Models of Deltaic and Inner Continental Shelf Landform Evolution

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Abstract

The morphology of passive continental shelves is dictated by the input of sediments from rivers and their redistribution by waves, currents, and gravity-driven flows. The pathways followed by sediments sculpt a landscape whose diversity is rarely matched on Earth's surface. Sediments are released to the shelf from triangularly shaped, elongated, and dendritic deltas. Barrier islands rise from gently sloping areas, tidal channels dissect flats and saltmarshes, fine sediments form broad convex deposits, and shallow submarine valleys convey sediments and water to the deep ocean. This morphological diversity is based on two main building elements: water and sediments. Fluxes of water and sediments are particularly suitable to be modeled with numerical methods based on the continuum hypothesis and hydrodynamics theory. In recent years, a series of models have been developed to explore and understand the formation of shelf landforms from the dynamics of sediment transport. Herein we present an overview of the most recent results on the modeling of deltaic and inner-shelf morphodynamics.

INTRODUCTION

Continental shelves are hidden subaqueous landscapes whose morphology is unique on Earth's surface. Compared with terrestrial landscapes, continental shelves display a gentle and smooth topography. They extend up to 100 km offshore, with slopes that vary from zero to half a degree, and maximum relief of few tens of meters (O'Grady et al. 2000). This uniformity might erroneously suggest that few processes are at work in these environments. On the contrary, the physical agents responsible for shelf morphodynamics are numerous and act at different spatial and temporal scales. Continental shelves are located at the boundary with land so that they are shaped by both marine and terrestrial processes. Moreover, sea-level oscillations incessantly transform terrestrial areas in marine environments and vice versa, thus increasing the landscape complexity.

Because direct experimentation to investigate shelf morphodynamic processes is hardly possible, especially at longer timescales, the utilization of computer models can help researchers to understand the dynamics of these environments. Computer models allow the quantitative testing of hypotheses on the importance of specific processes. Functional models can also have predictive capabilities and can be used to investigate the effects of human activities and climate change on the dynamics of sedimentary systems.

Herein, we present an overview of the most recent computer modeling results in this exciting research area. We focus the discussion on models that intend to simulate the long-term evolution of passive siliciclastic shelves. Passive siliciclastic shelves are important because their flat coastlines are inhabited by a large fraction of the world population and valuable natural resources, such as oil and gas, are stored in their sediments. Their morphology is dictated by the sediment input from rivers and the subsequent redistribution by waves, currents, and gravity-driven flows. As a result, a thick layer of sediments usually blankets these marine environments; therefore, shelf morphology is well suited to be studied with numerical models that treat both water and sediments as continuum media. These models can build on the wealth of scientific knowledge on the hydrodynamics and sediment transport of marine environments.

We limit our analysis to the relatively shallow waters of the inner- and mid-shelf, from the coastline to up to an arbitrary depth of around 100 m, without exploring the dynamics of the continental slope (e.g., McAdoo et al. 2000).

Finally, our focus is mainly on surface morphology, and we refer to other publications for an overview of much larger-scale shelf stratigraphy (Poag 1978, Christieblick & Driscoll 1995) or much smaller-scale bedforms that are ubiquitous in marine environments (Blondeax 2001, Dalrymple et al. 1978).

The morphology of the shallow shelf is closely interconnected to that of nearby terrestrial landscapes. Intercoupled terrestrial and marine agents shape the landscape, producing a richness of landforms that is rarely matched on Earth's surface (**Figure 1**). Rivers carry sediments that are stored in bays, estuaries, and deltas or are directly discharged into the shelf. Waves continuously reshape the shoreline by forming and destroying barrier islands and spits. Tidal inlets and channels dissect the shelf surface,

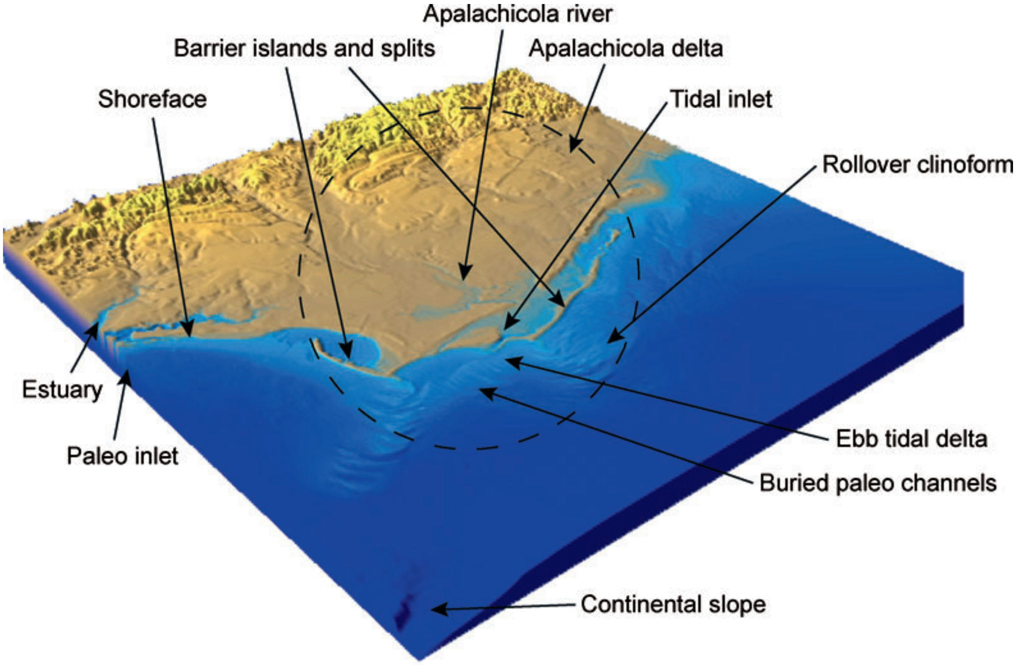

Figure 1

Morphology of the inner continental shelf, Apalachicola Delta, Florida.

controlling the fluxes of water and sediments between bays and the ocean. Waves, currents, and gravity-driven flows propagate the morphodynamic activity to the mid- and outer-shelf by fluxes of sediments that extend to the continental slope. When we add sea-level oscillations to the picture, the dynamics of the inner continental shelf becomes even more complex and fascinating. In a geologically short timescale (e.g., thousands of years), a rise in sea level can flood the nearby coastal plains, erasing or burying drainage systems and hillslope topography, while barrier islands and spits migrate inland or drown under the violence of storms. A drop in sea level, however, exposes large shelf areas to subaerial agents, promoting plant colonization, dissection of the shallow shelf topography by new streams, and landscape reworking by mass wasting processes. Models over medium to long time periods (i.e., 10^1 to 10^4 years) are thus needed to capture shelf morphology.

In the following paragraphs, we introduce state-of-the-art delta and shelf morphological models. A number of key complexities that hinder the rapid development of integrated delta and shelf models are also explained. The subdivision of the material in several morphological units and related efforts to model their dynamics provides an insight into the way modelers deal with the complexities of spatial- and temporal-scale and process integration. We hope that our overview of recent developments in delta and shelf models will guide the progress of modeling this complex environment.

MODEL CLASSIFICATION

Expanding the classification of de Vriend et al. (1993) for coastal models, we can divide shelf morphodynamic models based on their dimensionality into four categories:

- Two-dimensional (2-D) cross-shelf models, which neglect along-shelf variations in morphology and focus on the evolution of the shelf profile,
- 2-D along-shelf models, which consider either a constant cross-shelf profile or integrate across the shelf and concentrate on the evolution of the along-shelf morphology,
- Pseudo 3-D shelf area models, which are based on depth-averaged formulations for hydrodynamics and sediment transport, and
- Full 3-D models, which reproduce the full structure of the flow field coupled with the transport of sediments.

The reduction of the model domain in fewer dimensions is sometime possible because the shelf evolves at different timescales in the vertical, across-shelf and along-shelf directions.

Another way of classifying models that simulate the shelf morphology is based on the complexity of the algorithms utilized. Herein we divide the models in three groups: geometrical models, long-term integrated models, and high-resolution models. A morphological model for shelf development can in reality incorporate subcomponents belonging to different groups, depending on what processes the model focuses on.

Geometrical Models

The simplest type of model is based on the conservation of geometrical shapes that usually represent short-term equilibrium conditions. A typical example is the simulation of the transgression of a barrier island by conserving the shoreface profile (Cowell et al. 1995). These models are simple but can be very effective in simulating the long-term behavior of the system. However, since the geometry is fixed a priori, they cannot capture situations in which that particular geometry is not respected, namely during transient conditions.

Long-Term Integrated Models

In these models, the processes shaping the shelf landscape are schematized with simplified expressions that mimic their major morphodynamic characteristics. The equations used in the modeling framework spring from the integration of the processes at a higher level or are simply borrowed by well-studied concepts of physical modeling (e.g., advection-diffusion models). Whereas integrated models respect the principle of conservation of mass, they are less precise in the reproduction of the forces that act on the sediments and determine their motion.

These models usually redistribute sediments in different cells of the domain by applying a series of rules that mimic the physics of the processes. A representative example of the integrated modeling approach is the utilization of a diffusion-like equation to redistribute sediments along the shelf, but the formulation can be more complex, including advection components or more refined algorithms. A strong advantage of integrated models is the utilization of only a few parameters (diffusion coefficient, advection velocity) that can be tuned through comparison with shelf topography, whereas high-resolution models might need the determination of scores of parameters.

High-Resolution Models

High-resolution models are based on first principles regulating the hydrodynamics and physics of sediment transport. These models utilize state-of-the-art fluid dynamics modeling (e.g., large eddy simulations) to solve fluid mechanics equations (e.g., Navier-Stokes, shallow water equations) coupled to rules for sediment transport. Because the timescales of marine hydrodynamics range from seconds to hours, high-resolution models must use very short timesteps. Seldom are these models able to capture the long-term internal dynamics of the system, so convergence toward stable states is not always achieved. These models are usually applied to problems involving small temporal and spatial scales, and thus are widely used in the engineering community.

An example is the model Delft3D (Roelvink & van Banning 1994, Wang et al. 1995, Lesser 2004), based on the coupled description of small-scale hydrodynamic and sediment transport processes. The model utilizes a finite-difference staggered scheme that solves the three-dimensional (3-D) flow field coupled to suspended and bedload sediment transport, and it has already been successfully applied to model tidal inlets (Wang et al. 1995) and shoal patterns in estuaries (Hibma et al. 2004a), as well as a number of detailed case studies of delta systems (e.g., van Maren 2004).

COMPLEXITIES IN THE MODELING OF LARGE-SCALE SHELF MORPHOLOGY

Wright (1995) presents an overview of key scientific questions that need to be addressed to better understand inner-shelf morphodynamics. A number of these concepts can be used to drive the development of a new generation of computer models. Critical concepts for the correct modeling of shelf morphology are indicated in the following paragraphs.

Spatial Aspects: 3-D Modeling

Shelf models need to resolve not only absolute rates of sediment transport but also their spatial gradients because it is the spatial divergence of the sediment fluxes that leads to changes in morphology. In particular, across-shelf gradients are critical because they determine the inner-shelf profile and the redistribution of sediments across the entire shelf. The need for 3-D modeling is also evident when the studied area of the shelf is influenced by a variety of opposing processes, such as local dispersal of fluvial sediment by river plumes, as well as coastal and surf zone processes, which are often variable within the model domain. The Danube delta represents the textbook example of multiprocesses system. The most active distributary discharges a river plume into a limited delta area, and therefore fluvial processes are dominant in that particular zone. In locations of the delta that receive less sediment, the deposits are reworked by waves with the formation of beach ridges (Bhattacharya & Giosan 2003). A 3-D approach is thus imperative to capture this spatial variability.

High-Resolution Models Applied to Long-Term Simulations

The understanding of the physical processes at the base of shelf and nearshore hydrodynamics and sediment transport (e.g., Navier-Stokes equations, wave theory) has favored the development of high-resolution models for the short-term morphological evolution of coastal and shelf areas. However, the application of these models to long-term morphodynamics is still debatable and under careful scrutiny. Partly, this is an issue of computer run-time and the high cost of calculation. The models are routinely built on large data matrices that store lists of process parameters for gridcells (usually on the order of a few meters) with small timesteps (usually seconds to minutes), which continuously need to be handled and updated. But more importantly, high-resolution models do not have embedded key dynamics of large-scale morphological systems, as, for instance, equilibrium states to which the system is converging under general conditions. Large-scale shelf morphology is often the residual result of nonlinear processes that have opposing influences on sediment redistribution. Thus, small errors produced by high-resolution models can propagate and be amplified in long-term simulations. These potential drawbacks have facilitated the development of more simplified approaches in which the small-scale physics of the system has been reduced for a better understanding of the large-scale dynamics.

Also, shelf models should integrate the physical principles governing sediment redistribution with a geological framework that provides information on relic features from antecedent regimes. The current morphology of the shelf is in fact partly inherited from the past owing to sea-level oscillations. Similarly, the available sediment on the shelf reflects long-term processes and should be integrated as a boundary condition into a high-resolution model.

System Dynamics and Equilibrium States

Long-term modeling of shelf landforms is critically based on the understanding of the system dynamics and equilibrium conditions. An example of a morphological equilibrium state is the formation of the shoreface equilibrium profile as envisioned by Bruun (1954) and Dean (1991). After extensive field measurements these researchers postulated that the shoreface reaches, in the long term, a concave equilibrium profile function of sediment composition and local wave climate. Successful morphological models must then respect the equilibrium condition and maintain it during system evolution.

A model can thus (*a*) simulate in detail the processes responsible for shelf morphology. Equilibrium states and system dynamics are internally reached by the processes at play. The model then automatically respects these conditions and can focus on the long-term evolution, (*b*) include in the modeling framework the equilibrium conditions in a simplified formulation, and (*c*) reproduce in detail the processes at work, but it fails to capture the long-term dynamics of the system and their equilibrium states.

It is clear that the first of these modeling options is the most successful and that the last one cannot be adopted. When detailed models are unable to capture the dynamics of the system, simplified formulations are preferable. If it is not possible to correctly model the processes responsible for the equilibrium conditions, it is necessary to include these conditions in the modeling framework.

This methodological discussion also implies that a careful preliminary analysis needs to be carried out to determine the key dynamics of the system and possible equilibrium states. Unfortunately, high-resolution short-term models are often applied to long-term conditions without such analysis, leading to poor results.

A good example of a morphodynamic model based on equilibrium conditions is ASMITA (Stive et al. 1998). ASMITA was developed to study the interactions between a tidal lagoon and its adjacent coastal environment, and it represents an extension of ESTMORF (Wang et al. 1998), which was developed to study tidal basins. The model consists of five morphological units: a tidal basin, a flood basin, an ebb tidal delta, the channels and inlets linking the basin to the delta, and the adjacent coastline. Each unit is characterized by only one state variable. The most important hypothesis underpinning the model is that each unit has a specific equilibrium state, which depends on hydrodynamic conditions. The equilibrium condition is expressed in terms of an equilibrium sediment concentration, so that erosion (deposition) occurs in each unit if the sediment concentration is smaller (larger) than its equilibrium value. Sediments are then exchanged between the units through an advection-diffusion equation. If one or more units are disturbed (i.e., are out of equilibrium) the system reacts first by propagating the disturbance to the other units then all the disturbances are damped and the original equilibrium condition is recovered. The model can thus determine the morphological response of the system to an imposed modification within the lagoon or at the coast, as well as the timescale for equilibrium recovery. A successful application of the model is presented in Kragtwijk et al. (2004), in which the long-term evolution of two inlets in the Wadden Sea, subject to human interventions, is predicted.

2-D MODELS FOR CROSS-SHELF MORPHOLOGY

An important morphological characteristic of the shelf is the development of an equilibrium cross-shore profile. Under equilibrium conditions, all the incoming sediment is bypassed and deposited in the outer-shelf and continental slope. The cross-shelf equilibrium profile has been typically schematized as concave upward in wave-dominated inner-shelves where the input from rivers is negligible and convex upward in areas near deltas and river mouths. The development of both profiles has been the objective of several modeling efforts, but up to now a unique and universally accepted explanation has not been proposed for their development in time. The difficulties in modeling such a simple morphological attribute give evidence to the complexity of the processes responsible for shelf morphodynamics.

Naturally, the major disadvantage of any 2-D model is that it cannot describe lateral heterogeneity of the deposits, such as the lateral bypassing of sediment that would result from delta channel switching. They often simulate a monotonous coarsening-upward sequence in a 2-D deltaic setting and neglect the distinction between lobe and interlobe deposits. As such, any of the 2-D approaches that simulate cross sections are a representation of Walther's Law, which states that "in a continuous vertical sequence, the succession of facies vertically reflects the original contemporary lateral arrangement of facies in the area" (Brookfield 2004).

CONVEX-UPWARD CROSS-SHELF PROFILE IN WAVE-DOMINATED SHELVES

In areas where the sediment input from rivers is limited, the inner continental shelf usually presents a convex-upward profile. The profile stems from the equilibrium between onshore and offshore forces on bottom sediments, so that shoreward- and seaward-directed sediment fluxes exactly balance to produce no net shore normal transport. If hydrodynamic forces (waves and currents) were symmetrical, then the gravity force would produce a net sediment flux downslope, leading to shoreline disequilibrium. In fact, all the sediment will be eventually removed from the shallow inner-shelf and deposited offshore. A net onshore transport is thus necessary to maintain the convex profile. This net onshore flux can be due to the characteristics of the wave boundary layer, to preferential onshore transport during storms, or to the asymmetry from nonlinear wave interaction and sediment transport, but none of these explanations has an universal validity at each shelf location (see Niedoroda et al. 1995 and Dean & Dalrymple 2002 for a discussion). In morphodynamic models of a cross-shelf profile, the net onshore transport is usually included as a function of wave energy dissipation per unit volume (Dean & Maurmeyer 1983) or wave-bottom current areal power density (Niedoroda et al. 1995). The concept behind these approaches is that turbulence in the surf zone is the dominant force for sediment resuspension and that energy dissipation (a measure of turbulent fluctuations) has to be uniformly equal to the maximum value the sediment grains in a shoreline in equilibrium can withstand.

The concept of a concave profile, originally postulated for the beach profile by Bruun (1954) and Dean (1991), has been extended by Niedoroda et al. (1995) to the inner shelf and used to model the 3-D morphological evolution of the Adriatic sea, Italy (Niedoroda et al. 2005). An onshore net sediment transport component is crucial for any long-term modeling of shelf morphodynamics and it has to be included in the high-resolution modeling of wave-driven sediment transport or added as a simplified long-term component.

Whereas several researchers have investigated the development of the beach profile with analytical and numerical models (e.g., Stive & deVriend 1995), few studies have extended the approach to the inner- and mid-shelf. A complete 2-D approach for shelf evolution that accounts for wave-driven resuspension events was presented in Harris & Wiberg (2001, 2002). The model calculates suspended sediment concentration and flux based on wave climate, current velocities, and sediment size distributions. Model simulations show that a decrease in wave orbital velocity with water depth leads to cross-shelf gradients in bed shear stresses and net offshore transport of sediment. This is particularly true in steep shelves (slope approximately 0.5%) where the cross-shelf divergence of suspended sediment flux can create a winnowed erosional area with preferentially coarse material on the inner shelf and a fine-grained depositional area on the mid-shelf. These results suggest that shelf locations far from river deltas are always supply limited, either because waves are unable to resuspend enough sediment or because the winnowing of fine particles produces bed armoring, thus reducing further sediment entrainment.

CONCAVE-UPWARD CROSS-SHELF PROFILE AND CLINOFORM DEVELOPMENT

Shelf areas near river deltas and estuaries exhibit a convex-upward profile, produced by the sediment input from rivers. The concave profile is an expression of the rollover clinoform where the sediments of fluvial origin are accumulated. Models that investigate the redistribution of fluvial sediments in the shelf and the formation of the rollover clinoform are usually based on two equations, expressing the conservation of sediments (continuity) and the sediment flux as a function of waves, currents, and gravity. The continuity equation is:

$$\frac{\partial h}{\partial t} = -\frac{\partial S}{\partial x}, \tag{1}$$

where h is the elevation of the shelf and S is the volume of sediment transported in the x direction. Different models have been proposed depending on the choice of the sediment transport function S.

Diffusion Models

The simplest model assumes a sediment flux S proportional to the bottom slope (Kenyon & Turcotte 1985, Jervey 1988) so that the sedimentation rate is governed by a diffusion equation:

$$S = -D\frac{\partial h}{\partial x}, \quad \frac{\partial h}{\partial t} = D\frac{\partial^2 h}{\partial x^2}, \tag{2}$$

where D is the transport coefficient. The diffusion equation has been widely used to model foreland basins (e.g., Flemings & Jordan 1989). A sediment transport directly linked to the surface slope is typical of soil creep and landslides, so that the utilization of Equation 2 is appropriate when the sediment redistribution in the shelf occurs because of bulk-transport processes (Kenyon & Turcotte 1985). This assumption is generally thought to be valid for coarse-grained fan deltas, built, for example, on glacially influenced shelves. A similar approach has been derived from physical principles for fluvial sediment transport at the long timescale for rivers debouching into the ocean (Paola et al. 1992, Paola 2000) so that the diffusion equation is typically used in the subaerial topset of a delta. The coupling of a diffusion equation for the topset fluvial transport and a diffusion equation for the foreset marine component allows one to follow the evolution of the coastline and relate fluvial-deltaic deposition as a function of sea-level oscillations (Swenson et al. 2000, Marr et al. 2000). As indicated by Clevis et al. (2004), a diffusivity coefficient that decreases with depth can simulate the decrease in erosive energy in the coastal area and can produce more realistic-looking clinoform profiles in deltaic fronts. A number of modelers use a diffusivity coefficient that decreases exponentially with distance from the river mouth (Bursik 1995, Overeem et al. 2003).

Advection-Diffusion Models

The utilization of a diffusion equation for deltaic sediment redistribution produces a clinoform rollover that invariably coincides with the shoreline. In reality, in several subaqueous deltas, waves, currents, and mass-wasting processes transport the sediment from the mouth of the rivers to deeper locations, thus forming a compound clinoform that consists of a subaerial/subaqueous delta couplet (Swenson et al. 2005). Under these circumstances, a diffusion equation needs to be replaced with an advection-diffusion equation, where the advection component is a surrogate for across-margin sediment transport. The sediment transport flux and the sedimentation rate equation become

$$S = -kh - D\frac{\partial h}{\partial x}, \quad \frac{\partial h}{\partial t} = k\frac{\partial h}{\partial x} + D\frac{\partial^2 h}{\partial x^2}. \tag{3}$$

Kaufman et al. (1991) and Swenson et al. (2005) recognize that a depth dependence in the advection/diffusion coefficients k and D for wave and current sediment transport can move the rollover clinoform offshore and generate a subaqueous delta foreset. Furthermore, Swenson et al. (2005) were able to explicitly link the advection-diffusion equation to the wave-driven bottom shear stresses and suspended sediment flux, thus giving a physical base to Equation 3. The same formulation was utilized by Driscoll & Karner (1999) to study the 3-D development of clinoforms. They point out that a simple bidimensional schematization of the shelf fails to capture the geometric characteristics of the clinoform, and that both cross-shelf and along-shelf sediment transport need to be included in the modeling framework. For example, along-shelf diffusion diminishes the dip of the clinoform or might generate an onlap surface. This notwithstanding, it is important to recognize the general applicability of the advection-diffusion formulation to the redistribution of fluvial sediments in the inner-shelf.

Water Column Sediment Concentration Models

A class of more physically based models includes in the formulation the vertical segregation of sediment and flow in the water column. These models usually compute the concentration of suspended sediments in the water column in time so that deposition can be linked to near-bottom sediment concentration, whereas erosion is calculated by means of bottom shear stresses produced by wind waves and currents. A typical example is presented in Pirmez et al. (1998). Pirmez et al. (1998) explain the formation of the concave-up clinoform profile as a result of a distribution of deposition rates that first increase with increasing distance from the river mouth and then decrease in deeper waters. Deposition is in fact hindered in shallow water where turbulent shear stresses are too high for the particles to settle and sediment is bypassed to the topset region of the clinoform. With increasing water depth, bed shear stresses decrease and sediment is deposited in large quantities in the foreset region. In deeper water, the shear stresses are further reduced, but so are the sediments in suspension because most of them have been already deposited in the clinoform foreset. This bell-shaped distribution of deposition rates forms the well-known concave-up clinoform profile. A comprehensive formulation for the 3-D structure of suspended sediment transport in the shelf is presented in Harris et al. (2005). Harris et al. (2005) use the Estuarine and Coastal Ocean Model–Sediment (ECOM-SED), which adds suspended sediment transport and a near-bed layer of fluidized mud to the Princeton Ocean Model (POM) (Blumberg & Mellor 1987). The model is fully 3-D and includes a turbulence submodel, bottom boundary layer physics, sediment resuspension and settling, noncohesive sediment transport, and surface waves. In Harris et al. (2005), the model is used to single out the relative importance of suspended sediment and near-bed mud transport in the dispersal of riverine sediments. It is seen that gravity-driven flows at the shelf bottom as well as settling properties of fine-grained sediment both in the plume and in the fluid mud layer critically influence depositional patterns. These results strengthen the hypothesis that the vertical segregation of flow and sediment transport in the shelf is of fundamental importance for shelf morphodynamics (Wright 1995).

Models Accounting for Gravity-Driven Fluxes

In recent years, it has been proposed that gravity-driven fluxes of suspended mud might be partly responsible for bottom morphology and the formation of the clinoform geometry. Despite the fact that the gentle slopes of inner continental shelves rarely support autosuspension of turbid flows by gravity, it is possible that hyperpycnal layers form by wave- and current-induced resuspension. Under these conditions, the mixture of water and sediments becomes highly stratified and a dense sediment layer at the shelf floor dictates both deposition rates and the formation of the clinoform geometry. Gravity-driven fluxes can be simply included in the formulation by imposing dependence between the sediment flux and the bottom slope (Kenyon & Turcotte 1985, Syvitski et al. 1988). A more physics-based approach needs to account for the downslope pressure gradient induced by the weight of the turbid layer and the bottom shear stresses produced by waves and currents (Scully et al. 2003).

In the model of Friedrichs & Wright (2004), the sediments are moved offshore by hyperpycnal layers supported by wave- and current-induced resuspension. In this formulation the attenuation of wave agitation with depth needs to be compensated by an increase in slope, producing a concave-up profile, similar to what is observed near rivers around the world. Under these conditions, a dynamic equilibrium profile is established by which all the fine sediment coming from the river is bypassed to the outer-shelf without net deposition or erosion. This elegant model represents one end-member of shelf morphodynamics, in which the availability of fine sediments constantly maintains turbid near-bed layers.

TRANSPORT-LIMITED VERSUS SUPPLY-LIMITED CONDITIONS

The above hierarchical model organization for cross-shore profile evolution sheds light on the difference between transport-limited and supply-limited models. When the amount of available sediment is unlimited, the volume transported depends solely on the ability of fluvial discharge, waves, and currents to move the material. This condition can be defined as transport limited. A situation in which the transport of sediments depends not only on the transport capacity of the processes at play but also on the sediment availability is called supply limited.

An example of the supply-limited condition is presented in Pirmez et al. (1998). Their model shows that the characteristic concave-up shelf profile near river mouths is produced by intense deposition of incoming fluvial sediments at the foreset location and reduced deposition in deeper water. The decrease in deposition is simply caused by the lack of sediment in the water column because most of it was already deposited in the foreset region.

In deep water, the sediment transport is clearly supply limited and depends on sediment resuspension because the currents could carry more sediment if it were present in the water column. Supply-limited conditions appear to be relatively ubiquitous in the shelf, either because the shear stresses produced by waves cannot resuspend enough sediments or because the removal of fine sediments in energetic shelves leads to bed armoring (Harris & Wiberg 2001, 2002).

If changes in bottom elevation are directly linked to the divergence of the sediment flux then only transport-limited conditions can be reproduced. The model does not check whether the amount of sediment that can be carried by waves, currents and other processes is locally available, thus presupposing that the sediment flux always reaches its full capacity. These models can be defined as simple sediment flux models because changes in bottom elevation depend only on the divergence of sediment flux (**Figure 2**).

To capture supply-limited conditions in the shelf, two new components need to be included in the modeling framework (**Figure 2**):

1. A transport unit where the sediment resuspended from the bottom can be stored during the simulation. The unit can represent the water column for suspended sediment transport, or an active bottom layer that can be mobilized when the wave and current shear stresses are high.
2. Exchanges between the shelf and the transport unit (water column or active layer) are defined by precise relationships, for example, sediment entrainment and deposition.

The horizontal sediment fluxes then involve only the sediment available in the transport unit, and supply-limited conditions can develop when the sediment

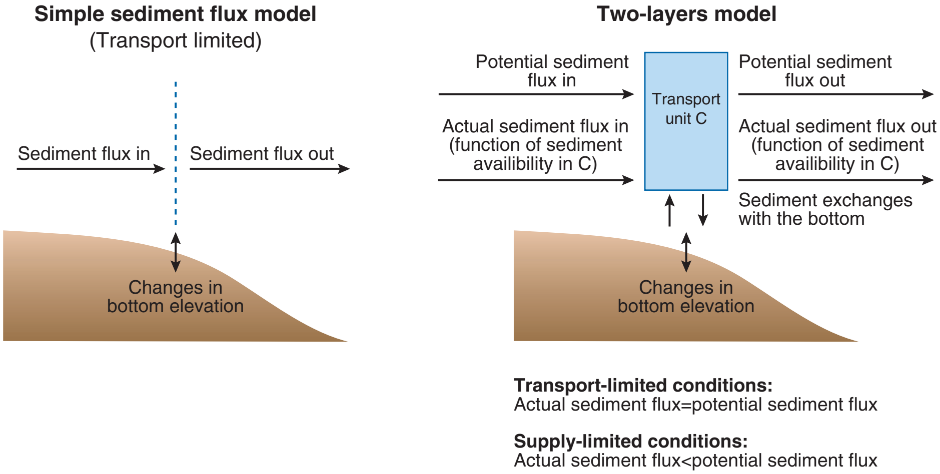

Figure 2

Methodological difference between simple sediment flux models and two-layer models. In two-layer models, the sediment is temporally stored in a unit (water column, active layer) before transport. Only two-layer models can capture the dynamics of supply-limited conditions.

entrained from the bottom is limited. The transport unit records not only the actual sediment entrainment but also the history of advective transport to the location under study. As a consequence, the sediment concentration at a particular point is not only a function of local morphological and hydrodynamic parameters but also of the pattern and fate of sediments during shelf evolution. For example, the potential flux can be specified as a function of bottom shear stresses and current velocity, whereas the actual flux will depend on the availability of sediments at the bottom, which can be limited in shelf areas with bedrock outcrops.

Models that include a transport unit can be defined as two-layer models, because two separate variables (bottom elevation and sediment concentration in the transport unit) contain all the sediments present in the shelf. Two-layer models are also able to simulate transport-limited conditions, whereas simple sediment flux models cannot recreate supply limited morphologies.

The introduction of a transport unit in the framework increases the complexity of the model, but it captures critical conditions in which the morphology stems from supply-limited dynamics.

VARIABILITY IN SEDIMENT SUPPLY AND DELTA DEVELOPMENT

Over time, 2-D models have been advanced to include multiple grain sizes (e.g., Rivenaes 1992) and time-variable sediment supply (Overeem et al. 2003). Presently, more advanced 2-D deltaic models explore the role of fluctuations in sediment delivery and investigate how the frequency and magnitude of events influence delta deposition by feeding the model with stochastic time series of discharge and sediment load (Hoogendoorn & Weltje 2006, Hoogendoorn 2006) or link the sedimentation model to climate-driven river sediment input modules (Overeem et al. 2005b). The present models do acknowledge the small-scale heterogeneities characteristic of deltaic deposits. Magnitude-frequency distribution of events exerts a fundamental control on these heterogeneities in delta sedimentation patterns. Large river floods may be rare compared with normal flow conditions, but their impact on deltaic development is presumed to be large as a result of high influx of material and high erosion potential. Large floods transport more sediment to the coastline and further offshore. Normal flow conditions transport less sediment and spread it out over a smaller area, but may occur more frequently, continuously supplying the depocenter with sediment.

As an example, discharge-magnitude-frequency distributions are reconstructed based on observational data using the discharge model of Hoogendoorn & Weltje (2006). The model simulates discharge time series, Q_{ti}, using two key parameters: (*a*) average discharge, $\bar{Q}$, representing the basin characteristics and the acting climate conditions, and (*b*) σ, the lognormal variability of discharge sequences, representing short-term variability. A random uniform deviate, ε, is used to determine the sequencing of the discharge events:

$$\ln Q_{t_i} = \ln \bar{Q} + \left(-\frac{\sigma^2}{2}\right) + \sigma\varepsilon. \tag{4}$$

Analysis of yearly discharge variation shows that, on an interannual temporal scale, a small σ is related to cold climates, whereas high values for σ are associated with warmer climate conditions (Hoogendoorn & Weltje 2006).

Subsequently, the generated discharge time series are input to a 2-D cross-shore delta model, DELTASIM, to simulate a simple progradational system and evaluate bed variability along the long profile. In these specific experiments, sea level is kept constant and the rate of sediment supply was calculated using Equation 3, where for the two experiments, the average discharge was 2000 $\mathrm{m}^3\ \mathrm{s}^{-1}$ and σ was set at 0.2 and at 0.7, respectively. The deposits of the first simulation (**Figure 3*a***) show a textbook example of delta progradation where the sediments are organized in a coarse delta plain, fine-sandy delta foresets and fine-grained, thin-bedded prodelta all with low heterogeneity. The second simulation (**Figure 3*b***) shows that the introduced variability results in larger heterogenity within the deposits, yet there is still an obvious fining trend of the sediments in an offshore direction. Bed thickness and grain size were recorded in a pseudowell at the shoreline of the long profile and corroborate the variability of thickness in the layers deposited.

2-D MODELS OF ALONG-SHELF MORPHOLOGY

As indicated by de Vriend et al. (1993), along-shore models presuppose a constant cross-shelf profile and focus on the formation of large-scale features along the coast. These models have been limited so far to the evolution of the coastline, without attempting a description of the entire shelf morphology. This notwithstanding, it is

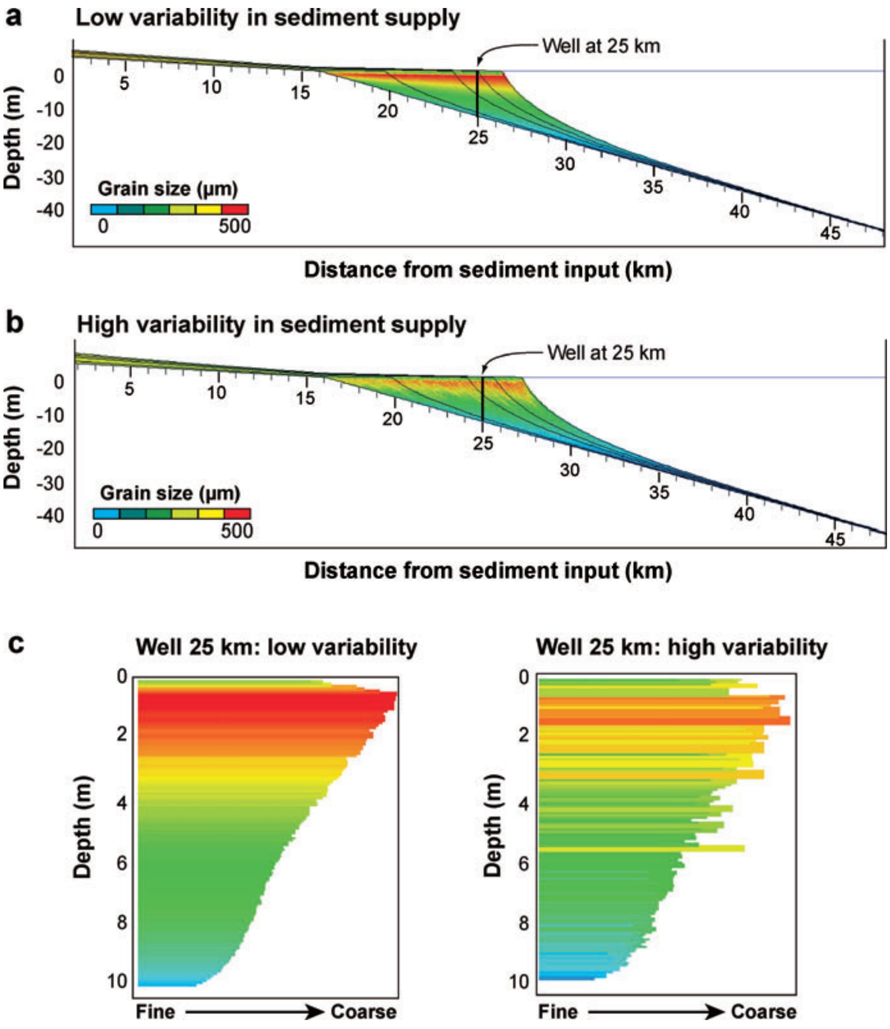

Figure 3

DELTASIM profiles show cross-shore deltaic development using synthetic time series of river sediment supply representing different variability in river sediment supply. (*a*) Low variability and (*b*) high variability in the discharge time series. The highest resulting variability in the deposits is found in the delta front consisting of alternations between clay, silt, and sand layers. (*c*) Pseudowells located at the shoreline. In (*a*) the deposits show a classical gradual coarsening-up with a thin layer of delta plain deposits. In (*b*) the deposits show more variability as a result of the variability in sediment supply (modified after Hoogendoorn 2006).

natural to consider potential applications to the entire inner shelf by a simple coupling of the coastline model to sea-level oscillations.

An example of an along-shore model is presented in Ashton et al. (2001). The model maintains a constant cross-shore profile and focuses on the longshore sediment transport driven by wind waves. Because the longshore flux depends on the angle between the coastline and the incoming waves, a strong feedback establishes between sediment flux and the coastline geometry. Model results show that when the angle between the waves and the shoreline is sufficiently large, the longshore sediment flux triggers the formation of large-scale features similar to capes and cuspate forelands. The model is based on a mesh of squared cells that can be either ocean or coastline, depending on the amount of sediment contained in each of them. This simplified framework allows the investigation of the formation of shoreline features at spatial scales up to hundreds of kilometers and temporal scales up to millennia (**Supplementary Figure 1** and **Supplemental Movie 1**, follow the Supplemental Material link from the Annual Reviews home page at **http://www.annualreviews.org**).

BARRIER ISLANDS FORMATION AND EVOLUTION

In passive siliciclastic margins, barrier islands are relatively common and represent a key component of the shelf landscape. Barrier islands form by the accumulation of sand owing to waves and currents combined with the effects of storm activity and sea-level oscillations.

Barrier islands are important for shelf morphology not only because they represent the highest element in the nearshore landscape, but also because during their transgression they considerably rework the morphology of the substrate, which ultimately determines the shelf morphology. The evolution of barrier islands and, in particular, their transgression has been investigated with different numerical models. In the pioneering work of Cowell et al. (1992, 1995), the barrier island is built by considering a constant shoreface geometry that translates along the shelf as a function of sea-level oscillations. Dillenburg et al. (2000) apply the model to the shelf of Rio Grande do Sul in Brazil during the Holocene, finding that the evolution of the barrier strongly depends on the substrate characteristics and vice versa. Prograded barriers form along coastal reentrances, whereas receded barriers form along coastal projections. A more recent model, GEOMBEST, introduced by Stolper et al. (2005) is able to handle substrates defined by distinctive stratigraphic units and the presence of a bedrock ocean floor. More importantly, GEOMBEST can be effective in areas in which the cross-shore morphology is dominated by the underlying topography and therefore can never achieve an equilibrium configuration.

More process-based models have been introduced in recent years to relate the morphological evolution of barrier islands to the processes responsible for sediment reworking. Storms et al. (2002) introduce a process-response model based on combining the continuity equation with an Exner equation approach to describe the spatial derivative of the sediment flux.

The model separately describes shoreface erosion by ocean storms and deposition processes that redistribute the sediments as a function of grain size along specific characteristic lengths. Because coarse or fine particles are deposited at different depths on the shelf, the model tracks the sorting of material and the corresponding stratigraphic architecture (**Supplemental Figure 2** and **Supplemental Movie 2**). Interestingly, sediment redistribution forms emergent islands that disconnect the bayside from the ocean. The newly developed barrier islands then follow sea-level oscillations and produce consistent results in terms of stratigraphic record.

DISPERSAL OF SEDIMENTS FROM RIVER PLUMES

As outlined by Wright (1995), shelf morphology is modified by the deposition of sediments from river plumes, yet the coupling of fluvial and-shelf mechanisms is often disregarded in models of shelf morphodynamics. The sediment input from rivers is usually regarded as a boundary condition, with specified values for sediment concentration and a flow discharge.

Exceptions are the models PLUME1.1, developed by Syvitski et al. (1998) for hypopycnal sediment dispersal, and INFLO1, developed by Skene et al. (1997) (see also Mulder et al. 1998, Kubo 2004, Kubo et al. 2005) to study hyperpycnal-turbity currents. Hypopycnal plumes flow buoyantly on the water surface because their sediment concentration is less than the salinity of the receiving basin. Physical models of hypopycnal plumes dating from the 1950s (Albertson 1950, Bates 1953) underlie the present PLUME model (Syvitski & Hutton 2001). In addition, the delta plume is affected by the angle of the river draining into the inner shelf, the coastal currents and wind direction, and the Coriolis force (**Supplemental Figure 3**).

Instead, hyperpycnal flows form when river discharge enters the ocean with a density of the water-sediment mixture greater than the density of salt water. In general, this means that the river needs to carry suspended concentrations in excess of 36 kg m^{-3} owing to buoyancy considerations, which happens mostly in extreme floods or in small flashy mountainous river basins. The most recent numerical model, Sakura (Kubo 2004), uses the layer-averaged three equations approach formulated by Parker et al. (1986). The model is capable of solving a hyperpycnal flow into a marine basin, entraining sediment from the bottom, and simulating the evolution of a hyperpycnal plume into a turbidity current (Kubo 2004, Kubo et al. 2005). It is remarkable that this model was first validated against flume tank experiments, and only when it showed good agreements was it incorporated into the modeling framework of SedFlux for long-term experiments (Syvitski & Hutton 2001).

3-D MODELS OF FLUVIAL-DOMINATED DELTAS

Many models have been designed to exclusively reproduce fluvial-dominated deltas, which are controlled solely by channel dynamics, mouth bar deposition, and delta plume sedimentation. There are a number of deltas around the world that probably justify this assumption, for example, coarse-grained fan deltas in fjords, the Volga delta in the shallow Northern Caspian Sea (Overeem et al. 2003), or the Atchafalaya delta prograding into Wax Lake along the U.S. Louisiana coast (Rouse et al. 1978).

Diffusive 3-D models that generically simulate a fluvial-dominated delta include DIBAFILL (DIffusion BAsin inFILL) (Quiquerez et al. 2000) and DIONYSOS [Diffusive Oriented Normal and Inverse-Simulation of Sedimentation (Granjeon & Joseph 1999, Rabineau 2001)]. Both models can deal with multiple grain sizes. The simplified model is justified because it is mainly used for long-term evolution and assumes that all transport is gravity driven. This makes these models appropriate for studies at the geological timescale, as it is done by comparing modeling results of 100 kyrs of shelf evolution in the Gulf of Lions, France, with seismic reconstructions and core data (Rabineau 2001).

Ritchie et al. (1999) presented a 3-D bulk sediment transport model specifically designed for fan deltas. The model is rule-based and uses simple slope- and discharge-dependent sediment transport to simulate lobe switches over the delta plain. It works with relatively large grid blocks (40 m by 40 m) and very coarse time resolution (20 year time steps).

Gawthorpe et al. (2003) model fan deltas under the influence of varying subsidence rates and sea-level change. The model results show that chronostratigraphic stratal surfaces are laterally not very extensive because different system tracts simultaneously develop within a basin over distances of a few kilometers.

AquaTellUs aims at shorter timescales than the previously discussed models (Overeem et al. 2000). The model mimics the evolution of a fluvio-deltaic system on exposed shelves under a fluctuating sea-level regime. It nests a 2-D profile model for which the erosion and sedimentation fluxes are calculated into a 3-D grid by embedding a dynamic flowpath. The model incorporates transport of multiple grain-size classes as well as rules for channel switching and delta floodplain sedimentation. Floodplain sedimentation is still a neglected process in deltaic models and it will have to be enhanced in the future to realistically simulate near-coastal delta morphology.

Another widely used model for fluvial delta development is presented in Sun et al. (2002). In this model, the delta is built by aggrading and avulsing river channels. The model combines a diffusional component for basin infilling to a cellular model for channel evolution. Of interest in this formulation is the channel avulsion mechanism that leads to delta formation and related 3-D stratigraphy. A channel avulses if the difference between the bed elevation and the nearby topography is less than a predetermined fraction (usually between 0.5 and 1) of the bankfull depth, as indicated by the field observations of Mohrig et al. (2000).

A more comprehensive approach is presented in SedFlux, which originated as a 2-D delta model (Syvitski & Daughney 1992) and has been recently developed in a 3-D formulation (Syvitski et al. 1998). The 3-D model incorporates a number of coupled physics-based routines to simulate stochastic channel switching, plume deposition, and longshore transport for multiple grain-sized classes as well as compaction or subsidence (Syvitski & Hutton 2001). SedFlux is capable of ingestion of daily climate data series [either real-world data or generated by the climate-driven hydrological model HydroTrend (Syvitski et al. 1998, Overeem et al. 2005b)].

As an example, Overeem & Goodbred (2005) link HydroTrend and SedFlux-3D to get more insight into the effect of monsoons and enhanced sediment supply on the long-term response of the Ganges-Brahmaputra delta (Goodbred & Kuehl 2000).

Generic SedFlux-3D simulations of the Ganges and Brahmaputra rivers show initially two distinct depocenters and slow progradation into the paleo-Bengal basin at the Early Holocene. A stable coastline was maintained even under extremely rapid sea-level rise, whereas more rapid progradation was observed in the Late Holocene despite lower sediment fluxes. However, there is a significant uncertainty in paleobathymetry and channel switching rates of both the Brahmaputra and Ganges rivers, resulting in markedly different stratigraphic realizations. The numerical modeling of the linked hydrological and sediment transport processes allows unraveling of the dominance of different processes and helps to put focused field studies into a larger perspective.

3-D MODELS OF TIDAL-DOMINATED DELTAS

To date, there are limited examples of 3-D models for tidal-dominated deltas despite several deltas being in this category. Van Maaren (2004) presents a modeling study exploring the dynamics of the tide– and wave-influenced La Bat delta in Vietnam.

Figure 4 shows a realization of a Delft3D experiment that couples river and tidal processes for a more strictly tide-dominated delta. The experiment set up is aimed at simulating representative conditions for the prehuman Fly delta in Papua New Guinea, Indonesia. It has been estimated that the river discharge and sediment load were significantly less than at present (Syvitski et al. 2005a), which suggests a relatively larger influence of tidal transport. This specific experiment simulates two months of morphodynamic evolution. Delft3D dynamically influences the activity of the different delta distributaries, with two active channels and one abandoned channel owing to flow diversion by midchannel tidal islands (**Figure 4**), which qualitatively is similar to the present conditions in the outer delta.

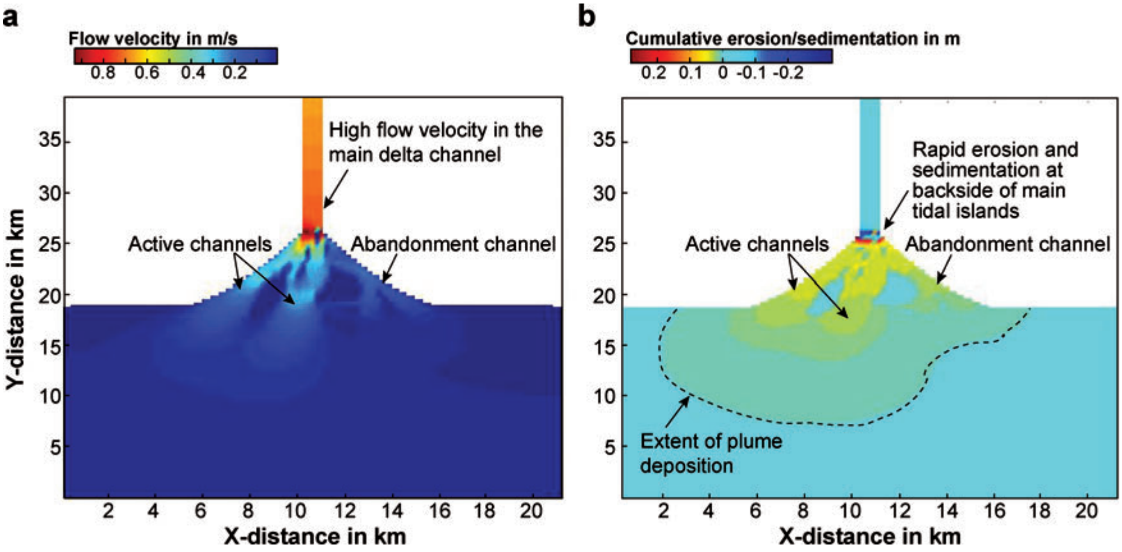

Figure 4

DELFT3D experiment representative for the Fly River, Papua New Guinea, Indonesia. (*a*) Flow velocity at a arbitrary time step. (*b*) Cumulative erosion and sedimentation after two months time.

INCISIONS IN THE CONTINENTAL SHELF

Contrary to terrestrial landscapes, few incisions dissect the inner- and mid-shelf and they are mostly limited to areas in which large rivers were able to scour wide paleovalleys that were subsequently reworked and partly filled by coastal processes. Examples are the Delaware shelf valley in front of the Delaware River and the Hudson shelf valley in front of the Hudson River on the U.S. East Coast shelf (Uchupi et al. 2001, Swift et al. 1980).

In contrast to the relative flatness of the inner- and mid-shelf, the nearshore displays several incisions that dominate the landscape. In marine environments, incisions are predominantly caused by currents, often of tidal origin. We can then identify tidal inlets and tidal channels as important features of coastal landscapes. Even though these incisions are not present in the mid-shelf, they have a fundamental role in redistributing sediments offshore and thus influence the entire shelf evolution.

Tidal Channels

The morphodynamic modeling of tidal incisions has received a notable impulse in recent years. The dynamics of the formation of tidal channels has been investigated in detail in Rinaldo et al. (1999a,b) and Fagherazzi et al. (2003). Such studies led to the formulation of long-term process-based models for tidal channel formation and evolution (Fagherazzi & Sun 2004, D'Alpaos et al. 2005; see **Supplemental Movie 4**). These models rely on a simplified approach for the shallow-water equations to determine the direction of the flow on tidal flats and the formation of tidal incisions under different scenarios. The key processes underlying the models are (*a*) the competition among different channels to capture the tidal prism, (*b*) the role of water discharge in scouring the channels through bottom shear stresses, and (*c*) the feedbacks between channel extension and discharge concentration at the channel head. This framework is very effective in reproducing the network of tidal channels, but is less precise in determining the distinct influence of ebb and flood on tidal morphology and the role of deposition in large-scale tidal landforms. Its application is therefore limited to shallow areas (shallow tidal flats, salt marshes) where the channel network is well defined and the sedimentation rate is relatively uniform.

More recently, simulations of large-scale tidal incisions have been performed by means of the high-resolution model Delft3D that couples tidal hydrodynamics to sediment transport (Hibma et al. 2004b, Marciano et al. 2005) (**Supplemental Figure 4**). The tidal channels are correctly reproduced in the simulations, and new insight is gained from the dynamics of the system. The model helps in understanding the separate role of ebb and flood in scouring new channels and the routes of sediment fluxes in the channel system. For example, continuous ebb-dominated channels form with flood-dominated side channels; flood and ebb channels seem to evade one another or they split into two branches (Hibma et al. 2004b).

To date, these models are applied to timescales of months to decades and are effective in describing the morphology of intertidal areas. However, it is often difficult to validate the model results against observations, especially for sediment transport

(Elias et al. 2006). To understand the role of tidal incisions on the general morphology of the shelf, the models need to be first placed in geographic context in relationship to other landscape units of the shelf system, then they need to be coupled to sea-level oscillations.

Fluvial Incisions

Similar to tidal incisions, fluvial incisions have important consequences on shelf morphology at the geological timescale. Sea-level oscillations have exposed the shelf to subaerial processes in the recent past, thus transforming it into a coastal plain for long periods of time. As a consequence, the shelf was dissected by streams, some of them being just the continuation of upland rivers and others locally formed by the routing of rainfall falling on the shelf surface. These incisions were subsequently erased or buried during sea-level rise and are identifiable in the shelf only through seismic profiles and cores. Although they are not present on the shelf surface, past fluvial incisions were still important for the morphological evolution of the shelf. In fact, sediment redistribution was governed by the location and morphology of the incoming rivers. In some shelf locations, large rivers were able to scour deep valleys that were not completely erased by wave action during sea-level rise. These valleys were then transformed in shallow submarine canyons and constitute an important feature of modern shelf morphology.

Fagherazzi et al. (2004) present a coupled continental shelf-coastal plain model for simulating fluvial incisions on the continental shelf during sea-level cycles. The model utilizes the DELIM morphological module (Howard 1994) for the development of fluvial drainage networks coupled to sea-level oscillations and nearshore processes. The model is able to identify the location of incised channels during sea level low stands and the related degree of incision (**Supplemental Figure 5** and **Supplemental Movie 3**).

Recently, a second model was proposed to investigate the quantitative behavior of river shelf sedimentary systems under glacioeustatic conditions (Meijer 2002). This cellular model is based on diffusive transport and directional stream transport applied to a square mesh and favors the formation of a diffuse channel system with several deltaic distributaries on the shelf during sea-level fall. The model reproduces river avulsion, delta-lobe switching, incision, and knickpoint migration during glacioeustatic cycles.

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

Tidal Inlets and Related Deposits

As indicated by Davis & Fitzgerald (2002), significant parts of passive siliciclastic margins are characterized by the presence of barrier islands separated by tidal inlets.

In this setting, the sediment input from rivers is not directly discharged to the shelf but is temporally stored in bays and estuaries, which communicate to the ocean through inlets. Tidal currents then convey the sediments in and out of the bay, regulating sediment distribution along the coast. Flood and ebb currents form two distinct depositional features, named flood- and ebb-delta, where large volumes of sediments are stored.

Several models have been proposed in the literature to explain the equilibrium geometry of tidal inlets (e.g., Bruun 1978, van de Kreeke 1990, Salles et al. 2005), but only recently the attention has shifted to their morphodynamic evolution and the link with the development of flood- and ebb-deltas. Wang et al. (1995) and Elias et al. (2006) explore the morphodynamic response of an entire inlet system to a change in tidal basin area owing to land reclamation (similar to the closure of the Lauwerszee and Zuiderzee in the Netherlands). Recently, van der Vegt et al. (2006) focus on the morphology of ebb deposits by using an idealized model based on a continuation technique that explores the dependence of solutions on parameter values (see also van Leeuwen et al. 2003). The tidal hydrodynamics are characterized by an ebb jet that forms two residual eddies at the inlet entrance. The two eddies scour an ebb-dominated channel at the center of the inlet that branches offshore in two flood-dominated incisions, in good agreement with field data collected along the Dutch coast.

Ranasinghe et al. (1999) couple the 3-D HAMburg Shelf Ocean Model (HAMSOM) (Backhaus 1985, Stronach et al. 1993) to a monochromatic wave transformation model and a sediment transport module to simulate the seasonal closure of tidal inlets in microtidal wave-dominated coasts.

Whereas short-term models of tidal inlet morphodynamics are already capturing changes in shelf morphology, the evolution of tidal inlets at the geological timescale deserves more attention. Tidal inlets dissect the shelf surface and likely migrate during sea-level oscillations. As a consequence, several buried paleofeatures that can be detected in seismic profiles are of tidal origin and represent the evolution of the inlet during glacioeustatic cycles. Similarly, ebb-deltas move inland during sea-level transgression and might give rise to depositional clinoforms that are different from fluvial clinoforms.

FUTURE RESEARCH NEEDS

Despite the recent developments in morphodynamic modeling of inner-continental shelves and river deltas, several questions remain unanswered. Herein we present four key concepts that need to be addressed in future research.

Nearshore Processes: The Big Eraser

In shelf landscapes, energy tends to concentrate at the coastline, where currents and tides are most effective in reworking the sediments. A critical question in shelf morphodynamics is whether the morphology of the shelf is the product of processes (i.e., waves and currents) currently acting at that particular shelf location or is just the residual of more energetic environments present when the sea-level was lower. The second proposal envisions a coastline that sweeps the shelf back and forth during sea-level cycles, thus determining the final morphology. This framework advocates for the inclusion in the morphological model of longer timescales based on glacioeustatic cycles. The power of nearshore processes in shaping the shelf landscape is evident in the current topography. Despite a sea-level rise of more than 100 m in the past 10 kyrs, there is basically no evidence of the previous terrestrial landscape on passive margin coastlines. The relative importance of current morphological change versus processes that acted at the geological timescale is then determined by the intensity of sediment reworking versus frequency because the most energetic coastal processes act at a particular shelf location only for a short period during every glacioeustatic cycle, whereas deep-water shelf processes can act for longer periods. Shelf models thus need to include antecedent topography and glacioeustatic cycles in their framework

Sea-Level Rise and Shelf Morphology: Only One Side of the Coin?

An aspect that clearly influences shelf morphology and our ability to model it is the fact that we are familiar with only one side of the coin, the shelf landscape during sea-level rise, whereas very little is known about the system during a drop in sea level. For example, we do not know whether barrier islands prograde offshore when sea-level declines, or whether estuaries and coastal bays reduce their number/extension during shoreline regression because many of them formed as drowned fluvial valleys. Clearly, major changes are affecting the landscape in a prolonged scenario of sea-level decrease, and unfortunately only a few examples of such conditions are available in areas characterized by glacial rebound and tectonic activity. Morphological models of shelf dynamics can thus play a critical role in understanding the evolution of the shelf during a sea-level regression and, more generally, during glacioeustatic cycles.

Shelf Morphology and the Coupling of Terrestrial and Marine Systems

Shelf morphology is not only influenced by sediment transport in marine environments but also inherits some key aspects of terrestrial landscapes and fluvial sediment transport. At various stages of the glaucioeustatic cycle, the shelf is transformed into a coastal plain and terrestrial features can be maintained in the shelf morphology. For example, even though most of the fluvial incisions that formed when the shelf was subaerially exposed are erased or buried during sea-level rise, some major paleovalleys connected to large rivers are still present on the shelf, such as the Hudson and Delaware shelf valleys. Of even more importance for shelf morphology is the input of sediments from rivers. These sediments and their reworking critically influence the shelf topography by changing sediment thicknesses, slopes, and, ultimately, the width of the shelf. Given the intertwined characteristics of terrestrial and marine systems, a holistic approach is deemed necessary. Modern numerical models of shelf morphodynamics should then include the terrestrial component and build a common framework for the coupling of marine and terrestrial processes.

Bridging the Gap: Upscaling Strategies for Delta and Shelf Models

One of the key issues in coastal and deltaic modeling is the strategy to integrate high-resolution, physics-based models with long-term models that use simplified approaches. The goal is to be able to bridge the gap between the prediction of short-term hydrodynamics and sediment transport and morphological changes taking place over much longer timescales.

One upscaling technique that has been used in several long-term integrated models to simulate detailed sedimentary development over long periods is to focus on the high-magnitude, low-frequency events, for example, river floods and ocean storms (Storms et al. 2003, Swenson et al. 2005). Basically, the models use variable time steps to simulate either individual high-magnitude events or periods with fair-weather that are morphologically of less importance.

This methodology is further explained with an example for a shelf with a strong fluvial input. **Figure 5** shows the discharge dynamics within a single year of a highly volatile river system, the Lanyang River, Taiwan (Syvitski et al. 2005b), which drains a small basin in steep mountainous terrain and is subject to frequent typhoons. The river flood events that carry 90% of the suspended sediment are selected from the daily record, and only those days are simulated in detail. The model averages over the intermittent days and deposition takes place as one single fair-weather layer. A 1000-year-simulation experiment at present-day climatic conditions has a mean daily discharge of 72 m^3 s^{-1}, whereas the peak discharge is 8660 m^3 s^{-1}. The sediment load varies tremendously, as well as the mean suspended load (from 0.35 kg m^{-3} in normal conditions to 285 kg m^{-3} during peak discharge). Only 7.4% of the days carry 90% of the total suspended sediment load for this specific river system.

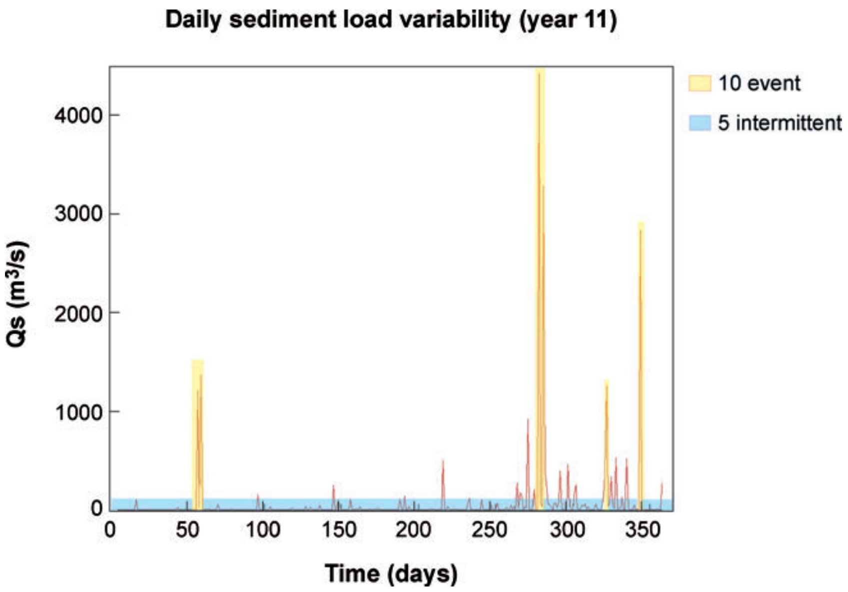

Figure 5

Illustration of the event-based upscaling approach for river fluxes into the shelf. Daily suspended sediment load predictions for an arbitrary year in a simulation of the Lanyang River show clustered peak discharge events owing to typhoons. The days that carry a threshold percentage of the total sediment load (e.g., 90%) are determined and only those days are simulated in detail.

High-resolution models are developing remarkably similar upscaling techniques that may help in extending the time frame of the simulations. One of the more promising methods is the so-called morphological factor approach (Lesser et al. 2004, Roelvink 2006). The morphological factor, n, simply increases the depth change rates by a constant factor so that after simulation of one tidal cycle the morphological changes over n cycles are modeled. These models are now being set up to run different input conditions over the same bathymetry. Then the weighted average of the bottom variations is merged to update the shelf morphology. Roelvink (2006) shows that this parallel online approach appears accurate and numerically stable, and it will provide us with the capability of running much longer-term simulations.

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Contents

Indexes

Errata

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