximum for an intermediate location (Figs. 3 and 7b).
- An increase in shelf slope relative to the coastal plain slope leads to a uniform incision along the river, reflective of transport-limited conditions (Figs. 5 and 7c).
- A decrease in sea level below the shelf break produces high incisions propagating upstream through knickpoints, reflecting detachment-limited conditions when the river reaches the underlying bedrock or a more resistant substrate (Figs. 2 and 7d).

The four mechanisms of incision can coexist in the same fluvial systems at different times, depending on the morphology of the shelf and the evolution of the rivers during sea-level oscillations.

As an example, a decrease in sea level in the Adriatic Sea, Italy, would produce a down-slope extension of the Po River of 500 km toward the retreating Mediterranean Sea, with localized incisions in the high stand deposits located near the present delta, and a generalized incision caused by the integration of the Apennine streams in the Po River drainage system. In fact the transformation of the Apennine rivers into tributaries of the Po creates a disequilibrium condition for the paleo-Po River, which led to a subsequent regrading through downcutting and valley incision.

Acknowledgments

This research was supported by the Office of Naval Research, Geoclutter Program (Contract no. N00014-05-1-0071), the EuroSTRATAFORM project (Contract no. N00014-03-C-0134), and by the Petroleum Research Fund, Award 42633-G8.

References

Bull, W.B., 1991. Geomorphic Responses to Climate Change. Oxford University Press, Oxford, 362pp.

Cattaneo, A., Trincardi, F., 1999. The Late-Quaternary transgressive record in the Adriatic epicontinental sea: basin widening and facies partitioning. In: Bergman, K.M., Snedden, J.W. (Eds.), Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation, vol. 64. SEPM Special Publication, pp. 127–146.

Cattaneo, A., Correggiari, A., Langone, L., Trincardi, F., 2003. The Late-Holocene Gargano subaqueous delta, Adriatic shelf: sediment pathways and supply fluctuations. Marine Geology 193 (1–2), 61–91.

Clevis, Q., De Boer, P.L., Wachter, M., 2003. Numerical modelling of drainage basin evolution and three-dimensional alluvial fan stratigraphy. Sedimentary Geology 163 (1–2), 85–110.

Clevis, Q., De Boer, P.L., Nijman, W., 2004. Differentiating the effect of episodic tectonism and eustatic sea-level fluctuations in foreland basins filled by alluvial fans and axial deltaic systems: insights from a three-dimensional stratigraphic forward model. Sedimentology 51 (4), 809–835.

Davies, T.A., Austin, J.A., 1997. High resolution 3D seismic reflection and coring techniques applied to Late Quaternary deposits on the New Jersey shelf. Marine Geology 143 (1–4), 137–149.

Donoghue, J.F., 1993. Late Wisconsinan and Holocene depositional history, northeastern Gulf of Mexico. Marine Geology 112, 185–205.

Duncan, C.S., Goff, J.A., Austin, J.A., Fulthorpe, C.S., 2000. Tracking the last sea-level cycle: seafloor morphology and shallow stratigraphy of the latest Quaternary New Jersey middle continental shelf. Marine Geology 170 (3–4), 395–421.

Fagherazzi, S., Howard, A.D., Wiberg, P.L., 2004. Modeling fluvial erosion and deposition on continental shelves during sea level cycles. Journal of Geophysical Research—Earth Surface 109 (F3).

Ferretti, M., Moretti, E., Savelli, D., Stefanon, A., Tramontana, M., Wezel, F.C., 1986. Late Quaternary alluvial sequences in the North Western Adriatic Sea from Uniboom profiles. Bollettino Oceanografia Teorica ed Applicata 4, 63–72.

Howard, A.D., 1994. A detachment-limited model of drainage-basin evolution. Water Resources Research 30 (7), 2261–2285.

Howard, A.D., Kerby, G., 1983. Channel changes in badlands. Bulletin of the Geological Society of America 94, 739–752.

Howard, A.D., Dietrich, W.E., Seidl, M.A., 1994. Modeling fluvial erosion on regional to continental scales. Journal of Geophysical Research—Solid Earth 99 (B7), 13971–13986.

Leopold, L.B., Maddock, T., 1953. The hydraulic geometry of stream channels and some physiographic implications. US Geological Survey Proffessional Paper 1145, 252.

Locker, S.D., Doyle, L.J., 1992. Neogene to recent stratigraphy and depositional regimes of the Northwest Florida inner continental shelf. Marine Geology 104 (1–4), 123–138, 29.

Mackin, J.H., 1948. Concept of the graded river. Bulletin of the Geological Society of America 59 (5), 463–512.

McKeown, H.A., Bart, P.J., Anderson, J.B., 2004. High resolution stratigraphy of a sandy, ramp-type margin—Apalachicola, Florida. In: Anderson, J., Fillon, R. (Eds.), Late Quaternary Stratigraphic Evolution of the Northern Gulf of Mexico Margin: Special Publication no. 79. Society for Sedimentary Geology, pp. 25–41.

Meijer, X.D., 2002. Modeling the drainage evolution of a river–shelf system forced by Quaternary glacio-eustasy. Basin Research 14 (3), 361–378.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic tectonic control of sediment discharge to the ocean—the importance of small mountainous rivers. Journal of Geology 100 (5), 525–544.

Niedoroda, A.W., Reed, C.W., Das, H., Fagherazzi, S., Donoghue, J.F., Cattaneo, A., 2005. Analyses of a large-scale depositional clinoformal wedge along the Italian Adriatic coast. Marine Geology 222, 179–192.

Roering, J.J., Kirchner, J.W., Dietrich, W.E., 1999. Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. Water Resources Research 35 (3), 853–870.

Schumm, S.A., 1993. River response to baselevel change: implications for sequence stratigraphy. Journal of Geology 101 (2), 279–294.

Schumm, S.A., Lichty, R.W., 1965. Time, space and causality in geomorphology. American Journal of Science 263, 110–119.

Starkel, L., Gregory, K.J., Thornes, J.B. (Eds.), 1991. Temperate Paleohydrology. Wiley, Chirchester, 568pp.

Summerfield, M.A., 1985. Plate tectonics and landscape development on the African continent. In: Morisawa, M., Hack, J. (Eds.), Tectonic Geomorphology. Allen and Unwin, Concord, MA, pp. 27–51.

Swift, D.J.P., 1973. Delaware shelf valley: estuary retreat path, no drowned river valley. GSA Bulletin 84, 2743–2748.

Talling, P.J., 1998. How and where do incised valleys form if sea-level remains above the shelf edge? Geology 26, 87–90.

Trincardi, F., Correggiari, A., Roveri, M., 1994. Late Quaternary transgressive erosion and deposition in a modern epicontinental shelf—the Adriatic semienclosed basin. Geo-Marine Letters 14 (1), 41–51.

Tucker, G.E., Slingerland, R.L., 1997. Drainage basin response to climate change. Water Resources Research 33 (8), 2031–2047.

Uchupi, E., Driscoll, N.W., Ballard, R.D., Bolmer, T., 2001. Drainage of Late Wisconsin glacial lakes and the morphology and Late Quaternary stratigraphy of the New Jersey Southern New England Continental Shelf and Slope. Marine Geology 172, 117–145.