ELSEVIER

Marine and Petroleum Geology 20 (2003) 901–910

Marine and Petroleum Geology

www.elsevier.com/locate/marpetgeo

The influence of flow parameters on turbidite slope channel architecture

Ben Kneller*

Institute for Crustal Studies, University of California, Santa Barbara, CA 93106, USA

Received 1 September 2002; accepted 17 March 2003

Abstract

Turbidite slope channels are analogous to fluvial channels in that they tend towards graded equilibrium profiles. The gap between the equilibrium profile and the actual sediment surface defines the accommodation, and it is the creation or removal of accommodation that governs the architectural style of turbidite channels on the slope. The factors that determine the tangent to the profile at a given point are the flow density, the flow thickness and the maximum settling velocity (a proxy for grain-size) of suspended sediment. These factors combine in a simple hydraulic relationship that illustrates how changes in these parameters affect the equilibrium gradient. In concept, graded channels behave like many sinuous fluvial systems in that the channels migrate laterally with little or no aggradation. Decrease in flow density or thickness, or increase in grain-size steepens the gradient and creates accommodation, allowing channels to aggrade. In fact without changes in other factors such as base level, channel aggradation should only occur when flow properties change. Increase in flow density or thickness, or decrease in grain-size reduce the gradient and remove accommodation, leading to erosional channels. Both long and short term changes tend from erosional to aggradational, with a tendency towards smaller and perhaps muddier flows with time.

Keywords: Gradient; Accommodation; Aggradation

1. Introduction

Channels in turbidite systems can be regarded as analogous to fluvial channels in that, for a given set of flow conditions, an equilibrium profile will exist for the channel on its path down the slope (Pirmez, Beauboeuf, Friedmann, & Mohrig, 2000, and references therein). Where the floor of the channel coincides with that hypothetical equilibrium profile, the channel may be said to be at grade. A channel profile is pinned at its lower end to base level. In a fluvial channel this pinning point is generally the shoreline, and base level is determined by sea-level or lake level. In a turbidite system, base level is notionally determined by gravity base, i.e. the lowest point to which turbidity currents on a particular pathway can flow (Fig. 1). In practice the effective base level for channels is most likely the point at which the flow becomes unconfined (generally the mouth of the channel). Since the channel mouth may prograde, this is not a truly fixed point. Also gravity base may be the aggrading surface of a sediment body at the base of slope, or within an intra-slope slope basin. However, it is assumed initially that the rate at which it shifts is small compared to rate of change of other factors in the system, and it can be considered fixed over the timescale of change in flow parameters. The concept of equilibrium profile and base level in turbidite systems has been eloquently described by Pirmez et al. (2000).

The purpose of this contribution is to show how changes in the equilibrium profile are consequent upon changes in flow properties, and that these changes may determine the architecture of turbidite channel systems. This paper considers only the control of flow parameters; the effect of dynamic structural control on slope development, and transitions from local to regional base-level on a ponded slope and other changes in base level are not treated here (Beauboeuf & Friedman, 2000; Pirmez et al., 2000; Prather, Booth, Steffens, & Craig, 1998; Winker, 1996).

1.1. Accommodation

Turbidite system architecture on the slope is determined by accommodation, which is defined here, in a similar sense to fluvial systems (Emery & Myers, 1996), as the space between the equilibrium profile down the transport pathway (the surface to which sediments can theoretically aggrade)

* Tel.: +1-617-253-9429; fax: +1-617-253-8928.
E-mail address: ben@crustal.ucsb.edu (B. Kneller).

0264-8172/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2003.03.001

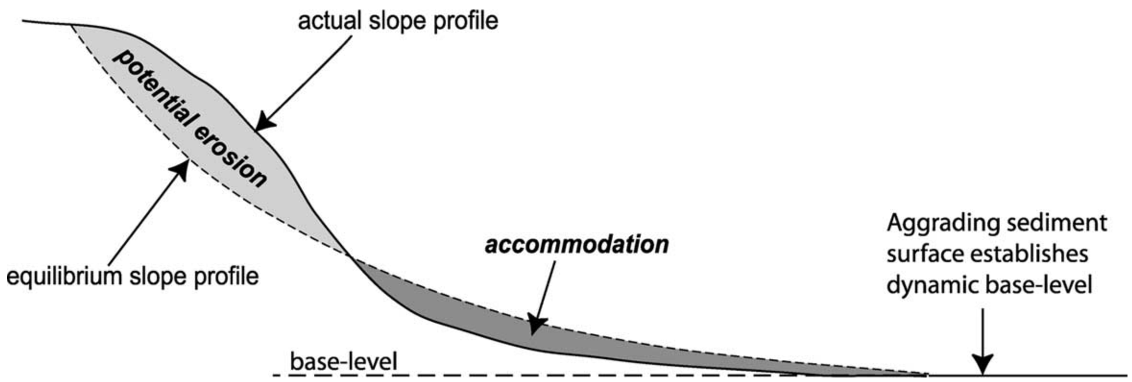

Fig. 1. Schematic illustration of equilibrium profile in relation to actual slope profile (modified from Samuel et al., 2003).

and the actual sediment surface (such as the floor of a channel or the surface of the slope on which a channel forms; Fig. 1). Thus the form of the equilibrium profile down a slope with respect to the actual slope determines the amount of accommodation at any one time. Where the actual slope profile lies above the equilibrium profile, there exists ‘negative accommodation’, i.e. the potential for erosion (Fig. 1). More importantly, changes in the equilibrium profile create or destroy accommodation. It is the response of channels to these changes that governs many aspects of their architectural development.

2. Slope algorithm

There are a variety of ways in which the true shape of the equilibrium profile might be determined numerically, from diffusional models (which may imitate, a posteriori, some features of natural profiles) to numerical simulations of individual turbidity currents, ranging from simple box models to those that attempt replicate the physical processes involved (e.g. those of Necker, Härtel, Kleiser, & Meiburg, 2000). While the latter constitute the best hope in the long term of predictively simulating real slope profiles, they are currently limited by computing power and their ability to deal with the extremely high Reynolds numbers of natural flows.

However, to illustrate the control exerted on the equilibrium profile by certain key physical flow parameters, I use a simple hydraulic equation that links the competence of the flow to its depth, density, and the gradient of the slope over which it moves. This presupposes that turbidity currents are the principal agents determining the form of the equilibrium profile, and that turbulent suspension is the principal means of long-range sediment transport. Clearly traction is important but it is assumed here to be a minor and short-range component of sediment transport whose contribution to the development of the equilibrium profile is minor.

2.1. Shear velocity

A convenient measure of the competence of the flow is the shear velocity, U_*. Shear velocity is effectively a measure of the effect of the flow on the bed, expressed in terms of a velocity. In depth-averaged flow

$$U_* = \sqrt{g\frac{\Delta\rho}{\rho}hS} \tag{1}$$

where h is the thickness of the flow, S is the tangent of the slope down which the flow moves, $\Delta\rho$ is the density difference between the flow and the ambient fluid (of density ρ), and g is the acceleration due to gravity. This is simply a modification of the familiar Chezy equation for open channel flow (Middleton & Southard, 1984). Since in general ρ and g can be treated as constants, the significant variables are $\Delta\rho$ (essentially the amount of sediment in suspension), h and S.

Strictly these relations are valid for open-channel flow in which the horizontal divergence can be ignored. However, Kneller, Bennett, and McCaffrey (1999) argue that expressions derived for open-channel flow can be applied to the inner region of gravity currents (i.e. the part below the velocity maximum), so the appropriate value of h is the height above the bed of the maximum horizontal velocity, and $\Delta\rho$ is depth-averaged over the thickness of the inner region of the flow. Thus the thickness term is related to total flow thickness by the relative height of the velocity maximum which is commonly about 0.2–0.3 the total flow thickness, h_T, and the density term is related to the depth-averaged density of the whole flow, ρ_T, via the shape of the vertical density profile. Thus expression (1) becomes

$$U_* = (g(\xi\Delta\rho_T/\rho)\zeta h_T S)^{1/2} \tag{2}$$

where ζ is the relative height of the velocity maximum and ξ is a factor determined by the shape of the density profile. Both ζ and ξ may vary with initial grain-size distribution, and as the current evolves.

2.2. Sediment suspension

Shear velocity is a convenient measure of flow competence since it can be used to define a simple criterion for the suspension of sediment of a given settling velocity, w_s (which is a function of grain size); where $U_* < w_s$ the grains will tend to be on the bed, and where $w_s \leq U_*$ the grains will tend to be in suspension. U_* is related to the mean flow velocity via the drag coefficient. Given this suspension criterion, one can substitute w_s for U_* into the relation above, and rearrange to give

$$S = \frac{w_s^2 \rho}{g \Delta \rho h} \tag{3}$$

where w_s is the settling velocity of grains (or grain aggregates such as flocs) in equilibrium between the flow and the bed (i.e. just coarser than the coarsest material in suspension) at a given point down the profile, and S is the tangent to the profile at that point. Thus the gradient of the slope is inversely related to the flow density and flow thickness, and directly related to the grain-size (via the settling velocity) of material in equilibrium with the bed, i.e. the coarsest grains in suspension, or the finest grains on the bed. Equilibrium slope is established and maintained by a negative feedback loop: if the slope is steeper than the equilibrium gradient, flows will accelerate and erode until the local slope is reduced to an equilibrium value (i.e. one at which there is neither net erosion nor net deposition); if the gradient is too gentle to maintain autosuspending currents, they will deposit and steepen the gradient till the equilibrium gradient is reached.

2.3. Variation in profiles

The common asymptotic form of slope profiles is a function of the loss of competence of flows as they move downslope, resulting in a progressive downslope fining and consequent downslope decrease in gradient. Segments of profiles with upward-convex curvature may be related to regions where the turbidity currents are autosuspending and thus accelerating over that portion of the slope. Since the flow size, density and grain-size supplied to the system are all likely to vary with position along a margin (depending upon the nature of the fluvial and shelf systems) and time (depending upon sea-level with respect to the shelf-margin), it is not possible to generalize the form of the equilibrium profile.

3. Basic channel types

3.1. Graded (neutral) channels

Where the gradient of the channel is in equilibrium with the flows passing down it, the channel is at grade. Assuming that base level for the profile remains fixed, and that there is no change in flow parameters, there is no shift in the equilibrium profile and no accommodation is created. If the channel is already at grade there is no possibility for the channel to aggrade, nor tendency to erode (Fig. 2). Such channels are constrained to migrate within a plane parallel to the equilibrium profile, analogous to the meander belt in a sinuous fluvial system. Many channels initiate with a relatively straight path, but undergo a phase of rapid

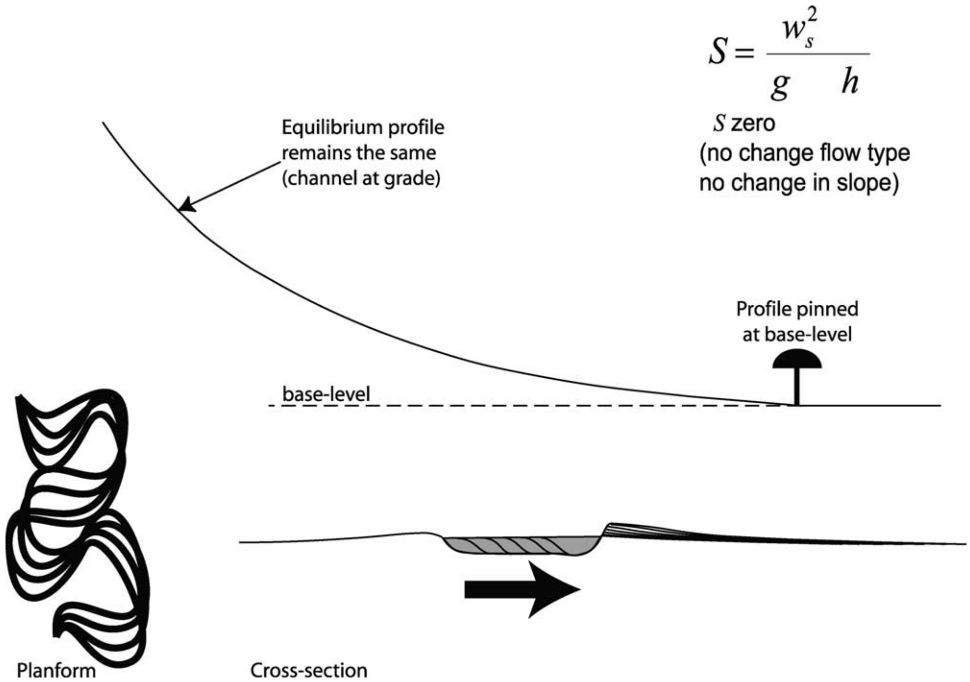

Fig. 2. Schematic illustration of neutral (graded) channel profile, with generalized planform and sectional views; flow parameters remain constant with time.

Fig. 3. Time slice of neutral channel, 80 ms below sea floor, offshore Indonesia. Image kindly supplied by Henry Posamentier.

meander development before reaching a steady-state sinuosity (Peakall et al., 2000, and references therein). Clearly the growth of meanders will reduce the local channel slope, but this probably represents an initial phase of channel gradient adjustment to flow conditions.

Seafloor images of such channels, and thin time slices from seismic may show river-like patterns of channel migration, with broadening and downstream sweep of meander-bends, and complex patterns of cross-cutting former channels (Fig. 3; see also Mayall & Stewart, 2000). They may also show scroll-bar-like features related to bend migration, and meander-bend cut-offs. Levees immediately adjacent to the active channel are commonly poorly developed or absent, though the channel system may form within a broader leveed valley (Morris & Busby-Spera, 1990).

In section, both at outcrop and in the subsurface, these channels show little or no aggradation, and the resultant sediment body is a composite sheet of coarse-grained sediment consisting of laterally amalgamated or migrating channel bodies (Kolla, Bourges, Urruty, & Safa, 2001; Mayall & Stewart, 2000; Morris & Normark, 2000; Samuel, Kneller, Raslan, Sharp, & Parsons, 2003). Seismic sections occasionally show internal reflectors inclined in the direction of channel migration (Fig. 4a 'lateral accretion packages' of Abreu et al., 2003). At outcrop, inclined surfaces analogous to epsilon cross-stratification have been described in such systems (Fig. 4b; Abreu et al., 2003; Elliott, 2000; Morris & Busby-Spera, 1990), and are interpreted as point-bar-like features related to channel migration.

3.2. Aggradational channels

If flow parameters change in such a way as to produce a steeper slope (by reduction in flow size or density, or increase in grain-size), the equilibrium profile steepens and rotates about its pinning point, generating accommodation that allows the channel to aggrade (Fig. 5). Aggradation of channels requires deposition both in the channel axis and the overbank areas, in order to maintain channel confinement.

In sea-floor images and thin seismic time slices, aggradational channels typically appear as single well-defined threads (Fig. 6), commonly of high seismic amplitude indicating coarse-grained 'active channel' deposits. Scroll bars are not evident, and cut-offs are typically infrequent compared with fluvial channels of comparable sinuosity (Peakall et al., 2000). Since most of the channel's history is buried in the subsurface, any evidence of channel movement will be revealed only by looking at a thicker sequence, or by taking successive time-slices. However, Peakall et al. (2000) noted that after an initial phase of rapid meander bend development, channel meanders commonly remain more or less fixed in position as they aggrade (Fig. 4), or migrate rather little.

In seismic section, aggradational channels often show relatively high angles of climb of the high amplitude reflections marking the channel axis, even when restored to true scale, suggesting that aggradation was rapid compared to rates of channel migration. Aggradation in systems with predominantly sandy overbanks is hard to demonstrate seismically, though has been described at outcrop (Barton, 1997; Camacho, Busby, & Kneller, 2002; Gardner, Borer, Melick, Mavilla, & Wagerle, 2003). In mixed or muddy systems, levees are typically better developed and can be more easily differentiated seismically. Aggradation of the levees occurs in parallel with that of the channel axis (Hackbarth & Shew, 1994; Normark, Damuth, & Wickens, 1997). Comparisons between ancient, coarse-grained active margin systems at outcrop (Morris & Busby-Spera, 1990) and large Pleistocene passive margin systems is problematic, but in both settings aggradational packages apparently consist of alternations of cut and fill that generate a net aggradational package (Fig. 7).

3.3. Erosional channels

Where flow parameters change in such a way as to decrease the local gradient, the effect will be that of

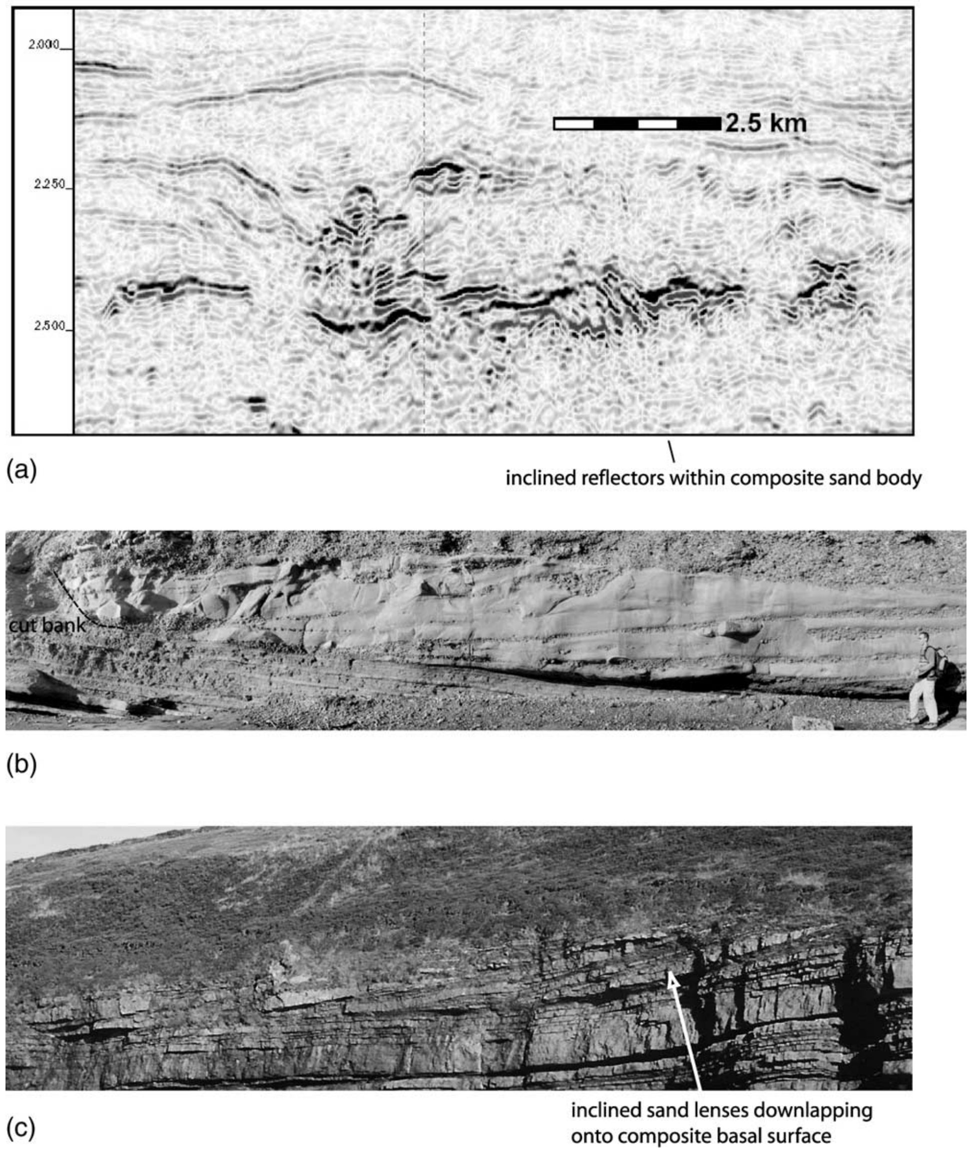

Fig. 4. (a) Seismic section of Pliocene channels from the western Nile Delta slope, showing composite sheet of high amplitudes related to laterally migrating channels (from Samuel et al., 2003). (b) Lateral accretion packages at outcrop, Rosario Formation (Late Cretaceous, Baja California, Mexico). Two metre thick sigmoidal gravel and sand bodies related to lateral channel migration (right to left) downlap onto composite surface marking migrating position of channel base. Flow towards viewer. Final position of channel marked by cut bank at left. (c) Lateral accretion packages at outcrop, Ross Formation (Carboniferous, Western Ireland). Sigmoidal sand bodies 7.5 m thick related to lateral channel migration (right to left) downlap onto composite surface marking migrating position of channel base. Flow away from viewer.

'flattening' the equilibrium profile, and reducing accommodation. If the channel (or the pre-channel slope) was already at grade, the effect will be to create an erosional channel (Fig. 8). Erosional channels form negative open features on the sea-floor (Fig. 9).

Where they are simple, single-stage, purely erosional features, they are commonly rather straight. In section, a purely erosional channel consists solely of an erosion surface, perhaps with a thin tractional lag deposit at its base (e.g. clast-supported gravel or coarse sandstone with cross-bedding). Many formerly erosional channels are defined by the deposits that fill them, which are not directly related to the processes that formed the original erosional conduit. A converse change in flow parameters (towards less energetic flows) is required to generate a channel fill within the erosional space. Ancient erosionally-based channel fills thus record at least two changes in flow properties, the first to initiate the erosion, and the second to initiate the fill (Fig. 10).

The ability of a slope or channel floor to achieve an equilibrium profile depends on whether currents flowing down it are capable of eroding the substrate. Where the bed material is coarse-grained, the establishment of an equilibrium profile may be prevented. This may occur where the bed consists of mixed-size sediment. Winnowing of the bed, perhaps associated with traction of the coarse bed material,

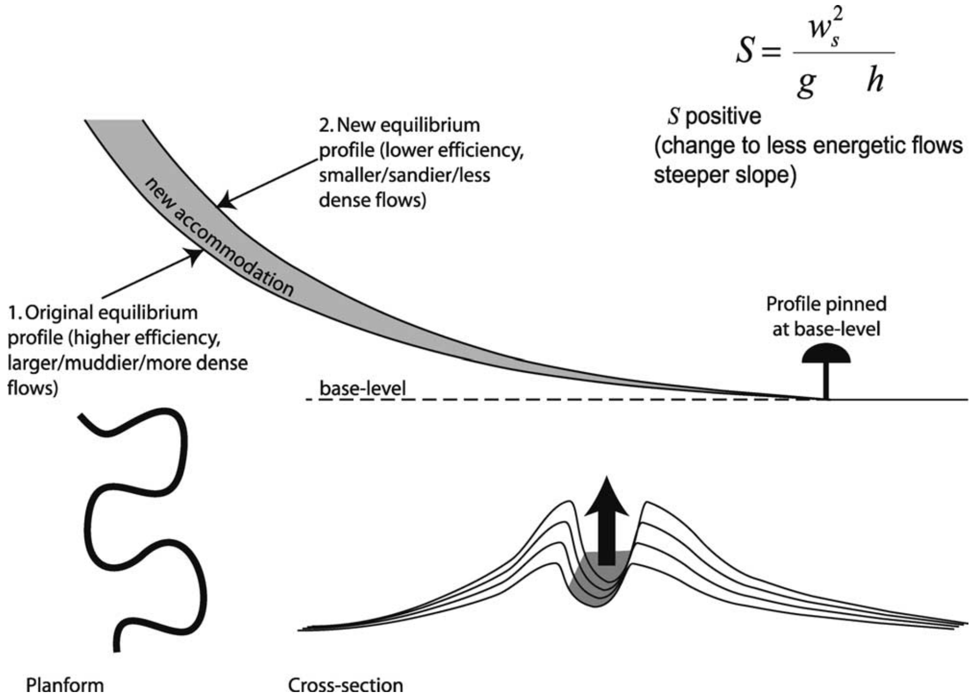

Fig. 5. Schematic illustration of aggradational channel, with generalized planform and sectional views.

may result in a coarse lag or armour layer that prevents any further erosion, and freezes the disequilibrium profile. This is especially likely where mass transport processes introduce a surface layer with a wide grain-size range, e.g. pebbly mudstones. Gravel layers are common in both modern and ancient submarine valley floors (Clifton, 1984; Cronin & Kidd, 1998; Hughes Clarke, Shor, Piper, & Mayer, 1990; Morris & Busby-Spera, 1988; Savoye, Piper, & Droz, 1993), in some cases apparently insulating underlying finer sediments from erosion (Peakall, Kneller, & McCaffrey, 1999).

4. Temporal changes in flow properties

4.1. Flow change and aggradational channels

Several lines of evidence suggest that aggradational channels may be associated with changes in flow. Firstly, leveed channels (slope fans; Type 3 systems of Mutti, 1985; Mutti & Normark, 1987; bypass facies assemblage of Prather et al., 1998) commonly occur at the tops of fourth-order sequences, and in some cases (but not all) are associated with sea-level rise (Winker, 1996; Badalini, Kneller, & Winker, 2000; Prins & Postma, 2000). The bypass facies assemblage in the Plio-Pleistocene of the Gulf of Mexico (Prather et al., 1998) is associated with a steeping of gradient, and has low sand-to-mud ratios compared with the underlying 'ponded' facies assemblage. Secondly, aggradational leveed channels may succeed erosional channels at the same location during sea-level rise (Fig. 11; Winker, 1996; Badalini et al., 2000; Beauboeuf & Friedman, 2000). Thirdly, channel narrowing with time in aggradational leveed channels has been documented from a variety of systems, ranging from the 'inner levees' of large muddy systems (Deptuck, Steffens, Barton, & Pirmez, 2003) and small active margin sandy systems (Normark, Piper, & Hiscott, 1998), to the progressive narrowing with time of the youngest Mississippi Fan

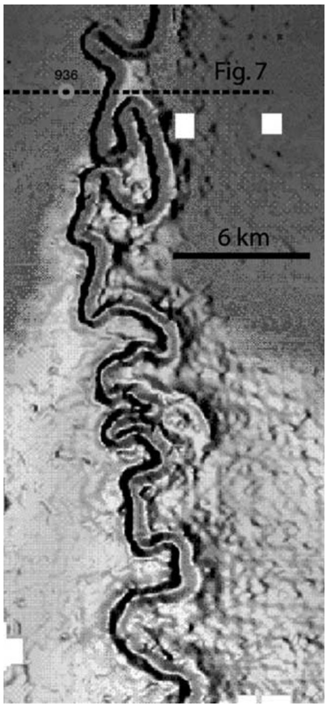

Fig. 6. Rendered bathymetry over Amazon fan channel at ODP site 936, approximately 450 km from shelf edge, illustrating single channel thread visible at sea floor (Pirmez et al., 2000).

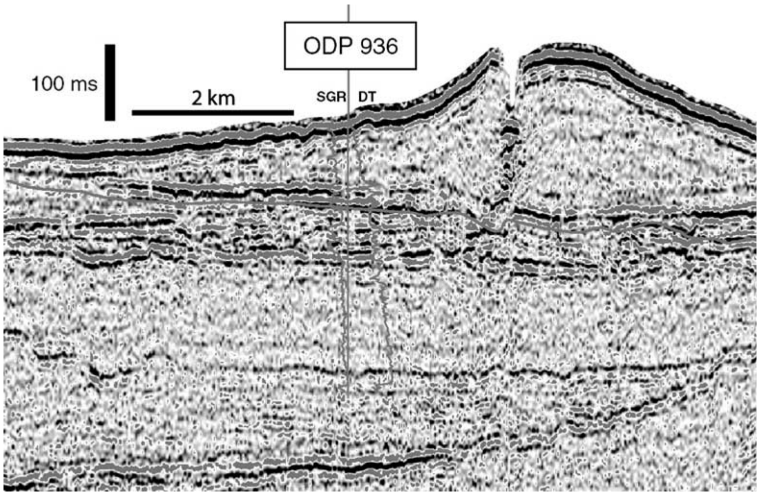

Fig. 7. Seismic section through ODP site 936 illustrating high angle, aggradational nature of the channel (Pirmez et al., 2000).

channel (Stelting, 1985); this progressive narrowing suggests a reduction in discharge with time during fourth-order (circa 100 ka) cycles.

In summary, changes in grain-size mix, flow size and gradient may all be associated with aggradation in channel systems. It appears that flows associated with aggradational channel-levee systems may become both smaller and muddier with time, illustrating the point that the three principal controls (i.e. grain-size, flow size and flow density) can operate independently of one another.

4.2. Time-scales of change

On short time-scales, flow properties are probably not consistent from one flow to the next, and it is likely that the magnitude of flows (and perhaps other properties also, such as density) follows some exponential or power-law distribution (Rothman, Grotzinger, & Flemings, 1994; Winkler & Gawenda, 1999). Although the 'average' flow may determine the long-term evolution of the system, it is likely that, as with rivers, the occasional very large flows have the greatest effect on architecture. In turbidite systems, out-size flows are likely to be responsible for abrupt shifts in channel position and the creation of erosion surfaces in channel systems that in the longer term are graded (neutral) or aggradational (Kolla et al., 2001; Camacho et al., 2002; Beauboeuf, 2003).

The development of many slope channel systems on a longer time scale involves the generation of a large-scale initial erosional container (canyon) that is subsequently

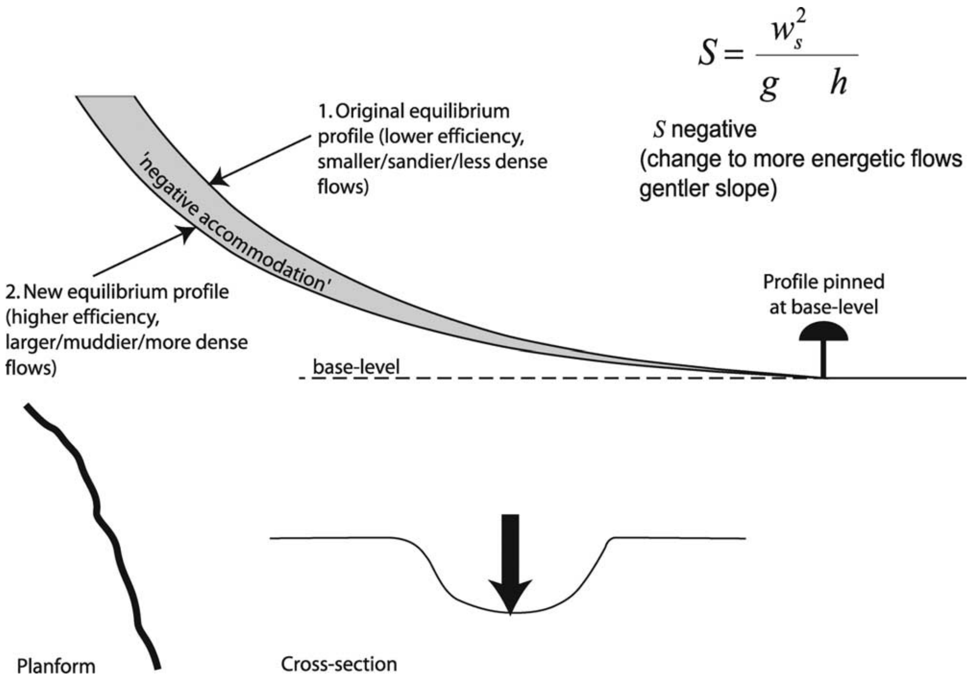

Fig. 8. Schematic illustration of erosional channel with generalized planform and sectional view.

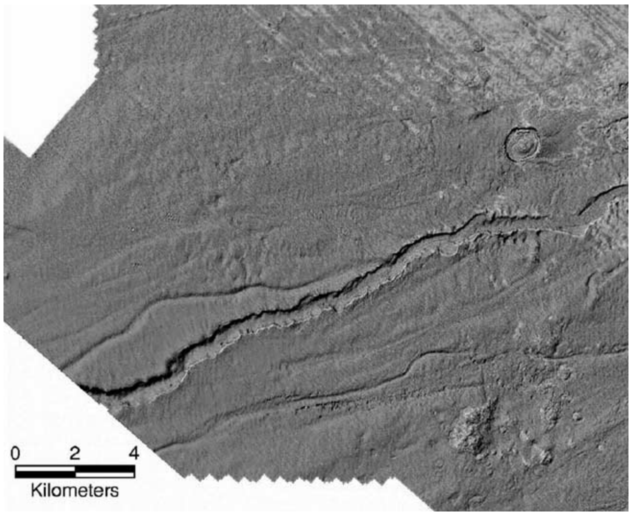

Fig. 9. Erosional channels at the sea floor (rendered bathymetry with seismic amplitude), offshore Trinidad; flow from left to right (Brami et al., 2000).

infilled by a variety of erosional and neutral to aggradational channels, culminating in a leveed channel system that may spill out of the erosional container (Mayall & Stewart, 2000; Samuel et al., 2003; Wonham, Jayr, Mougamba, & Chuilon, 2000). Although the fill sequences within these (presumably third-order) complexes involve complex alternations of channel architectures, the overall trend is from erosional to aggradational, i.e. from more competent flows to less competent flows.

The kinetics of deposition and erosion may preclude the establishment of an equilibrium profile if the properties of the flows down the slope, and the consequent change of the equilibrium profile, are changing more rapidly with time than the depositional and erosional response. In these circumstances the slope profile will lag behind the hypothetical equilibrium. This is perhaps most likely during shut-down of the system (e.g. during sea-level rise) when the sedimentation rate falls as the flow properties are changing rapidly.

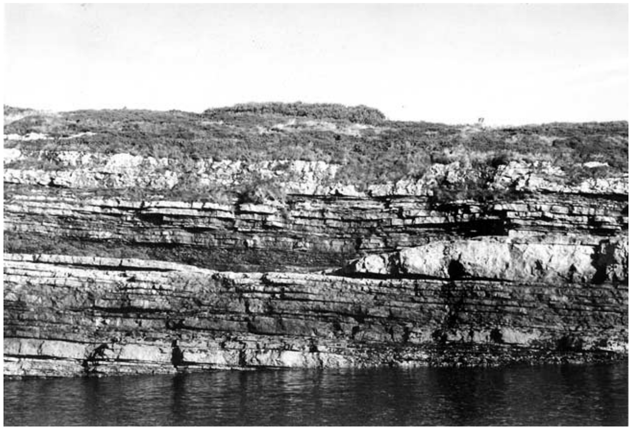

Fig. 10. Erosional channel with muddy fill, Ross Formation (Carboniferous, Western Ireland). Flow roughly perpendicular to cliff. Channel cut about 5 m deep.

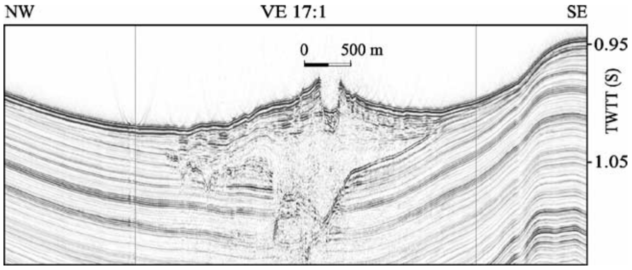

Fig. 11. Aggradational leveed channel built during late Pleistocene sea level rise over site of former erosional channel (partially plugged with mass transport deposits). Trinity Brazos system, upper slope, western Gulf of Mexico.

5. Conclusions

Many systems, perhaps most, are constantly in a state of dynamic adjustment as long as turbidity currents are being supplied to the system. Graded channels may approximate to a steady state on the time-scale of multiple flows, but both aggradational and erosional channels evolve in response to changes in flow size, density and/or grain-size. Indeed, in the absence of change in external factors such as base level, the very existence of erosional or aggradational channels depends upon temporal change in flow properties. An understanding of the factors controlling changes in the properties of the flows is, at best, sketchy. Nonetheless, it is self-evident that both sea-level change and more direct climate parameters such as rainfall are likely to have an impact. General sequence stratigraphic models for deep-water systems (Richards, Bowman, & Reading, 1998) suggest that sea level can have a major impact on total sediment volume delivered to the deep water, and also on the ratio of sand to mud. The generation of large flows in the deep water depends on sediment availability, both in shelf edge systems and on the transport pathway (introduced into canyons by smaller turbidity currents, longshore drift, etc.). Sediment availability depends not only on proximity of the shoreline to the shelf-edge, but also on the sediment flux to (and through) the shoreline, which is directly controlled by total precipitation and the magnitude frequency distribution of floods (which also governs the direct generation of turbidity currents via hyperpycnal flow; Mulder & Syvitski, 1995).

It appears that in many systems during sea-level rise the diminution in flow size and perhaps flow density (consequent on the retreat of shelf-edge deltas and the generation of smaller failures) outweighs the effect of reduction in maximum grain-size available to the deep-water system as sand becomes sequestrated on the shelf. However, these effects are bound to be complicated by local factors, such as the existence of mixed systems involving both failure-generated and flood-generated flows (Mutti et al., 2003; Normark et al., 1998), and the overprint of earthquake repeat intervals on flow magnitudes in tectonically active settings.

Gravity-driven deformation of the slope, mud and salt diapirism, regional tectonics and the establishment of local base-levels due to ponding and avulsion (Pirmez et al., 2000) all add to the likelihood that the channel slope profile will not achieve equilibrium determined solely by flow parameters. Nonetheless, understanding the impact of flow parameters on submarine channel systems may take us a little closer to unraveling their undoubted architectural complexity.

Acknowledgements

I gratefully acknowledge constructive reviews by George Postma and Thierry Mulder, and many stimulating discussions with Bill McCaffrey, Mason Dykstra and Laura Faulkenberry. I would like to thank Emiliano Mutti for his invitation to participate in the meeting at which this paper was given, and to Gary Steffens for his patient efforts to coax this manuscript along.

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*, this issue (doi: 10.1016/j.marpetgeo.2003.08.003).

Badalini, G., Kneller, B., & Winker, C. (2000). Architecture and processes in the Late Pleistocene Brazos-Trinity turbidite system, Gulf of Mexico continental slope. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 16–33). Houston: GCSSEPM Foundation.

Barton, M. D. (1997). Basin floor fan and channel-levee complexes, Permian Bell Canyon formation. *American Association of Petroleum Geologists 1997 Annual Convention, Tulsa*, *9*.

Beauboeuf, R. T. (2003). Deep-water leveed channel complexes of the Cerro Toro formation, Upper Cretaceous, Southern Chile. *Marine and Petroleum Geology*, in press.

Beauboeuf, R. T., & Friedman, J. (2000). High resolution seismic/sequence stratigraphic framework for the evolution of Pleistocene intra-slope basins, Western Gulf of Mexico: depositional models and reservoir analogs. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 40–60). Houston: GCSSEPM Foundation.

Brami, T. R., Pirmez, C., Heeralal, C. A. S., & Holman, K. L. (2000). Late pleistocene deep-water stratigraphy and depositional processes, offshore Trinidad and Tobago. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 104–115). Houston: GCSSEPM Foundation.

Camacho, H., Busby, C. J., & Kneller, B. C. (2002). A new depositional model for the classical turbidite locality at San Clemente State Beach, California. *American Association of Petroleum Geologists Bulletin*, *86*, 1543–1560.

Clifton, H. E (1984) Sedimentation units in stratified resedimented conglomerates Palaeocene submarine canyon fill, Point Lobos, California, In *Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists*, Memoirs 10 (pp. 429–441).

Cronin, B. T., & Kidd, R. B. (1998). Heterogeneity and lithotype distribution in ancient deep-sea canyons; Point Lobos deep-sea canyon as a reservoir analogue. In D. A. V. Stow, & J. C. Faugeres (Eds.), *Contourites, turbidites and process interaction* (*Vol. 115*) (pp. 315–349). *Sedimentary geology*, Amsterdam/Netherlands: Elsevier.

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*, this issue (doi:10.1016/j.marpetgeo.2003.01.004).

Elliott, T. (2000). Depositional architecture of a sand-rich, channelized turbidite system: the upper carboniferous ross formation, Western Ireland. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 342–373). Houston: GCSSEPM Foundation.

Emery, D., & Myers, K. (Eds.), (1996). *Sequence stratigraphy*, Oxford: Blackwell Science 297 pp.

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 the Permian Brushy Canyon outcrops, West Texas. *Marine and Petroleum Geology*, this issue (doi:10.1016/j.marpetgeo.2003.07.004).

Hackbarth, C. J., & Shew, R. D. (1994). Morphology and straigraphy of a Mid-Pleistocene turbidite leveed channel from seismic, core, and log data. In A. Bouma, P. Weimer, & B. Perkins (Eds.), *Submarine fan and turbidite systems* (pp. 127–133). Houston: GCSSEPM Foundation.

Hughes Clarke, J. E., Shor, A. N., Piper, D. J. W., & Mayer, L. A. (1990). Large-scale current-induced erosion and deposition in the path of the 1929 Grand Banks turbidity current. *Sedimentology*, *37*, 613–629.

Kneller, B. C., Bennett, S. J., & McCaffrey, W. D. (1999). Velocity structure, turbulence and fluid stresses in experimental gravity currents. *Journal of Geophysical Research, Oceans*, *104*, 5281–5291.

Kolla, V., Bourges, P., Urruty, J. M., & Safa, P. (2001). Evolution of deep-water Tertiary sinuous channels offshore Angola (West Africa) and implications for reservoir architecture. *American Association of Petroleum Geologists Bulletin*, *85*, 1373–1405.

Mayall, M., & Stewart, I. (2000). The architecture of turbidite slope channels. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 578–586). Houston: GCSSEPM Foundation.

Middleton, G. V., & Southard, J. B. (1984). Mechanics of sediment movement. *Society of Economic Palaeontologists and Mineralogists Short Course No. 3*, 401 pp.

Morris, W. R., & Busby-Spera, C. J. (1988). Sedimentologic evolution of a submarine canyon in a forearc basin, Upper Cretaceous Rosario formation, San Carlos, Mexico. *American Association of Petroleum Geologists Bulletin*, *72*, 717–737.

Morris, W., & Busby-Spera, C. J. (1990). A submarine-fan valley-levee complex in the Upper Cretaceous Rosario Formation; implication for turbidite facies models. *Geological Society of America Bulletin*, *102*, 900–914.

Morris, W. R., & Normark, W. R. (2000). Sedimentologic and geometric criteria for comparing modern and ancient sandy turbidite elements. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 606–628). Houston: GCSSEPM Foundation.

Mulder, T., & Syvitski, J. P. M. (1995). Modelling of erosion and deposition by sediment gravity flows generated at river mouths. *Journal of Sedimentary Research*, *68*, 124–137.

Mutti, E. (1985). Turbidite systems and their relations to depositional sequences. In G. G. Zuffa (Ed.), *Provenance of arenites* (pp. 65–93). Dordrecht/Boston: Reidel.

Mutti, E., & Normark, W. R. (1987). Comparing examples of modern and ancient turbidite systems; problems and concepts. In J. K. Leggett, & G. G. Zuffa (Eds.), *Marine clastic sedimentology; concepts and case studies* (pp. 1–38). London: Graham and Trotman.

Mutti, E., Tinterri, R., Benevelli, G., di Biase, D., Fav, L., Mavilla, N., Cavanna, G., & Cotti, A. (2003). Deltaic, mixed and turbidite sedimentation of ancient foreland basins. *Marine and Petroleum Geology*, this issue (doi:10.1016/j.marpetgeo.2003.09.001).

Necker, F., Härtel, C., Kleiser, L., & Meiburg, E. (2002). High-resolution simulations of particle driven gravity currents. *International Journal of Multiphase Flow*, *28*, 279–300.

Normark, W. R., Damuth, D. E., & Wickens, H. D. (1997). Sedimentary facies and associated depositional elements of the Amazon Fan. *Proceedings of the Ocean Drilling Program, Scientific Results*, *155*, 611–651.

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.

Peakall, J., Kneller, B. & McCaffrey, B (1999). A classic submarine canyon analogue revisited; high-resolution architecture of the La Jolla Group, San Diego. In *American Association of Petroleum Geologists International Conference and Exhibition (Birmingham), abstracts, 83* (p. 1332).

Peakall, J., McCaffrey, W. D., Kneller, B. C., Stelting, C. E., McHargue, T. R., & Schweller, W. J. (2000). A process model for the evolution of submarine fan channels; implications for sedimentary architecture. In A. Bouma, & C. Stone (Eds.), *Fine-grained turbidite systems* (pp. 73–87). *American Association of Petroleum Geologists Memoir 72*.

Pirmez, C., Beauboeuf, R. T., Friedmann, S. J., & Mohrig, D. C. (2000). Equilibrium profile and baselevel in submarine channels: examples from Late Pleistocene systems and implications for the architecture of deepwater reservoirs. In P. Weimer, R. M. Slatt, J. Coleman, N. C. Rosen, H. Nelson, A. H. Bouma, M. J. Styzen, & D. T. Lawrence (Eds.), *Deep water reservoirs of the world* (pp. 782–805). Houston: GCSSEPM Foundation.

Prather, B. E., Booth, J. E., Steffens, G. S., & Craig, P. A. (1998). Classification, lithologic calibration, and stratigraphic succession of seismic facies of intraslope basins, deep-water gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, *82*, 701–728.

Prins, M. A., & Postma, G. (2000). Effects of climate, sea level, and tectonics unraveled for last deglaciation turbidite records of the Arabian Sea. *Geology*, *28*, 375–378.

Richards, M., Bowman, M., & Reading, H. (1998). Submarine-fan systems; I. Characterization and stratigraphic prediction. *Marine and Petroleum Geology*, *15*, 689–717.

Rothman, D. H., Grotzinger, J. P., & Flemings, P. (1994). Scaling in turbidite deposition. *Journal of Sedimentary Research Section A—Sedimentary Petrology and Processes*, *64*, 59–67.

Samuel, A., Kneller, B., Raslan, S., Sharp, A., & Parsons, C. (2003). Prolific deep marine slope channels of the Nile Delta, Egypt. *American Association of Petroleum Geologists Bulletin 87*, 541–560.

Savoye, B., Piper, D. J. W., & Droz, L. (1993). Pliopleistocene evolution of the Var deep-sea fan off the French Riviera. *Marine and Petroleum Geology*, *10*, 550–571.

Stelting, C. E. (1985). Migratory characteristics of a mid-fan meander belt, Mississippi Fan. In A. H. Bouma, W. R. Normark, & N. E. Barnes (Eds.), *Submarine fans and related turbidite sequences* (pp. 283–290). New York: Springer.

Winker, C. D. (1996). High-resolution seismic stratiraphy of a Late Pleistocene submarine fan ponded by salt-withdrawal minibasins on the Gulf of Mexico continental slope. *Proceedings of the 28th Annual Offshore Technology Conference, Dallas, Offshore Technology Conference*, 619–628.

Winkler, W., & Gawenda, P. (1999). Distinguishing climatic and tectonic forcing of turbidite sedimentation, and the bearing on turbidite bed scaling; Palaeocene–Eocene of northern Spain. *Journal of the Geological Society, London*, *156*, 791–800.

Wonham, J. P., Jayr, S., Mougamba, R., & Chuilon, P. (2000). 3D sedimentary evolution of a canyon fill (lower Miocene-age) from the Mandorove Formation, offshore Gabon. In D. A. V. Stow, & M. Mayall (Eds.), (*Vol. 17*) (pp. 175–197). *Deep-water sedimentary systems; new models for the 21st century*, Oxford: Pergamon.