Marine and Petroleum Geology 28 (2011) 716–727

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

A model of submarine channel-levee evolution based on channel trajectories: Implications for stratigraphic architecture

Zoltán Sylvester*, Carlos Pirmez[1], Alessandro Cantelli

Shell Projects and Technology, Houston, TX 77001-0481, USA

A R T I C L E I N F O

Article history:
Received 28 November 2009
Received in revised form
2 May 2010
Accepted 25 May 2010
Available online 2 June 2010

Keywords:
Submarine channels
Lateral migration
Aggradation
Incision
Channel-levee system
Stratigraphic architecture
Chronostratigraphic diagram
Turbidity current

A B S T R A C T

Channel-levee systems are frequently interpreted as having a long history of cut-and-fill by channel-shaped features of different scales. Results from a simple geometric model based on a centerline migration algorithm combined with a vertical channel trajectory show that an incising-to-aggrading trajectory of a single channel can produce realistic morphologies similar to systems observed on the seafloor and subsurface, including features such as a basal erosional surface, coeval inner and outer levees, internal erosional boundaries, and terraces draped by inner levee deposits. Channel migration results in composite erosional surfaces that are distinct from topographic surfaces, and their formation does not require larger than usual erosional flows. Many submarine channels interpreted as underfit were probably carved by flows similar to the ones that eroded and deposited the entire channel system. We suggest that the features of most submarine channel-levee systems do not require large temporal variations in flow magnitude but can be explained by a simpler model whereby incision, migration and aggradation of a single channel form over time results in an apparently complex system.

1. Introduction

In recent years, as high-resolution seafloor images and high-quality three-dimensional seismic datasets have increasingly become subjects of careful study, substantial progress has been made in understanding the morphology, stratigraphy, and evolution of submarine channel-levee systems (e.g., Abreu et al., 2003; Babonneau et al., 2002; De Ruig and Hubbard, 2006; Deptuck et al., 2003, 2007; Fildani et al., 2006; Kolla et al., 2007; Normark et al., 1998; Pirmez et al., 2000; Pirmez and Imran, 2003; Straub and Mohrig, 2008). However, some of the complexities that result from long-term channel evolution and the interplay of channel incision, aggradation, lateral migration, and levee deposition, are still poorly understood. These large, long-lived submarine channels and valleys are often thought to have a complex history of cut-and-fill and a corresponding multi-scale hierarchy of erosional surfaces (Abreu et al., 2003; Hubbard et al., 2009; Mayall et al., 2006; Samuel et al., 2003). The scales of the erosional surfaces are sometimes linked to flow size, larger cuts being eroded by larger flows and later filled by lower discharge or 'underfit' currents (Deptuck et al., 2003; Kolla et al., 2007). An analogous problem is the interpretation of the modern-day Grand Canyon topography: is it the result of a series of extremely large floods, followed by a dramatic decrease in discharge, or the cumulative effect of long-term erosion by a river with discharges similar to the present-day Colorado River (e.g., Spencer and Pearthree, 2001).

Building on the increasing number of high-resolution seismic studies that provide better constraints on channel evolution, we set out to investigate the origin of erosional surfaces in slope channel systems and the relationships between geomorphic evolution and stratigraphic architecture. High-quality three-dimensional seismic datasets that have been interpreted in detail (e.g., De Ruig and Hubbard, 2006; Deptuck et al., 2003, 2007) suggest that: (1) within individual submarine channel systems, channel size variability is relatively small, (2) channels migrate in a systematic way and their placement is far from random (Labourdette, 2008; Labourdette and Bez, 2010). Starting from such observations, we have developed a three-dimensional geometric model for submarine channel-levee systems. Our model accounts for lateral channel migration, incision, aggradation, channel and overbank deposits, cutoffs, and includes a simple depth-dependent facies distribution. While it shares some characteristics with existing three-dimensional models of fluvial (Cojan et al., 2005; Pyrcz and Deutsch,

* Corresponding author.
E-mail address: zoltan.sylvester@shell.com (Z. Sylvester).
[1] Present address: Shell Nigeria E&P, Lagos, Nigeria.

0264-8172/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2010.05.012

2005; Pyrcz et al., 2009; Willis and Tang, 2010) and submarine channels (Pyrcz and Strebelle, 2006; Labourdette, 2008; Labourdette and Bez, 2010; McHargue et al., 2011), our model includes several important new features: (1) development of valley morphology through long-term channel erosion; (2) long-term levee deposition resulting in consistent channel-levee and inner-to-outer levee relationships; and (3) existence of a realistic geomorphic surface with a single, unfilled channel form at all times. This last feature allows us to represent the model results not only in physical stratigraphic space but in a precise three-dimensional chronostratigraphic framework as well. The purpose of this paper is to describe this model and discuss the implications for channel-levee morphology and stratigraphy.

Although the model output examples presented here are not specific to the outcrops visited during the SEPM Research Conference focusing on Stratigraphic Evolution of Deep-Water Architecture (Fildani et al., 2009), large-scale geometries generated by our model are comparable to some of the channel-levee systems of the Magallanes Basin exposed in southern Chile. The coarse-grained channel deposits of the Cerro Toro Formation are part of a major channel-levee system that follows the axis of an elongated foreland basin (Hubbard et al., 2008). The best subsurface analog for this formation is the axial channel belt of the Austrian Molasse Basin (De Ruig and Hubbard, 2006; Hubbard et al., 2009). The scale of these axial channel belts renders even the largest outcrops too limited to decipher the channel-belt-scale, three-dimensional architecture, but the channels of the Molasse Basin are well imaged and mapped in three-dimensional seismic data, and show consistent channel migration and aggradation. Outcrops of the Tres Pasos Formation provide examples of the outcrop expression of laterally migrating, much smaller sinuous channels (Shultz et al., 2005, their Fig. 19), with details that resemble some of the model outputs. Despite the huge differences in scale, grain size, and basinal setting, both of these channel systems can be modeled through the evolution of a simple channel-overbank surface, a concept described in the following sections.

2. Two-dimensional model

2.1. Description

As a starting point, we attempt to reproduce a typical strike-oriented cross section of a channel-levee system. Cross sections of submarine channels in 3D seismic data and outcrops often seem highly complicated, showing a number of erosional surfaces of different scales (e.g., Campion et al., 2000; Deptuck et al., 2003; Mayall et al., 2006). However, in the few cases where it is possible to map individual channel forms over relatively large distances such as on shallow, high-resolution seismic data (Deptuck et al., 2003, 2007), channel forms of individual systems tend to have a characteristic, relatively constant size and shape. Furthermore, migration of a single channel shape, with varying degrees of aggradation and lateral migration, seems to create the complex channel stacking patterns observed in these well-documented case studies. Clark and Pickering (1996, their Fig. 8) suggest that various channel complexes result as a function of lateral versus vertical stacking of a single channel through time. If we replace the channel bodies with empty channel forms cut into a flat 'overbank' surface, in a similar manner to De Ruig and Hubbard (2006, their Fig. 11), this concept can be formulated in the framework of topographic surfaces that change through time due to contemporaneous erosion and deposition.

A parabola is used for the parameterization of the erosional channel form (Fig. 1). The channel centerpoint is the channel midpoint at the top. At each time step t, the new location of the centerpoint is defined by a horizontal component dx and a vertical

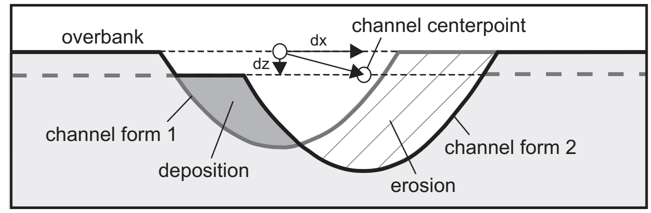

Fig. 1. Simple two-dimensional model of a migrating channel form (with constant dimensions) and flat overbank surface. Surface resulting after one time step (with negative dz, i.e., erosion) is shown with thick black line.

component dz applied to the coordinate at the previous time step. If dz is positive, the channel form aggrades and its shape and size remain the same; if dz is negative, the channel form is still described by the same parabola, but the distance between the channel base and the flat overbank surface becomes larger. The additional erosional depth is added to the channel form by extending the parabola upward, to the overbank surface (right side of channel in Fig. 1). This modeling step mimics channel bank erosion through repeated downcutting and bank failure on one side of a migrating channel, a process that is probably important in most submarine channels and valleys (e.g., Deptuck et al., 2003, their Fig. 10). While several conceptual models that have been previously drawn up illustrate the relative importance of aggradation and lateral migration for large-scale channel architecture (e.g., Clark and Pickering, 1996; Kolla et al., 2007), our model includes the possibility of channel incision as well.

The parameters x and z define the *channel trajectory.* The 'channel trajectory' concept is similar to the shoreline trajectory: just like shoreline trajectories are useful for describing shoreline migration and the resulting sequence stratigraphic patterns in a dip section (Helland-Hansen and Martinsen, 1996; Kim et al., 2006; Wolinsky, 2009), channel trajectories can be used to conceptualize and quantify channel evolution in a slope-parallel section. Long-term channel evolution is likely to result in a horizontal channel trajectory component (dx) that changes sign several times as the direction of migration changes at a given location. In contrast, some seismic studies (Deptuck et al., 2003, 2007; Hubbard et al., 2009) suggest that the vertical component of the channel trajectory is unlikely to change sign so frequently, and often it consists of a single incision-aggradation cycle, with no clear evidence for numerous large-scale reincisions. For sake of simplicity, the vertical component of the channel trajectory is modeled here as a single incision-aggradation cycle (Fig. 2). However, if deemed necessary, vertical trajectories of any complexity, e.g., with multiple cycles of incision and aggradation can be modeled. Fig. 2 shows the result from a horizontal channel trajectory that is sinusoidal through time, combined with one incision-to-aggradation cycle in the vertical dimension.

Although the model described until now is useful for visualizing the large-scale stratigraphic architecture that corresponds to different channel trajectories, it has two important limitations. First, it does not produce realistic levee architectures: the overbank layers are always horizontal and are only deposited if the channel is aggrading. Second, the parabolic channel form is always concave-up and intersects the overbank area at a sharp angle. This is reasonable if erosion predominates, and the parabola is probably a good approximation of entirely erosional channel forms, but channel deposits usually do not have the sharp-edged wedge shape seen in Fig. 1. In fluvial channels, deposition occurs largely on the inner sides of meander bends, and the resulting topographic surface tends to be smooth and convex-up (e.g., Allen, 1985). To account for this geometry, a depositional channel form, based on a Gaussian curve and inspired by the work of Imran et al. (1998), is

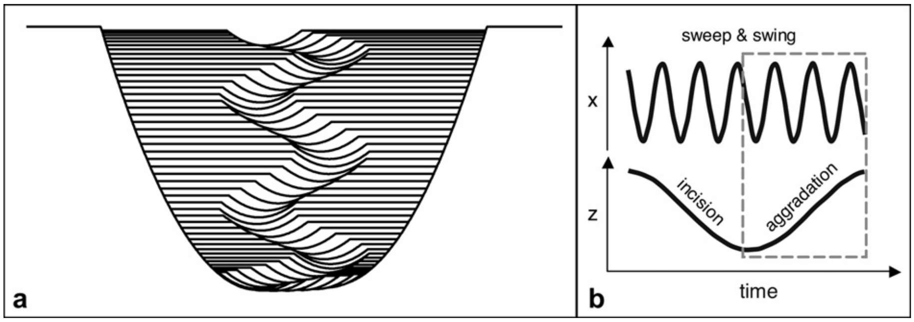

Fig. 2. Stratigraphic architecture (a) resulting from moving a constant channel form through a single incision-aggradation cycle in the vertical direction and several sweep and swing cycles in the horizontal direction, shown in (b). Dashed rectangle in (b) shows the time of aggradation (that is preserved in the stratigraphy). x and z are the coordinates in the horizontal and vertical directions, respectively.

used to create convex-up surfaces where deposition occurs (Fig. 3). While Imran et al. (1998) use Gaussians for both deposition and erosion, we prefer the parabola for the erosional shape, mostly because quadratic erosional surfaces are easily extended upwards. Deposition takes place where the depositional channel form lies above the preexisting topography.

To create more realistic levee geometries, during each time step, levee deposits are modeled as wedges that linearly thin away from the channel (Fig. 3). Simplified sediment transport equations suggest exponential decrease of turbidite bed thickness (e.g., McCave and Swift, 1976), and of fluvial levee thickness (Pizzuto, 1987) away from the channel. Therefore, from a theoretical point of view, exponential thinning of levee layers is preferable to a linear model. However, Skene et al. (2002) have shown that, for the majority of the studied submarine channel-levee systems, the exponential model is statistically indistinguishable from the linear one. Thus, for the purposes of the present model, a linear thinning of the individual levee layers is a reasonable approximation, although the model can be easily modified to include other levee thickness decay functions. Additional details of levee development, such as the enhanced flow stripping and increased deposition on outer banks, with the resulting levee asymmetry (Straub et al., 2008), are not present in the model.

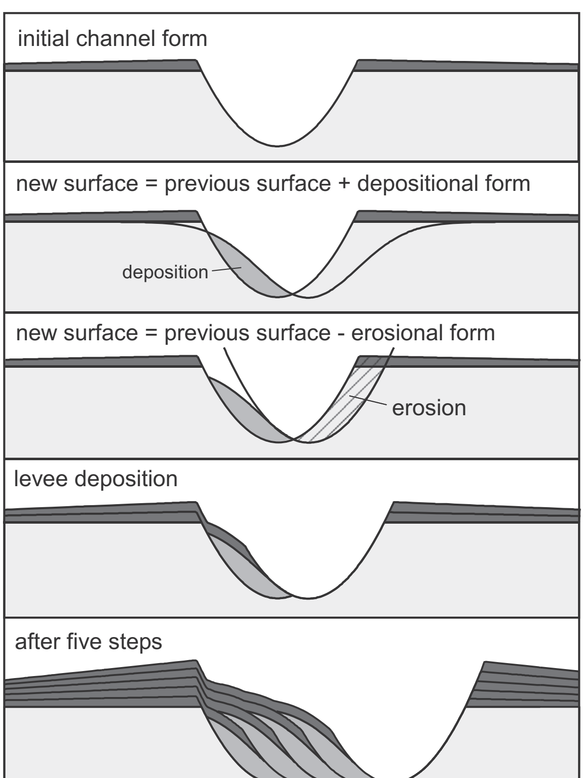

Fig. 3. Illustration of five time steps using the enhanced two-dimensional model. Only lateral migration (no incision/aggradation) is present in this case. The diagrams for the first and second time steps illustrate how the algorithm works.

Levee layers drape the preexisting topography, and, as a result, they modify the surface morphology through simple vertical aggradation. In contrast with the channel forms that have a constant surface morphology, it is the shape of the levee layer that stays the same, and the surface expression of the levee layer is variable, depending on preexisting topography.

During aggradation, overbank deposits close to the channel must be deposited at the same rate as the channel is aggrading if the channel relief is to remain the same over time. This also means that the levee thicknesses deposited at each time step have to match approximately the dz components of the channel trajectory.

2.2. Results

If there is no incision or aggradation (d$z = 0$), the two-dimensional model should result in a point-bar like overall architecture (Fig. 3). Overbank layers behave as drapes. As a result, the stepped erosional relief over the initial left channel margin is preserved during levee deposition. If the channel migrates laterally, deposition takes place along the inner bank and erosion occurs along the outer bank. The depositional channel form will determine the channel morphology on the inner bank, and the erosional channel surface will shape the cutbank. The resulting channel cross section becomes asymmetric. Levee deposits in the resulting models directly link to fine-grained layers (drapes) that are interbedded with the channel deposits (Fig. 3).

Despite the simplicity of this two-dimensional model, complex geometries and relationships between inner and outer levees result when the channel trajectory is more complicated. If we assume that the vertical component of the channel trajectory consists of an incisional phase followed by an aggradational phase, and the horizontal component includes several cycles of back-and-forth movement, as a result of channel migration (swing and sweep), the architecture will have a number of large, composite and time-transgressive erosional surfaces (Fig. 4; see also Discussion). Erosional remnants on the left side of the system develop during the incisional phase (Fig. 5). The remnants form terraces that are often preserved throughout the evolution of the system; levee deposits drape these terraces. The next step is to populate the layers with a sedimentary facies or a rock property (e.g., grain-size

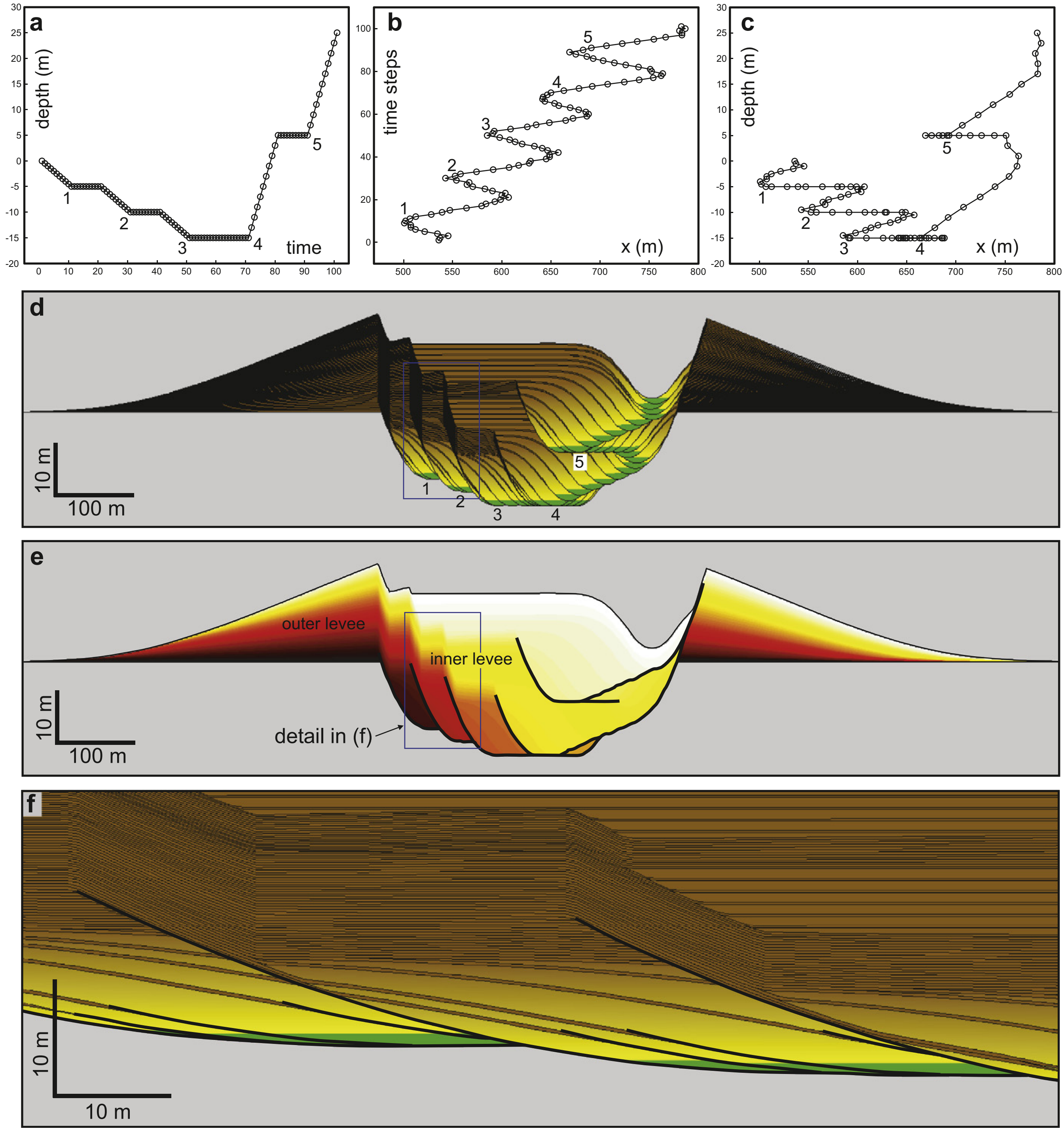

Fig. 4. Example of a cross section generated with the two-dimensional model. (a) Vertical component of the channel trajectory, consisting of an initial incisional phase and a later aggradational phase, with a number of intervening periods with no vertical displacement. (b) Horizontal component of the channel trajectory: a sinusoidal curve with a drift toward the right, and a shorter-term back-and-forth movement due to swing and sweep. (c) Combining the vertical and horizontal components gives the actual channel trajectory. (d) Architecture of the channel-levee system built with the trajectory shown in (c). The colors show a depth-dependent facies distribution (green = channel lag/base deposits; yellow = sand; brown = shale). (e) Architecture colored by time (dark red = old; white = young). Large composite erosional surfaces shown with thick black lines. Note that no erosion occurs in the upper left side of the system, despite the complicated architecture that links the outer and inner levees. (f) Detail of the architecture, without any vertical exaggeration. All erosional surfaces shown with thick black lines.

distribution, porosity, permeability). Because the model tracks elevation above the thalweg at all points in time, it is easy to relate sediment properties to channel topography. An elevation-dependent facies model, which assumes decreasing grain size as height above channel thalweg increases, is a simple method used here to illustrate the large-scale distribution of facies (Fig. 4d).

3. Three-dimensional model

The two-dimensional model is a useful tool to understand the influence of the channel trajectory on the geometries of channel and overbank deposits. However, some of the complexity that results from the strong three-dimensionality of sinuous submarine

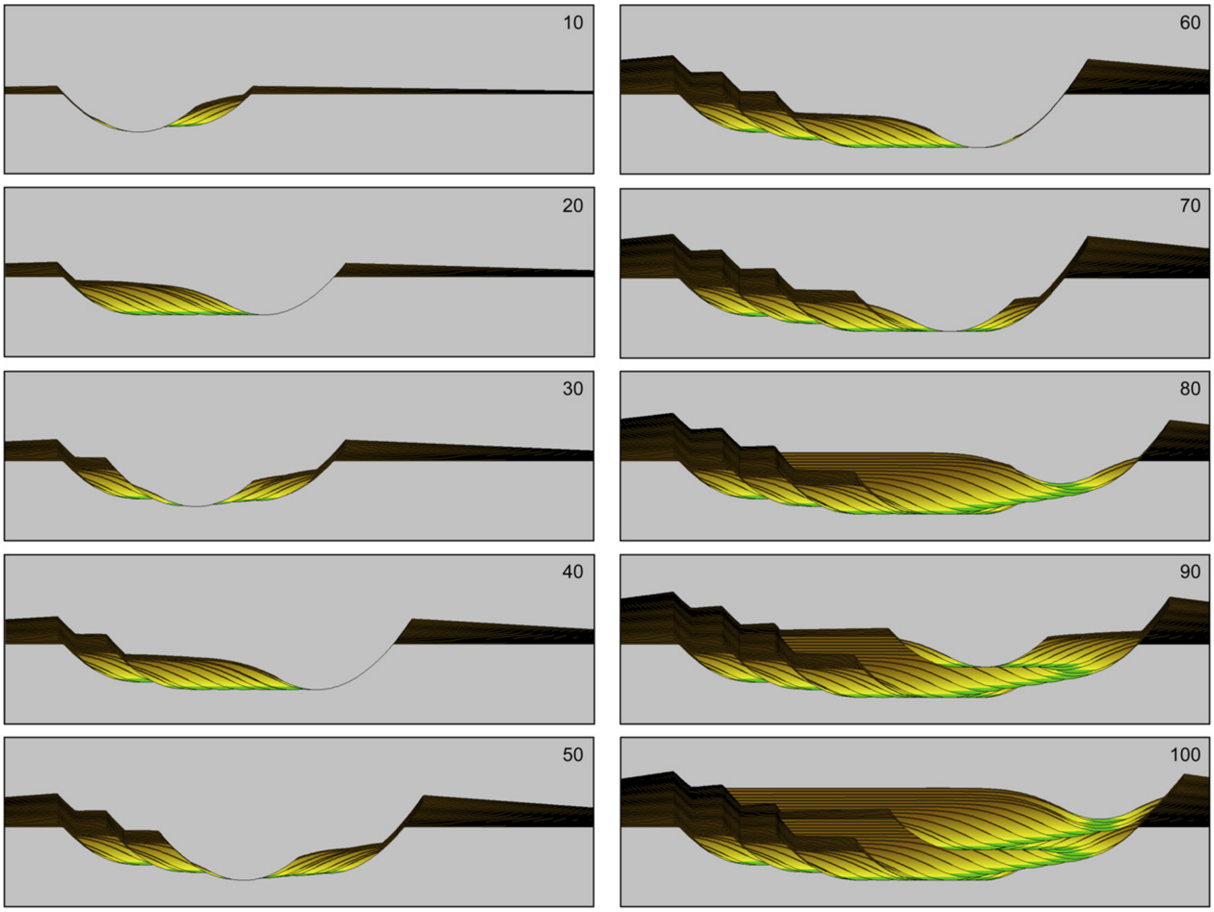

Fig. 5. Time evolution of the facies architecture of the channel-levee system shown in Fig. 4. Numbers in the upper right corners represent time steps. Facies color code is the same as in Fig. 4.

channels is not represented in the 2D model. For example, in real systems it is common to intercept the same channel several times with a cross section, but there can be only one channel form present at any time and at any level in the 2D model cross sections. Therefore, the obvious next step is to extend the model to three dimensions.

3.1. Description

The three-dimensional model combines the vertical component of the channel trajectory with a set of consistently migrating channel centerlines. For centerline generation, we adopted the kinematic channel evolution model of Yi (2006), where the depth-averaged flow field in a sinuous channel is calculated using steady flow in a straight channel as the base state. The channel migration rate is linked to the flow field at each point along the centerline. The model can be adopted for simulating both submarine and fluvial channels (Yi, 2006). Key geometric characteristics of submarine channels are comparable to those of fluvial channels (Pirmez and Imran, 2003), and subtle differences in the plan-view centerline migration patterns are unlikely to affect the overall three-dimensional morphology and stratigraphy. Instead, the important differences arise from the more pronounced levee development and higher rates of aggradation in submarine systems (see Discussion below). Therefore, any centerline migration model (e.g., Frascati and Lanzoni, 2009; Howard and Knutson, 1984; Ikeda et al., 1981; Sun et al., 2001; Zolezzi and Seminara, 2001) that produces regularly migrating sinuous patterns can be used to illustrate the three-dimensional complexities of the modeled channel-levee systems. The differences in plan-view migration patterns of fluvial and submarine channels, for example meander asymmetry, frequency of compound meanders and of neck-cutoffs, are still poorly understood and are not the subject of this study.

Centerline migration algorithms, including the one used here, always result in erosion of the outer banks and deposition on the inner banks. However, evidence from flume experiments and seismic data suggest that turbidity currents can also deposit sediment preferentially on the outer banks (Kane et al., 2008; Straub et al., 2008). It is likely that such 'plastering' occurs mostly when the flows are out of equilibrium with the channel. Outer-bank deposition, if coupled with erosion of the inner bank, results in reduction of sinuosity (Kane et al., 2008; Straub et al., 2008); if the inner bank erosion is limited or absent and therefore it does not balance the outer-bank deposition, asymmetric filling of the channel is the result. This process is not modeled by current centerline migration algorithms and it is missing from the channel trajectory model described here; our model focuses on the processes that form, maintain and migrate the channel, rather than the flow types likely to be characteristic of channel abandonment and filling.

For relatively short stretches of the channel system, the vertical component of the channel trajectory is assumed constant. This approach is consistent with observed channel longitudinal depth profiles that tend to be approximately parallel in along-channel cross sections for several tens of kilometers (e.g., Deptuck et al., 2007). Inclusion of realistic along-channel variations of slope (e.g., knickpoints) would certainly make the model more realistic and would change some of the details of the three-dimensional architecture. However, all presently available centerline models assume spatially constant slope along every centerline.

The surfaces corresponding to the erosional channel form, the depositional channel form, and the levee deposits are calculated for each time step, using the same parameterizations as in the 2D model. We used Matlab® to generate surfaces and to visualize the results.

3.2. Results

A model has been generated using one hundred channel centerlines and one incision-to-aggradation cycle, with a smooth, sinusoidal transition between incision and aggradation (Figs. 6, 7, 8a–c). The result is a channel-levee system with a composite erosional surface with scalloped margins (Fig. 9). This erosional surface develops during both the incisional and aggradational phases, and it does not require a change in the characteristic

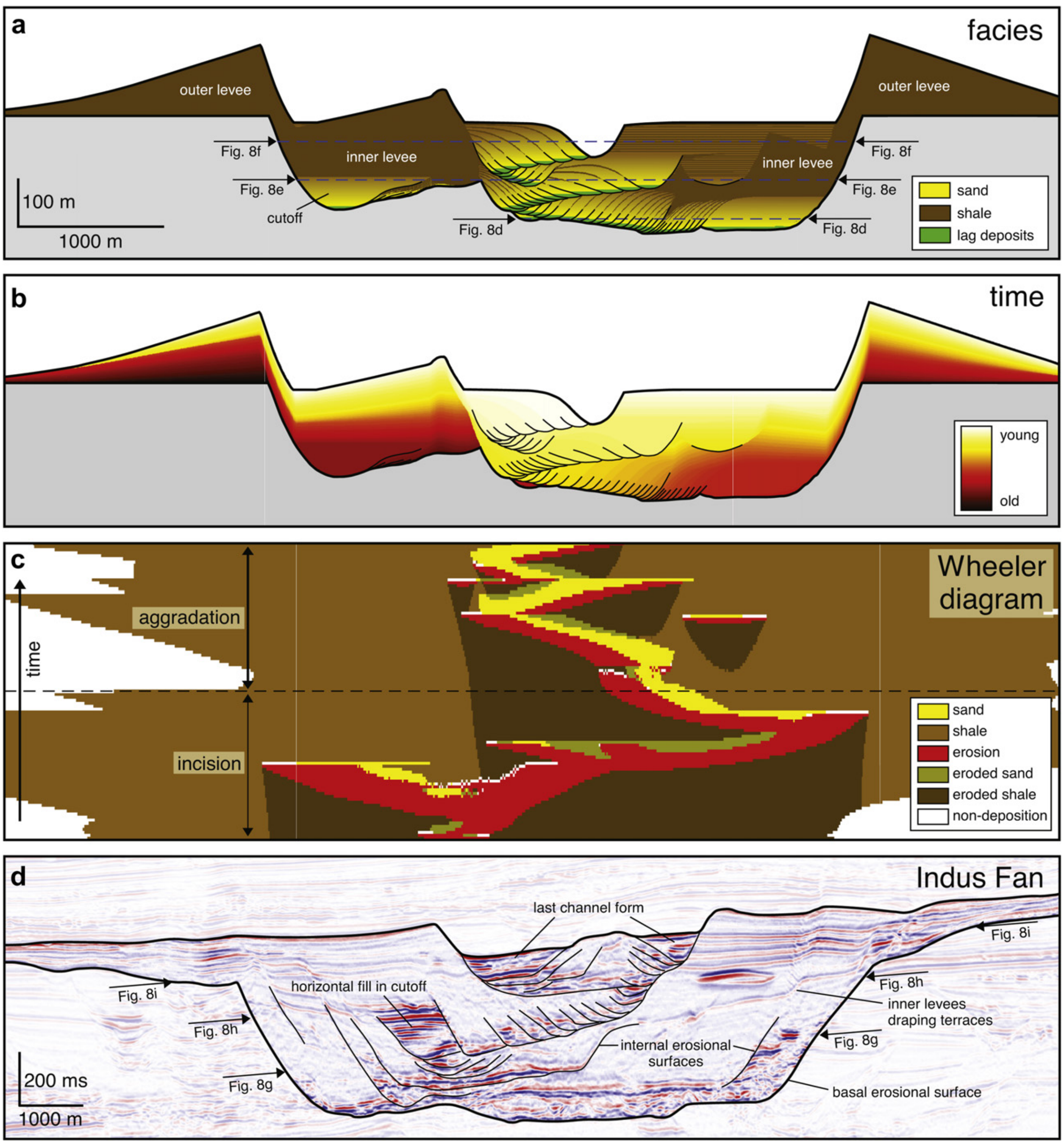

Fig. 6. (a) Cross section from a model generated with 100 centerlines and an incisional- to aggradational vertical channel trajectory. The colors reflect qualitative, depth-dependent facies model. (b) The same cross section colored by time. (c) Chronostratigraphic (Wheeler) diagram. (d) Representative seismic cross section from channel-levee system CLS3 of the Indus Fan (for context, see Deptuck et al., 2003), showing similarities with the model results. This system has gone through more aggradation than the one shown in (a) and (b); as a result, there is no major relief difference left between the outer and inner levees.

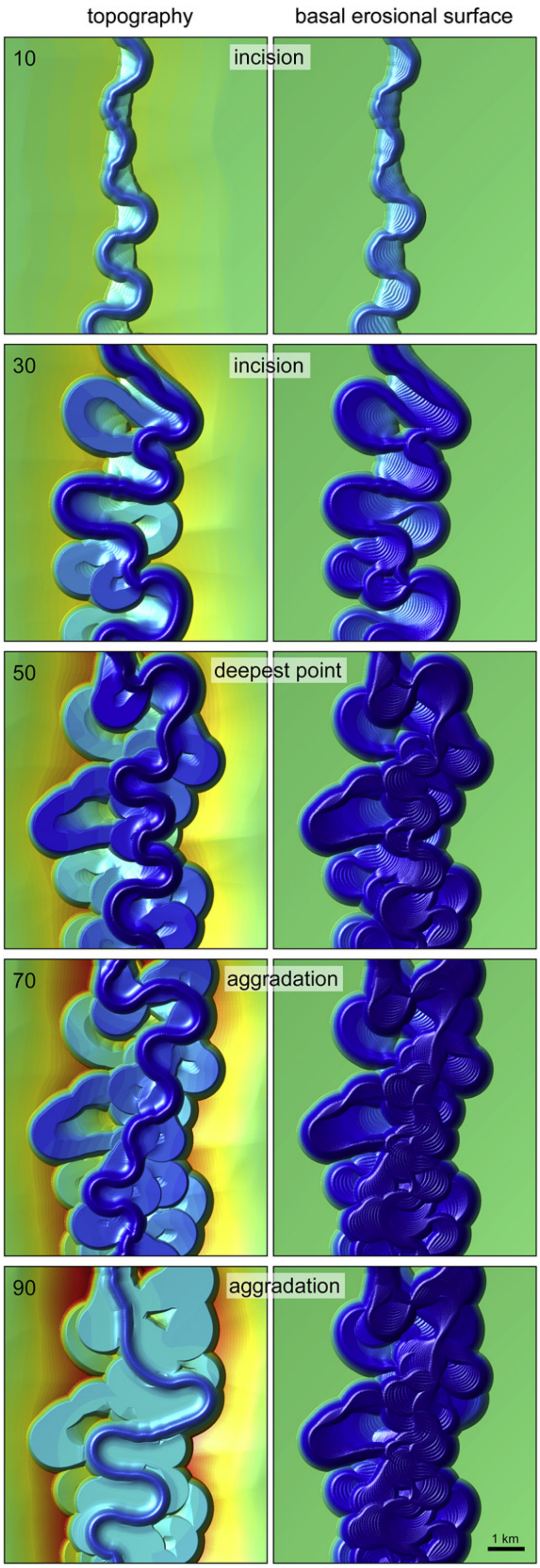

Fig. 7. Topography and the corresponding basal erosional surface of the model shown in Fig. 6, at different time steps. Time steps are shown in the upper left corner of the topographic maps. Red colors correspond to high elevation, blue colors to low elevation. At any given time, there are significant differences between the topographic and erosional surfaces.

channel dimension. We coupled the modeled surfaces with the elevation-dependent facies distribution (coarser-grained deposits deeper in the channel) to generate the model outputs in Figs. 6a and 8d–f. Horizontal sections through the model (Fig. 8d–f) show a gradual transition from a large number of overall coarser-grained channel threads at the bottom of the valley to better-defined threads toward the top, surrounded by terraces filled with finer-grained inner levee deposits. Inner and outer levees (*sensu* Deptuck et al., 2003) often continuously grade into each other. The top surface (Fig. 7, left side) shows a number of terraces that are draped by inner levees and can form during both the incisional and aggradational phases. Their development in the model is identical to the terraced canyon evolution described by Babonneau et al. (2004) on the Zaire Fan: abandoned channel segments that correspond to neck-cutoffs or pseudo-cutoffs (Deptuck et al., 2007) become locations of inner levee deposition that preserves the erosional steps along the outer bank for a relatively long time. The abundance of such terraces in some submarine channel-levee systems suggests that cutoffs can be common when the aggradation rate is not too high.

A strike section from the model (Fig. 6a) illustrates the high level of architectural complexity resulting from the three-dimensionality of sinuous channels. Channel migration creates abundant inclined layering. However, the apparent dip on the stratigraphic surfaces is variable, and in channel-parallel sections these deposits may look like horizontal channel fill. Channel migration and the associated erosion on the outer banks also result in a number of erosional surfaces, in addition to the basal boundary of the system. Like incised valleys on the shelf (Strong and Paola, 2008), erosional surfaces larger than the basic channel form are stratigraphic boundaries and do not correspond to a single point in time or a single topographic surface (Figs. 6c, 7, 8a–c). Although outer levees tend to preserve more sediment from the early incisional phase than the fill of the valley (cf. Deptuck et al., 2003), the model suggests that, assuming laterally extensive overbank deposition, there is no clear-cut age difference between inner and outer levees and parts of apparent large erosional surfaces in seismic data may represent continuous deposition that drapes preexisting terraces (Fig. 6b, c).

Cross sections from a large submarine channel-levee system (CLS) of the Indus Fan (CLS C3 of Deptuck et al., 2003, their Fig. 1) show significant similarities with the model (Figs. 6d, 8g–i). Horizon slices from a new 3D seismic volume through CLS C3 suggest a transition from numerous channel threads at the base of the valley to a smaller number of threads toward the top, in a similar manner to the model (Fig. 8g–i). Channel-ward dipping inclined reflections (Fig. 6d) suggest that the inner banks are built like point bars, i.e., as a result of deposition on the inner bank coeval with channel lateral migration. The architecture seen in CLS C3 implies that this channel-levee system developed through the migration of a single channel form, in a similar way to that described with the 3D model. The resulting stratigraphy seems to be dominated by deposits resulting from the lateral migration of a single channel thread, rather than a large number of cut-and-fill events.

If we assume that the vertical channel trajectory is unlikely to switch suddenly from long-term incision to long-term aggradation and has a relatively flat segment during the transitional time between incision and aggradation (Figs. 2, 4a), the basal part of the channel system will be dominated by lateral migration. Long-term lateral migration without much aggradation can result in numerous crosscutting relationships between channel threads and give the impression of a relatively disorganized system (Figs. 7, 8d, g). The system seemingly becomes simpler and more organized as aggradation starts to predominate and much fewer channel threads are captured in slope-parallel slices. However, no major changes in channel type or behavior – e.g., from braided to sinuous, or from

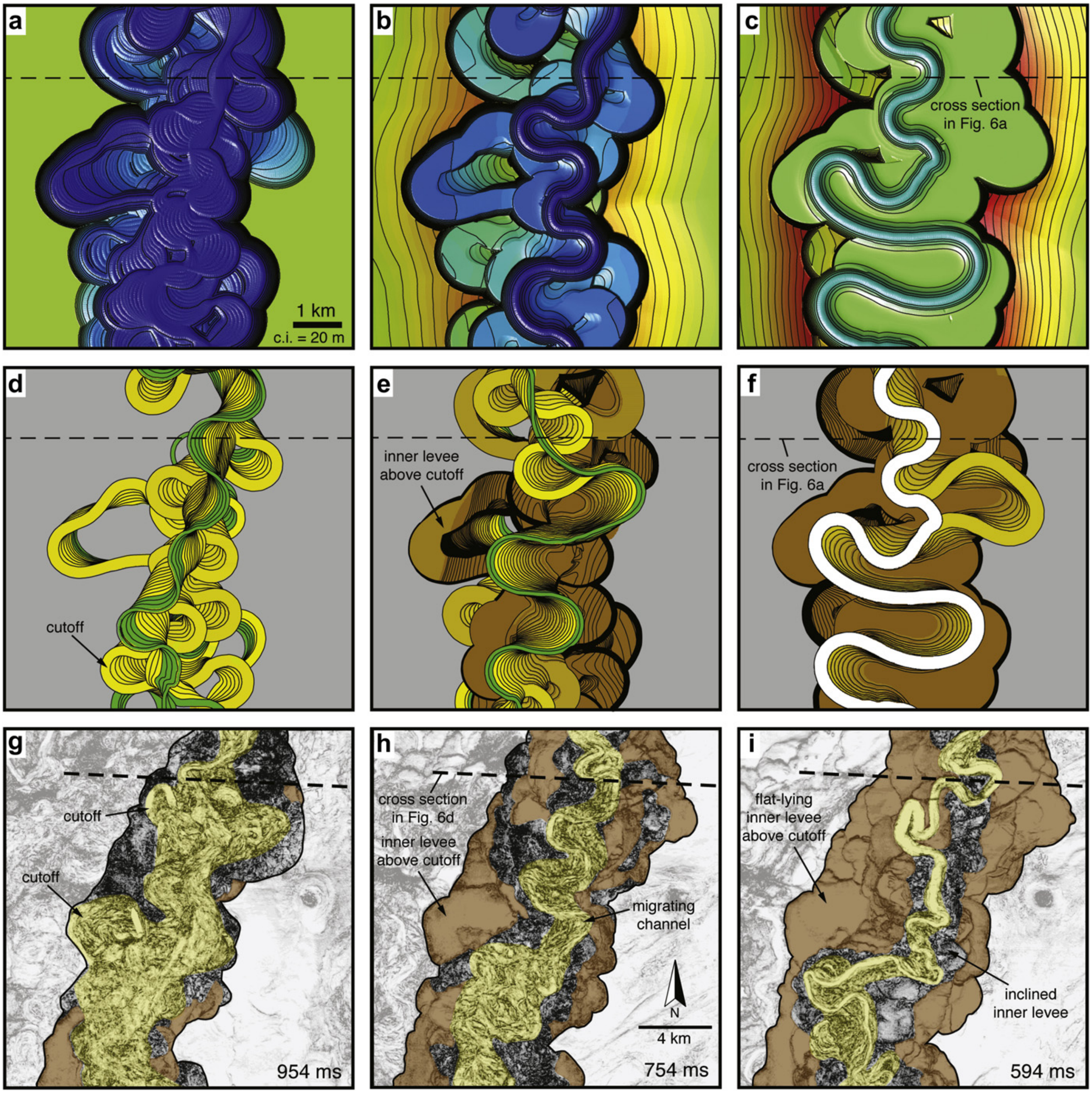

Fig. 8. (a) Basal composite erosional surface of the model shown in Fig. 6. Red colors correspond to high elevation, blue colors to low elevation. (b) Topographic surface at time of maximum incision. (c) Topographic surface at the end of aggradation. (d–f) Horizontal sections through stratigraphy, from base to top. Lines represent stratigraphic surfaces; color coding for facies is identical to that of Fig. 4d. Locations of sections are shown in Fig. 6a. (g–i) Seafloor-parallel horizon slices through channel-levee system CLS3 (as defined in Deptuck et al., 2003), from base to top, from a volume of seismic coherence (black = low coherence; white = high coherence). Areas shown in brown are flat-lying inner levees in terraces; areas colored in light yellow are zones of channel migration. Compare with the stratigraphic sections in figures (d–f).

frequent filling and cutting to reduced cut-and-fill – are needed for this transition to take place.

4. Discussion

4.1. Erosional surfaces: basic channel form versus composite surfaces

Submarine channel systems are often analyzed using a hierarchical approach (Gardner et al., 2003; Abreu et al., 2003; Campion et al., 2000; Mayall et al., 2006): individual turbidite beds stack to form channel fills; channels are parts of the fills of larger erosional features; and all these elements can be located inside an even larger erosional form. While hierarchical models are useful to describe the wide range of scales present in these systems and to build reservoir models with the appropriate level of detail, it is important to recognize that boundaries between hierarchical levels are often arbitrary and that large erosional surfaces do not always reflect some allogenic influence, but can be the result of channel migration (e.g., Figs. 6 and 8).

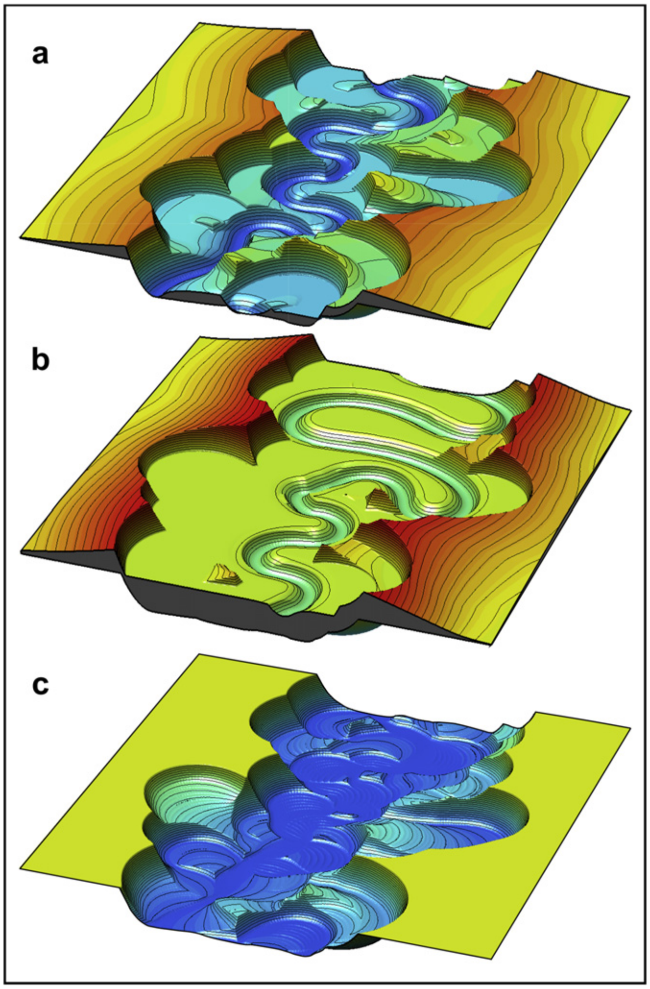

Fig. 9. Three-dimensional views of the surfaces shown in map view in Fig. 8a–c. (a) Topography at time of maximum incision; (b) Final topography; (c) Basal erosional surface. Contour interval is 20 m.

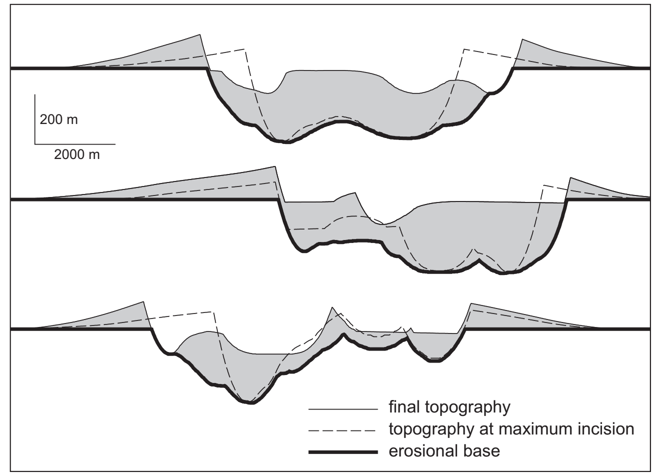

Fig. 10. Example cross sections showing the difference between the basal erosional surface, which is a stratigraphic surface, and the topographic surface at the time of maximum incision, which is a geomorphologic or time surface.

The channel trajectory model highlights the fundamental difference between erosional surfaces related to a characteristic discharge, and erosional surfaces that are the result of long-term channel migration. The first type is the same as the basic channel form of a system, corresponds to a bathymetric feature on the seafloor, and within one system, it is likely to have a relatively low variation in size. Systematic channel migration happens at this scale, as it is driven by the flows that determine the basic channel size. The second type of surface records the migration through time of the basic channel form and therefore its scale and geometry is a function of the channel migration history. These larger erosional surfaces are time-transgressive and do not exist at any time as bathymetric features on the seafloor. A valley that is larger than the basic channel form does develop during the incisional phase (e.g., time step 70 in Figs. 7 and 9a) but there are significant differences between this time surface and the composite basal erosional surface (Fig. 10).

4.2. Erosional surfaces and flow size

The channel trajectory model shows that realistic valleys and valley fill architectures can develop while the average discharge remains approximately the same. Smaller channels inside a larger erosional cut are often interpreted as the result of a major reduction in flow size (Deptuck et al., 2003; Kolla et al., 2007). While this is clearly a possibility, we suggest that large changes in average discharge are not necessary to explain most of the features we observe in such systems; a long-term switch from somewhat erosional to slightly depositional flows is sufficient. Plan-view expressions of slope channels provide evidence that the large erosional surfaces do not result from much larger flows. If the valley surface was created by high-discharge flows, one would expect to see a sinuous plan view, with valley walls that are roughly parallel to each other. This is not the case however: most such boundaries are irregular and strongly scalloped (Babonneau et al., 2002; Deptuck et al., 2003; McHargue et al., 2011). Most of these scallops result from the widening of the valley wall by the migrating sinuous channel (Fig. 7). Although most of the widening and scallop development occurs during incision, new scallops can develop during aggradation as well. A large-discharge channel or valley should also undergo at least some lateral migration; however, no such large-scale valley migration deposits have been described so far. Further updip, where the channel-levee systems become largely non-depositional submarine canyons, there is evidence that the size of the canyons is not related to flow size (Normark and Carlson, 2003).

Flow discharge frequency data is not available from submarine channels, although indirect evidence based on the thickness and grain size of overbank deposits suggests relatively little flow variability over time in the case of the Amazon channel-levee system (Pirmez and Imran, 2003). The channel trajectory model shows that the complex stratigraphy of a channel-levee system such as seen in the Indus Fan (Figs. 6, 8) can be reproduced with simple rules. It is sufficient to have a single channel size through the entire evolution of the channel-levee system, suggesting that there is no need for large variations in flow size.

4.3. Vertical channel trajectory and reincisions

A necessary condition for the formation of typical channel-levee architectures (Figs. 4, 6) is that the vertical channel trajectory follows a long-term, relatively smooth cycle of net incision, followed by net aggradation. Long-term net incision can result from adjustment to a smooth equilibrium profile during early channel evolution, following – or during – tectonic deformation (Heiniö and Davies, 2007; Clark and Cartwright, 2009), and after channel avulsion events (Pirmez et al., 2000). The cause for a switch to the aggradational phase is still unclear. Once the channel-levee system reaches equilibrium (the bottom of the incision-aggradation cycle, Fig. 4a), the switch to aggradation may be caused by: (a) reduced slope due to structural deformation, (b) relatively small, but systematic changes in flow properties, as caused by delta progradation or relative sea-level changes. Although the idea that channel behavior, that is, the vertical channel trajectory parallels the relative sea-level history (e.g., Samuel et al., 2003; McHargue et al., 2011) is attractively simple, adjustment to a smooth equilibrium profile requires no sea-level changes for the incision to occur. In addition, high-resolution age dating of a channel system directly linked to a delta would be necessary to unequivocally demonstrate that channel incision occurred during relative sea-level fall and aggradation during relative sea-level rise.

In the two-dimensional and three-dimensional models presented above, we have chosen relatively simple vertical trajectories, consisting of a single cycle of incision and aggradation. This is in contrast with the idea of frequent reincision surfaces. For instance, Mayall et al. (2006) suggest that “repeated cutting and filling is a feature of just about every channel studied.” Samuel et al. (2003) also interpret numerous reincisions in slope valleys of the Nile Delta.

In our model, a realistic topographic surface with channel-levee morphology exists at every time step. In contrast, a cut-and-fill model requires a period of erosion, followed by a period of deposition, with an ever-changing channel depth. To build the internally complex channel-levee systems that we observe in many seismic datasets, this back-and-forth switch between erosion and deposition would need to occur repeatedly, tens or even hundreds of times. Although structural evolution of the slope can have significant influence over submarine channel evolution (Deptuck et al., 2007), and channel avulsions can result in reincisions (Deptuck et al., 2003; Pirmez et al., 2000), it is unlikely that structural deformation or avulsions have the periodicity required to produce the frequent and regular back-and-forth switching between erosion and deposition associated with cut-and-fill evolution of channels. In slope channels, structural changes and avulsions are more likely responsible for longer-term cycles of incision and aggradation. The longitudinal extent of these reincision surfaces is restricted to the area affected by the deformation or avulsion, and the surfaces are composite erosional events of variable size. Channel avulsion results in the introduction of a knickpoint along the channel profile, and upstream migration of such knickpoints can lead to channel incision and planform shortening (cutoffs) for at least a few tens of kilometers (Pirmez et al., 2000; Pirmez and Flood, 1995; Heiniö and Davies, 2007). Large composite erosional surfaces can also form due to a decrease in the *rate* of aggradation, without any reincision (Fig. 4). These surfaces will be more extensive in a slope-parallel direction than the erosional boundaries forming during relatively stable aggradation combined with lateral migration (e.g., Fig. 6a, b).

4.4. Lateral migration and aggradation

Deep-marine deposits associated with ancient submarine channels are often viewed as channel-shaped cuts with sub-horizontal fill. Even apparent systematic lateral channel migration is interpreted as the result of repeated filling, lateral shift, and reincision (Kolla et al., 2007, their Fig. 16b; Mayall et al., 2006). This cut-and-fill interpretation is at odds with the idea that channels are open conduits with a clear morphological expression during most of their lifetime. Channel-shaping turbidity currents, like a river in flood, are likely to cause significant erosion on the outer banks of the channel, and deposit sediment on the inner banks. A significant part of the channel deposits modeled here are inclined strata that are generally of higher relief, but comparable in geometry to fluvial point-bar units.

There is growing evidence that channel migration is a key process that determines the overall architecture of submarine channel-levee systems. Inclined channel-margin seismic reflections suggesting lateral migration of submarine channels have been documented from several systems (Abreu et al., 2003; Babonneau et al., 2010; Deptuck et al., 2007; Flood et al., 2009; Kolla et al., 2007; Posamentier and Kolla, 2003; Schwenk et al., 2005). Sandy submarine channel deposits with inclined layering and systematic lateral migration have been described from an increasing number of outcrops (Abreu et al., 2003; Arnott, 2007; Dykstra and Kneller, 2009; O’Byrne et al., 2006; Schwarz and Arnott, 2007; Shultz et al., 2005; Wynn et al., 2007). Limited seismic bandwidth may have prevented widespread recognition of submarine lateral migration deposits (Abreu et al., 2003). Sub-horizontal filling of channels is only expected after channel abandonment, that is, at times when cutoffs or avulsions occur (Fig. 6d). Such geometries must be more common in environments where avulsions are frequent and both sinuosity and lateral migration are reduced, such as in distributive channel systems. Thus, it is possible that many of the channels with cut-and-fill geometries seen in outcrop represent sections through ancient submarine aprons rather than sinuous slope channels.

While the large-scale architectures shown here have many similarities with fluvial models, there are two key differences: (1) aggradation usually is more important in submarine channels than in fluvial ones (Kolla et al., 2007; Peakall et al., 2000; Wynn et al., 2007); and (2) for similar channel size, levees of submarine channels tend to be thicker than fluvial levees. Ultimately the high rates of overbank deposition and the potential for high aggradation rates reflect that the excess density of turbidity currents relative to the ambient water is about 50 times smaller than the excess density of a river compared to the ambient air density (Imran et al., 1999). Turbidity currents frequently overspill their channels and rates of overbank deposition are likely to be high (Pirmez and Imran, 2003). High sedimentation rates in both the channel and overbank area are necessary for significant channel aggradation to occur. Even if no age data is available, the ratio between lateral migration and channel aggradation can be measured in well-imaged submarine channels. For two time intervals in the evolution of the Benin Major

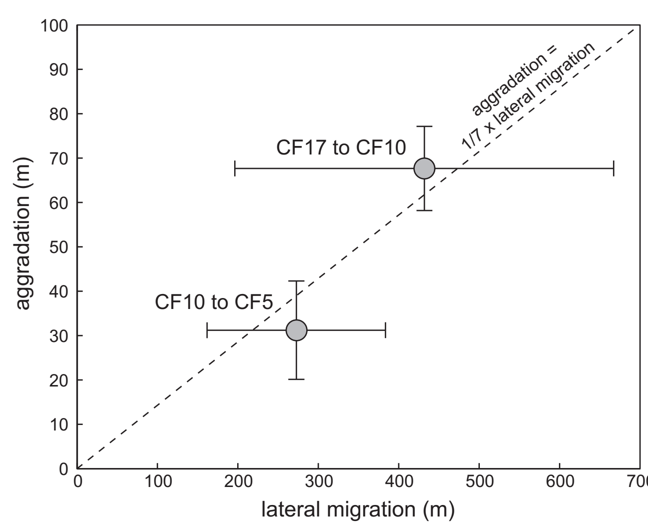

Fig. 11. Aggradation plotted against lateral migration for two time intervals, Benin Major channel-levee system. Measurements, made on maps and along-channel sections of Deptuck et al. (2007), represent the maximum lateral displacements of channel bends in plan view (lateral migration), and vertical distances (aggradation) from channel form (CF) 17 to CF 10 and from CF 10 to CF 5. Error bars correspond to two standard deviations.

channel on the Niger Delta slope, lateral migration is *only* ~6.7 and ~8.2 times larger than vertical aggradation (Fig. 11; see Deptuck et al., 2007 for context). These ratios are probably one order of magnitude smaller than those characteristic of meandering fluvial channels (Peakall et al., 2000).

This order-of-magnitude difference between aggradation rates in fluvial and submarine channels also means that typical point-bar like geometries are less common in submarine channels than in fluvial systems. Well-defined point-bar geometries only develop if the aggradation rate is small relative to the lateral migration. If the aggradation rate is significant, the sand-rich channel-base deposits are laterally thinning onto one or both sides of the channel. However, even in this case, the channel-base deposits may not be filling the channel; instead they aggrade the channel floor while preserving the cross-sectional geometry through coeval levee aggradation. Unfortunately many outcrops only preserve the coarse-grained remnants from the basal part of the channel and therefore do not allow an unequivocal reconstruction of channel relief and morphology at the time of deposition.

4.5. Further work

The simple model described here provides valuable insights into channel-levee architecture and evolution. However, there are a number of key points where improvements are clearly possible. First, much remains to be learned about the differences in channel migration patterns in fluvial and submarine systems and the adaptability and applicability of centerline migration models to turbidity currents. Second, the plan-view and vertical evolution of channels should be coupled in a single model with variable along-channel slope. Third, additional work on the relationships between channel-levee topography and the distribution of lithofacies and grain size will improve the facies and reservoir property volumes that result from the model.

5. Conclusions

The centerline-based channel trajectory model described here generates channel-levee geometries similar to those observed in seismic data and confirms our hypothesis that these systems form as a result of relatively continuous migration of a single channel form. The model suggests that formation of large canyon fills with complex stratal geometries does not require a switch from initially large-discharge turbidity currents to low discharge flows. Rather, they can be explained and modeled using a single channel size that follows a long-term incision-aggradation cycle. Channel deposits grade outward into coeval inner levees. Inner levees can continuously grade into coeval outer levees if the flow thickness is sufficiently large. The three-dimensional geometries of submarine channel-levee systems can be highly complex, even if there is a single incision-aggradation cycle. Large erosional boundaries are common both at the base of the valley and within the valley fill, but they are not necessarily the result of significant reincisions, and because of their composite nature they do not correspond to chronostratigraphic or topographic surfaces. Many, if not most, submarine channel systems have a simpler history of channel incision, aggradation, and flow variability than previously thought.

Acknowledgements

Discussions with Bradford Prather, Mark Deptuck, Ciaran O'Byrne, and Mark Barton were influential in the development of the ideas presented here. In addition, Mark Deptuck's seismic mapping of submarine channels was a key ingredient for developing the model. Thanks to Matthew Wolinsky for discussions and help with Matlab coding, Ao Yi for providing the code for centerline generation, Bradford Prather, Martin Grecula, Keith Campbell, and Daniel Minisini for reviewing an earlier version of the manuscript, journal reviewers Ian Clark, Andrea Fildani, and Michael Pyrcz for constructive reviews, Mark Hempton for supporting this work, and Shell International Exploration and Production Inc. for the permission to publish it.

References

Abreu, V., Sullivan, M., Pirmez, C., Mohrig, D., 2003. Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels. Marine and Petroleum Geology 20, 631–648.
Allen, J.R.L., 1985. Principles of Physical Sedimentology. George Allen & Unwin, 272 pp.
Arnott, R., 2007. Stratal architecture and origin of lateral accretion deposits (LADs) and conterminuous inner-bank levee deposits in a base-of-slope sinuous channel, lower Isaac Formation (Neoproterozoic), East-Central British Columbia, Canada. Marine and Petroleum Geology 24, 515–528.
Babonneau, N., Savoye, B., Cremer, M., Klein, B., 2002. Morphology and architecture of the present canyon and channel system of the Zaire deep-sea fan. Marine and Petroleum Geology 19, 445–467.
Babonneau, N., Savoye, B., Cremer, M., Bez, M., 2004. Multiple terraces within the deep incised Zaire Valley (ZaiAngo Project): are they confined levees?. In: Geological Society London Special Publication, vol. 222 91–114.
Babonneau, N., Savoye, B., Cremer, M., Bez, M., 2010. Sedimentary architecture in meanders of a submarine channel: detailed study of the present Congo turbidite channel (Zaiango project). Journal of Sedimentary Research 80, 852–866.
Campion, K., Sprague, A., Mohrig, D., Lovell, R., Drzewiecki, P., Sullivan, M., Ardill, J., Jensen, G., Sickafoose, D., 2000. Outcrop expression of confined channel complexes. In: GCSSEPM Foundation 20th Annual Research Conference, Deep-Water Reservoirs of the World, pp. 127–150.
Clark, I.R., Cartwright, J.A., 2009. Interactions between submarine channel systems and deformation in deepwater fold belts: examples from the Levant Basin, Eastern Mediterranean sea. Marine and Petroleum Geology 26, 1465–1482.
Clark, J., Pickering, K., 1996. Architectural elements and growth patterns of submarine channels: application to hydrocarbon exploration. AAPG Bulletin 80, 194–221.
Cojan, I., Fouche, O., Lopez, S., Rivoirard, J., 2005. Process-based reservoir modelling in the example of meandering channel. In: Leuangthong, O., Deutsch, C.V. (Eds.), Geostatistics Banff 2004. Springer, pp. 611–620.
De Ruig, M.J., Hubbard, S.M., 2006. Seismic facies and reservoir characteristics of a deep-marine channel belt in the Molasse foreland basin, Puchkirchen Formation, Austria. AAPG Bulletin 90, 735–752.
Deptuck, M.E., Steffens, G.S., Barton, M., Pirmez, C., 2003. Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea. Marine and Petroleum Geology 20, 649–676.
Deptuck, M.E., Sylvester, Z., Pirmez, C., O'Byrne, C., 2007. Migration–aggradation history and 3-D seismic geomorphology of submarine channels in the Pleistocene Benin-major Canyon, western Niger Delta slope. Marine and Petroleum Geology 24, 406–433.
Dykstra, M., Kneller, B., 2009. Lateral accretion in a deep-marine channel complex: implications for channellized flow processes in turbidity currents. Sedimentology 56, 1411–1432.
Fildani, A., Normark, W.R., Kostic, S., Parker, G., 2006. Channel formation by flow stripping: large-scale scour features along the Monterey East Channel and their relation to sediment waves. Sedimentology 53, 1265–1287.
Fildani, A., Hubbard, S.M., Romans, B.W., 2009. Stratigraphic evolution of deep-water architecture – examples of controls and depositional styles from the Magallanes Basin, southern Chile. SEPM Field Trip Guidebook, vol. 10, 73pp.
Flood, R.D., Hiscott, R.N., Aksu, A., 2009. Morphology and evolution of an anastomosed channel network where saline underflow enters the Black Sea. Sedimentology 56, 807–839.
Frascati, A., Lanzoni, S., 2009. Morphodynamic regime and long-term evolution of meandering rivers. Journal of Geophysical Research 114, F02002. doi:10.1029/2008JF001101.
Gardner, M.H., Borer, J.M., Melick, J.J., Mavilla, N., Dechesne, M., Wagerle, R.N., 2003. Stratigraphic process-response model for submarine channels and related features from studies of Permian Brushy Canyon outcrops, West Texas. Marine and Petroleum Geology 20, 757–787.
Heiniö, P., Davies, R.J., 2007. Knickpoint migration in submarine channels in response to fold growth, western Niger Delta. Marine and Petroleum Geology 24, 434–449.
Helland-Hansen, W., Martinsen, O., 1996. Shoreline trajectories and sequences: description of variable depositional-dip scenarios. Journal of Sedimentary Research 66, 670–688.
Howard, A.D., Knutson, T.R., 1984. Sufficient conditions for river meandering: a simulation approach. Water Resources Research 20, 1659–1667.
Hubbard, S.M., Romans, B.W., Graham, S.A., 2008. Deep-water foreland basin deposits of the Cerro Toro Formation, Magallanes basin, Chile: architectural elements of a sinuous basin axial channel belt. Sedimentology 55, 1333–1359.

Hubbard, S.M., De Ruig, M.J., Graham, S.A., 2009. Confined channel-levee complex development in an elongate depo-center: deep-water tertiary strata of the Austrian Molasse basin. Marine and Petroleum Geology 26, 85–112.

Ikeda, S., Parker, G., Sawai, K., 1981. Bend theory of river meanders. Part 1. Linear development. Journal of Fluid Mechanics 112, 363–377.

Imran, J., Parker, G., Katopodes, N., 1998. A numerical model of channel inception on submarine fans. Journal of Geophysical Research 103, 1219–1238.

Imran, J., Parker, G., Pirmez, C., 1999. A nonlinear model of flow in meandering submarine and subaerial channels. Journal of Fluid Mechanics 400, 295–331.

Kane, I.A., McCaffrey, W.D., Peakall, J., 2008. Controls on sinuosity evolution within submarine channels. Geology 36, 287–290.

Kim, W., Paola, C., Swenson, J.B., Voller, V.R., 2006. Shoreline response to autogenic processes of sediment storage and release in the fluvial system. Journal of Geophysical Research 111.

Kolla, V., Posamentier, H.W., Wood, L.J., 2007. Deep-water and fluvial sinuous channels—characteristics, similarities and dissimilarities, and modes of formation. Marine and Petroleum Geology 24, 388–405.

Labourdette, R., 2008. 'LOSCS' Lateral Offset Stacked Channel Simulations: towards geometrical modelling of turbidite elementary channels. Basin Research 20, 431–444.

Labourdette, R., Bez, M., 2010. Element migration in turbidite systems: random or systematic depositional processes? AAPG Bulletin 94, 345–368.

Mayall, M., Jones, E., Casey, M., 2006. Turbidite channel reservoirs—key elements in facies prediction and effective development. Marine and Petroleum Geology 23, 821–841.

McCave, I., Swift, S.A., 1976. A physical model for the rate of deposition of fine-grained sediments in the deep sea. Geological Society of America Bulletin 87, 541–546.

McHargue, T., Pyrcz, M.J., Sullivan, M.D., Clark, J.D., Fildani, A., Romans, B.W., Covault, J.A., Levy, M., Posamentier, H.W., Drinkwater, N.J., 2011. Architecture of turbidite channel system on the continental slope: patterns and predicitions 28 (3), 728–743.

Normark, W.R., Carlson, P.R., 2003. Giant submarine canyons: is size any clue to their importance in the rock record? In: Chan, M.A., Archer, A.W. (Eds.), Extreme Depositional Environments: Mega End Members in Geologic Time Geological Society of America Special Paper 370, pp. 175–190.

Normark, W.R., Piper, D.J.W., Hiscott, R.N., 1998. Sea level controls on the textural characteristics and depositional architecture of the Hueneme and associated submarine fan systems, Santa Monica Basin, California. Sedimentology 45, 53–70.

O'Byrne, C., Barton, M., Steffens, G.S., Pirmez, C., Buergisser, H., 2006. Architecture of a laterally migrating channel complex: Channel 4, Isaac Formation, Windermere Supergroup, Castle Creek North, British Columbia, Canada. In: Steffens, G.S., Nilsen, T.H., Studlick, J.R.J., Shew, R.D. (Eds.), Atlas of Deepwater Outcrops. AAPG Studies in Geology 56, 115–118.

Peakall, J., McCaffrey, B., Kneller, B., 2000. A process model for the evolution, morphology, and architecture of sinuous submarine channels. Journal of Sedimentary Research 70, 434–448.

Pirmez, C., Flood, R., 1995. Morphology and structure of Amazon Channel. Proceedings of the Ocean Drilling Program, Initial Reports 155, 23–45.

Pirmez, C., Imran, J., 2003. Reconstruction of turbidity currents in a meandering submarine channel. Marine and Petroleum Geology 20, 823–849.

Pirmez, C., Beaubouef, R.T., Friedmann, S.J., Mohrig, D.C., 2000. Equilibrium profile and baselevel in submarine channels: examples from Late Pleistocene systems and implications for architecture in deepwater reservoirs. Deep-Water Reservoirs of the World, 20th Annual GCSSEPM Foundation Bob F. Perkins Research Conference, Gulf Coast Section. SEPM 20, 782–805.

Pizzuto, J.E., 1987. Sediment diffusion during overbank flows. Sedimentology 34, 301–317.

Posamentier, H.W., Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. Journal of Sedimentary Research 73, 367–388.

Pyrcz, M., Strebelle, S., 2006. Event-based geostatistical modeling: application to deep-water systems. In: Gulf Coast Section – SEPM Twenty-Sixth Annual Research Conference, pp. 893–922.

Pyrcz, M.J., Deutsch, C.V., 2005. Conditioning event-based fluvial models. In: Leuangthong, O., Deutsch, C.V. (Eds.), Geostatistics Banff 2004. Springer, pp. 135–144.

Pyrcz, M.J., Boisvert, J.B., Deutsch, C.V., 2009. ALLUVSIM: a program for event-based stochastic modeling of fluvial depositional systems. Computers & Geosciences 35, 1671–1685.

Samuel, A., Kneller, B., Raslan, S., Sharp, A., Parsons, C., 2003. Prolific deep-marine slope channels of the Nile Delta, Egypt. AAPG Bulletin 87, 541–560.

Schwenk, T., Spieß, V., Breitzke, M., Hübscher, C., 2005. The architecture and evolution of the Middle Bengal Fan in vicinity of the active channel–levee system imaged by high-resolution seismic data. Marine and Petroleum Geology 22, 637–656.

Schwarz, E., Arnott, R.W.C., 2007. Anatomy and evolution of a slope channel-complex set (Neoproterozoic Isaac formation, Windermere Supergroup, Southern Canadian Cordillera): implications for reservoir characterization. Journal of Sedimentary Research 77, 89–109.

Shultz, M.R., Fildani, A., Cope, T.D., Graham, S.A., 2005. Deposition and stratigraphic architecture of an outcropping ancient slope system: Tres Pasos Formation, Magallanes Basin, southern Chile. In: Geological Society London Special Publications, vol. 244 27–50.

Skene, K.I., Piper, D.J.W., Hill, P.S., 2002. Quantitative analysis of variations in depositional sequence thickness from submarine channel levees. Sedimentology 49, 1411–1430.

Spencer, J.E., Pearthree, P.A., 2001. Headward erosion versus closed basin spill over as alternative causes of Neogene capture of the Ancestral Colorado River by the Gulf of California. In: Young, R.A., Spamer, E.E. (Eds.), Colorado River: Origin and Evolution. Grand Canyon Association, Grand Canyon, Arizona, pp. 215–222.

Straub, K.M., Mohrig, D., 2008. Quantifying the morphology and growth of levees in aggrading submarine channels. Journal of Geophysical Research 113, F03012. doi:10.1029/2007JF000896.

Straub, K., Mohrig, D., McElroy, B., Buttles, J., Pirmez, C., 2008. Interactions between turbidity currents and topography in aggrading sinuous submarine channels: a laboratory study. Geological Society of America Bulletin 120, 368–385.

Strong, N., Paola, C., 2008. Valleys that never were: time surfaces versus stratigraphic surfaces. Journal of Sedimentary Research 78, 579–593.

Sun, T., Meakin, P., Jøssang, T., 2001. A computer model for meandering rivers with multiple bed load sediment sizes 1. Theory. Water Resources Research 37, 2243–2258.

Willis, B.J., Tang, H., 2010. Three-dimensional connectivity of point-bar deposits. Journal of Sedimentary Research 80, 440–454.

Wolinsky, M.A., 2009. A unifying framework for shoreline migration: 1. Multiscale shoreline evolution on sedimentary coasts. Journal of Geophysical Research 114, F01008. doi:10.1029/2007JF000855.

Wynn, R.B., Cronin, B.T., Peakall, J., 2007. Sinuous deep-water channels: genesis, geometry and architecture. Marine and Petroleum Geology 24, 341–387.

Yi, A., 2006. Modeling of flow and migration of subaerial and submarine meandering channels. Unpublished PhD thesis, University of South Carolina, 163pp.

Zolezzi, G., Seminara, G., 2001. Downstream and upstream influence in river meandering. Part 1. General theory and application to overdeepening. Journal of Fluid Mechanics 438, 183–211.