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Autogenic cyclicity of foreset sorting in experimental Gilbert-type deltas

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Abstract

Gilbert-type deltas are commonly characterised by steep foreset bedding. Changes in the foreset characteristics such as grain size, grading, alternating sand and gravel are often interpreted as records of changes of base level or sediment input due to diurnal, seasonal or climatic forcing. To aid such interpretations, an important question is to what extent cyclicity in the foreset characteristics can be explained by autogenic processes rather than exogenic forcing. Experimental deltas were generated with gravelly sand under constant boundary conditions and a varying width–depth ratio of the feeder system. The foresets of the narrow feeder system are regular and show gradual upward fining. The foresets of the wide feeder system, in contrast, show quasi-cyclic patterns of coarsening and fining during the delta progradation. The cyclicity is caused by the emergence of a channelised point feeder system with migrating gravel side bars, which distributes the sand and gravel laterally in a non-uniform manner. This spectacular change of foreset architecture is fully explained by the autogenic response of the feeder system to the width. These experiments are contrasted with experiments and data from literature in the framework of the delta classification of Postma [Postma, G., 1990. Depositional architecture and facies of river and fan deltas: a synthesis. In: Colella, A. and Prior, D.B. (eds), 1990. Coarse-grained Deltas. Spec. Publ. 10 of the Int. Ass. of Sedimentologists, Blackwell Scientific, Oxford, UK, 13–28].

Keywords: Gilbert-type deltas; Fining-upward grading; Cyclicity

1. Introduction

Gilbert-type deltas emerge where rivers debouch into relatively deep basins and the sediment load of the river is dropped at the zone of flow expansion. A basin is defined as relatively deep when the settling path of the sediment transported to the basin margin is much shorter than the delta foreset. The settling path is very short for bedload, longer for suspended load and much longer for hyperpycnal plumes. For the hyperpycnal case a Gilbert-type delta can only form when the delta slope (and basin depth) is much larger than that in the bedload case. Settling and deposition of the feed sediment at the delta front then leads to oversteepening, which initiates the gravitational downslope transport processes such as grain flows that freeze at a high-angle to create the characteristic foresets (Jopling, 1965; Nemec, 1990; Kleinhans, 2005).

The size and location of the deltas provide a record of base level, water and sediment supply as a proxy to past climate conditions on Earth (e.g., Bowman, 1990;

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Mastalerz, 1990; Horton and Schmitt, 1996) and also on Mars (Kleinhans, in press; Hauber, 2005). Moreover, variations in the internal architecture of these deltas may provide a record of synsedimentary tectonic activity at the basin margin as well as changes in the basin water level and sediment supply (e.g., Colella and Prior, 1990; Postma, 1995; Benvenuti, 2003; Lønne and Nemec, 2004) and even cycles of seasonal and diurnal sediment supply (e.g., Mastalerz, 1990). To interpret this record, detailed knowledge of the formative processes is a prerequisite. More specifically, insight is needed as to which cyclic features in the foresets may be created by autogenic variations of fluvial processes on the emergent part of the delta and gravitational processes on the submerged part.

Much work on formational processes of deltas has already been done (e.g., Jopling, 1965; Colella and Prior, 1990; Sohn et al., 1997; Rojas and Le Roux, 2005). Ferentinos et al. (1988) found different depositional styles as a result of the type of feeder system (line or point feeding), which was later incorporated in the delta classification of Postma (1990). The aim of this paper is to demonstrate the complexity in stratification introduced by widening of the feeder and delta from an artificial, narrow two-dimensional Gilbert delta to a wider, more three-dimensional Gilbert delta. The approach is experimental in order to have well-constrained boundary conditions. In particular, the experiments will demonstrate that an unconfined-flow feeder system ('line feeder') generates straightforward fining-upward grading in the foresets, whereas a channelised-flow feeder system ('point feeder') generates autogenic quasi-cyclic variations. These experiments will be compared to other experiments and field data from literature representing different deltas in Postma's classification.

2. Methods and materials

The basic experimental data are presented in Table 1. The experiments were carried out in a flume at St. Anthony Falls Laboratory, which had a length of 7 m and a depth of 0.38 m. For wide "D" experiments the width (W) was 0.158 m and for the narrow "N" experiment the width was 0.075 m. The experiments were designed to have very large ratios of basin to fluvial water depth and dominant bedload. The experimental setup is the same as in Kleinhans (2005) except that the flume was wider. (The extensive experimental N-series are discussed in Kleinhans (2005); herein only N1 in the narrow flow is discussed for comparison with the new D experiments.) Water depth in the basin (h_0) was kept constant with a downstream weir between 0.08 and 0.3 m deep. Water discharge (Q, $q=Q/W$) was fed from a constant-head tank into the upstream end of the flume. The sediment (q_b) was fed from a sediment feeder providing a continuous inflow of dry, well-mixed sediment into the water at the upstream end of the flume. The river system on the delta developed to its own equilibrium slope (S) and water depth (h_1) for the given discharge and sediment load. Water depth (h_1) was measured through the glass wall and in the middle of the flume, whereas the bed slope and the top of the foresets were determined at the end of each experiment from bed level measurement at every 0.1 m along the delta through both sidewalls. The accuracy of water depth is ± 1 mm ($\pm 10\%$). The input sediment was unimodal with an approximately logarithmical distribution with percentiles of $D_{10}=0.29$, $D_{16}=0.36$, $D_{50}=1.20$, $D_{65}=2.13$, $D_{84}=3.79$ and $D_{90}=4.91$ mm, and with a geometric mean grain size $D_m=1.18$ mm and the geometric standard deviation $\sigma=2.85$ mm. The gravel fraction (>2mm) was 37%.

At a few positions along the delta, the bed was sampled vertically for grain size analysis by dry sieving in horizontal layers of 1.5–2 cm thickness over a length of 0.15–0.20 m. The toeset (over a length of 0.2 m immediately downstream of the delta slipface) and the topset were sampled separately. The

Table 1
Basic experimental data

#	h_0 (m)	W (m)	q (m^2/s)	h_1 (m)	S (–)	C (cm/min)	q_b (m^2/s)	α (°)
D1	0.203	0.158	3.1e − 04	0.010	0.056	1.67	6.2e − 05	31–41
D2	0.080	0.158	3.1e − 04	0.008	0.057	3.75	5.0e − 05	33–45
D3	0.083	0.158	4.6e − 04	0.010	0.061	7.69	1.4e − 04	32–48
D4	0.085	0.158	6.1e − 04	0.010	0.066	12.86	2.4e − 04	32–43
D5	0.281	0.158	6.7e − 04	0.012	0.071	7.50	5.7e − 04	
N1	0.200	0.075	3.1e − 04	0.008	0.063	7.92	3.9e − 04	31–38

The flume was 0.158 m wide for the D experiments and 0.075 for the N experiments. The water temperature was 10 ± 1 °C in all experiments. Symbols are explained in the text.

D_m and σ are used herein to compare the samples to the feed sediment:

$$D = 2^{\psi_m}$$

$$\psi_m = \sum_{i=1}^{N} \bar{\psi}_i p_i$$

$$\sigma = 2^{\sigma_a}$$

$$\sigma_a^2 = \sum_{i=1}^{N} \left(\bar{\psi}_i - \psi_m\right)^2 p_i$$

in which ψ=arithmetic mean size (related to the sedimentological grain size ϕ as $\psi = -\phi$), ψ_i=class middle (in-between sieve mesh sizes) of a size fraction i, p_i=abundance (probability) in size fraction i, σ=geometric standard deviation, and σ_a=arithmetic standard deviation.

3. Results

The results are shown in photographs (Figs. 1 and 2), the profiles collected after the experiments (Fig. 3) and the vertical sorting data (Fig. 4). In all experiments, a prograding delta developed with steep foresets almost as high as the basin water depth and a thin wedge-shaped fluvial topset. A thin bottomset formed by fine sediment settling from suspension (Fig. 1). The deltas developed with a height slightly less than the water depth in the basin, and maintained an equilibrium alluvial top slope and a migrating downstream slipface at angle α near the angle of repose. Initially sediment accumulated at the base of the empty flume until the pile had built almost up to the water surface. At that point a delta started to build out in downstream direction at a celerity C and the initial disturbance of flow and sediment entry was limited to a stable scour hole 0.05 m long. Since the top slope length of the delta was an order of magnitude larger while the water depth (h_1) was only about 0.01 m, this initial disturbance had no effect on water and sediment delivery to the delta brinkpoint. The volume of the initial disturbed sediment deposit was always confined to the first 0.1–0.15 m along the flume, and was excluded from the samples and photographs.

The fluvial topsets of the N and D experiments differed dramatically: the lateral distribution of sand and gravel was uniform in N1 but strongly non-uniform in the D experiments (Fig. 2a). The narrow delta (N1) developed a fluvial topset of planar stratification at an angle equal to that of the water surface slope of the flow

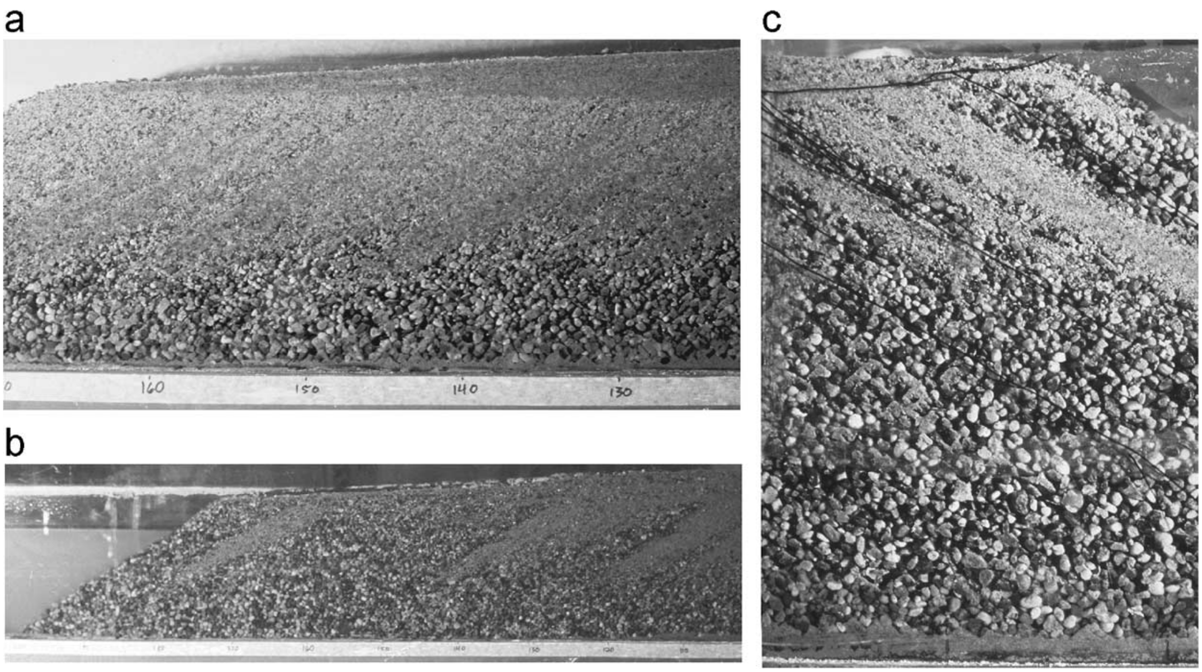

Fig. 1. (a) Side view of delta N1 (flow to the left). From bottom to top the sediment composition gradually changes from gravel to sandy gravel to sand (although the sand preferentially deposits near the glass wall where the pore space between glass and gravel allows it). The alluvial topset (darker, with horizontal base) is gravelly sand. (b) Side view of delta D1 (flow to the left). There are sandy and gravelly foresets related to non-uniform supply on the delta top because of bar migration. The top of the foresets is truncated by the channels in the topset. (c) Side view of delta D5 (flow to the right). There are sandy and gravelly foresets related to non-uniform supply.

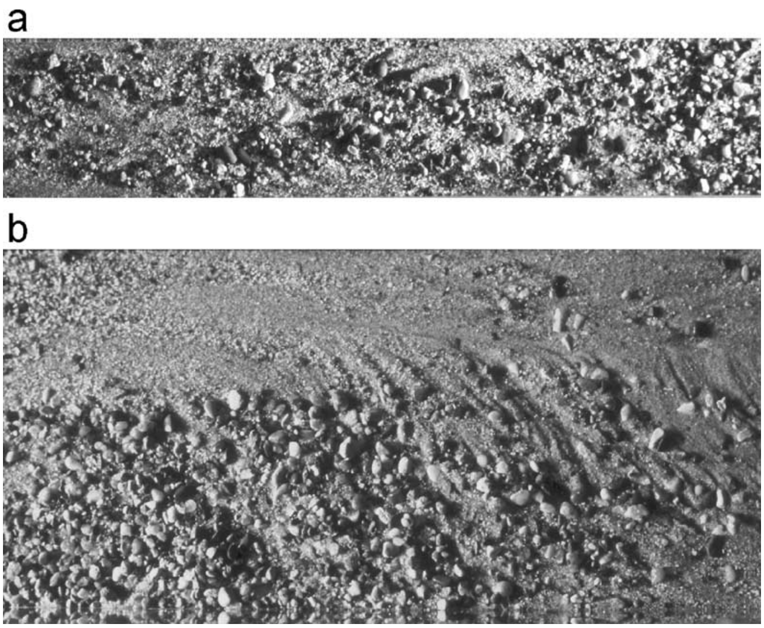

Fig. 2. (a) Top view of delta N1 over the full flume width of 0.075 m (flow to the left). The gravel and sand are uniformly distributed over the width of the flume. The bed surface was covered with pebble clusters or bedload sheets. (b) Top view of delta D1 over the full flume width of 0.158 m (flow to the left). The sand and gravel are separated by side bar formation, where the gravel is deposited in the bar and the sand in the slightly deeper channel.

on top of the delta (Fig. 1a). The topset slope of N1 was constant in all cases except in the most upstream few centimeters where water and sediment entered the flume (Fig. 3). Pebble clusters and sorted bedload sheets were observed on the topset. The topset slopes of the wider D experiments, in contrast, showed an alternating pattern

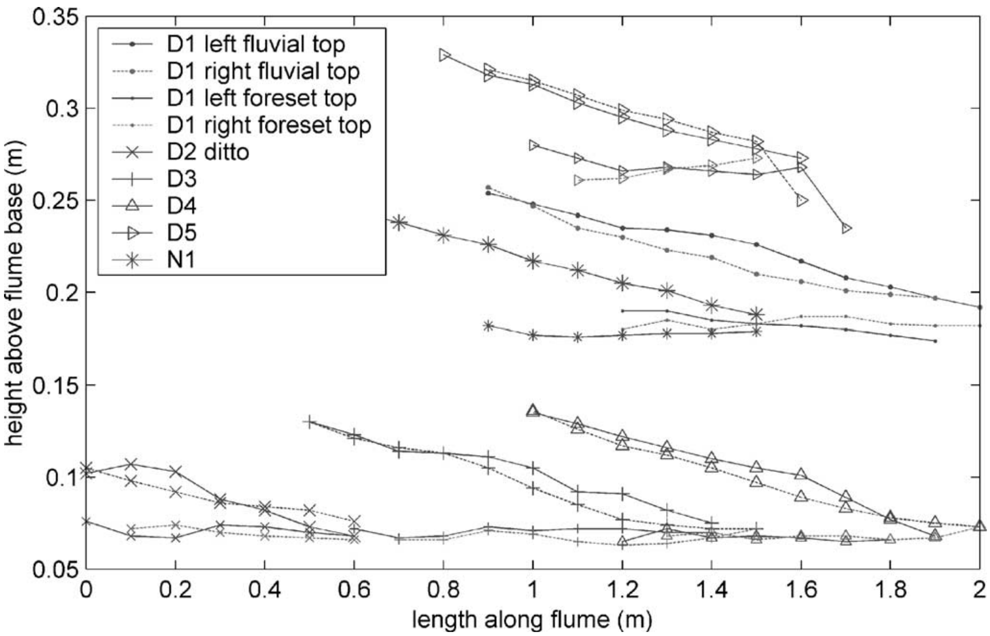

Fig. 3. Alluvial profiles along the delta tops (arbitrary offset along flume, true heights, slipfaces/foresets not shown). Large symbols: topographic profiles along the top of the deltas. Small symbols: height of transition between foresets and topset. For the wide deltas the profiles are given along the left and right side of the deltas, indicating the variability due to the presence of bars.

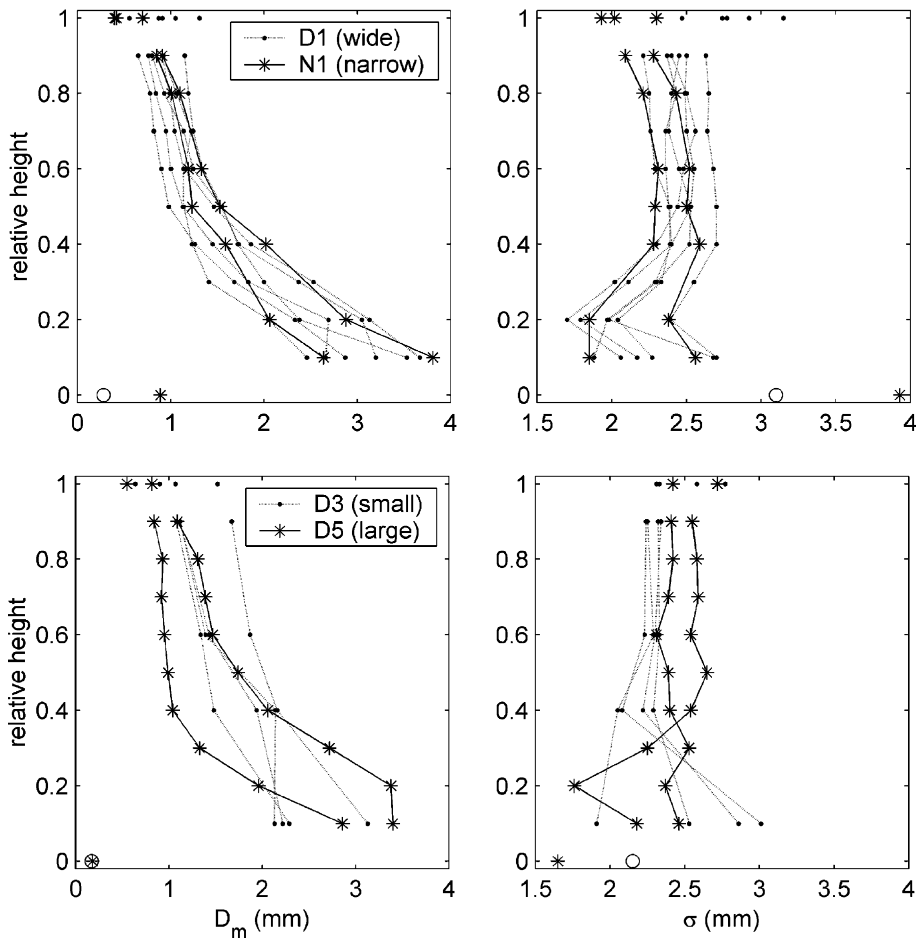

Fig. 4. Sediment sorting data compared for deltas D1 (wide) and N1 (narrow) and for D3 (small) and D5 (large). The sieve samples were collected in the left and right half of various parts of the delta. The left-hand graphs show the vertical profiles of D_g. The right-hand graphs show the vertical profiles of σ. The height of the samples is scaled with delta height at the brinkpoint. At relative height = 1 the topset sample compositions are given, and at height = 0 the bottomset (downstream of the delta) compositions are given. The two lines for N1 represent the sediment at the final basin margin (coarser) and of an earlier stage (finer).

of high gravelly side bars with pebble clusters, and low sandy channels (Fig. 2b). No bedload sheets were observed. As a result, the fluvial topset consisted of cross-bedded and planar bar deposits, in places scoured by the migrating channel a few millimeters deeper. This is also reflected in measured profiles of the foreset top (Fig. 3), which show the same alternating irregularities as the delta top profiles due to the alternating bars. In both narrow and wide deltas, the fluvial topset aggraded during the experiment. On average, the topset of N1 consisted of better-sorted sediment compared to the upper foresets (Fig. 4), whereas the topset of the D deltas was considerably less well sorted.

The foresets were gradually fining-upward in N1 and less gradual with abrupt changes in the D deltas (Fig. 1). As described in detail in Kleinhans (2005), the gradual upward fining in the N1 delta resulted from the regular grain flow process as follows. At the basin margin the flow expands and the sediment transported by the feeder system is deposited at the static angle of repose. This oversteepening of the delta front proceeds until a threshold is exceeded and the oversteepened volume flows down as a grain flow, depositing at the dynamic angle of repose which is a few degrees smaller than the static angle. During the grain flow, kinematic sorting takes place which moves the large grains to the top of the grain flow. Meanwhile, the large grains easily move over the small grains and deposit downslope, whereas the small grains are deposited further up the slope (Kleinhans, 2004, 2005; and references therein).

The sandy foresets in the D deltas were deposited downstream of the sandy channels (Fig. 1 and 2). The delta prograded a few centimeters further at this point until an equilibrium was reached of both downslope and lateral expansion of the grain flow to the less prograded side. These sideways expanding grain flows were laterally non-uniform and did not only sort the sediment along the foreset, but also pushed the large grains to the less prograded delta side (downslope of the gravelly side bar). Some gravel was also transported over the gravel bar (Fig. 2b). As a result of the asymmetric sediment supply, the foreset downslope of the bar was much more gravelly than at the side of the sandy channel. When the channel migrated to the other side of the delta during delta progradation, the pattern was reversed. Overall, a quasi-cyclic alternation of sandy and gravelly foresets was observed at both sides of the wide D deltas (Fig. 1b). Interestingly, the net vertical fining (expressed as D_m) for comparable narrow and wide deltas (D1 and N1, Fig. 4) is fairly similar although the sorting (expressed as σ) is poorer for D1. The similarity is due to the sample size necessary for sieving, which exceeds the length scale of the sand and gravel foresets in the experiments.

The toesets formed by settling of fine sediment that was suspended at the brinkpoint. The finest suspended sediment flowed into the basin as a very dilute turbidity current, with a settling horizon at about half the basin water depth. When this sediment was overrun by the prograding delta, it became a bottomset. The sediment in the toeset generally was finer than the D_{10} of the input sediment and fined downstream, although occasionally coarse gravel from the grain flow was mixed near the delta toe, leading to large mixture standard deviations (Fig. 3). In general the toeset contribution to delta progradation was negligible.

The progradation rate (C) of the deltas was nearly constant because of the constant water and sediment source, but decreased slightly due to the increased sediment storage in the fluvial topset. As the deltas prograded, the slope of the fluvial feeder system decreased a little bit near the basin margin. Consequently, deposition took place in the upstream direction until the equilibrium slope was reached again. Since the distance between the point source of water and sediment was increasing due to the progradation, an increasing volume of sediment was required for the slope adjustment, and the sediment transport rate at the basin margin decreased slightly. In the N1 delta, which preferably deposited sand in the topset, the foreset sediment also gradually coarsened downstream (Fig. 4). The rates of change of these processes obviously depend on the equilibrium slope (and thus topset volume) of the feeder system, the input sediment transport rate and composition and the basin depth and width (and thus delta volume).

4. Discussion

A dramatically different stratification emerged in the experiments for an increase in width of only a factor of two, which was entirely caused by the shift from a line feeder to a point feeder. It is conceivable that this shift would also occur in the case of several point feeders. These results clearly indicate that delta deposits must be interpreted with care by balancing the variations in stratification due to autogenic processes of the feeder system with the variations due to diurnal or seasonal cycles of water and sediment supply, or climate-induced sediment supply changes. These small-scale experiments are relatively simple with constant boundary conditions and rather narrow basins in both the narrow and 'wide' experiments. The experiments are obviously simplified because the width of the delta is equal to that of the feeder system. Nevertheless the essential processes and deposits common in Gilbert-type deltas were duplicated in the experiments despite the differences in scale and basin width. Despite the completely controlled and constant boundary conditions in the laboratory experiments, there is autocyclic grading. It is likely that this result is also valid for some natural deltas in lakes and other basins within certain limits of basin depth.

It is obvious that many processes can generate (quasi-)cyclic sand and gravel deposits, such as wave reworking, tidal action, climatic change in the hinterland and so on (e.g., Colella and Prior, 1990; Horton and Schmitt, 1996; Rojas and Le Roux, 2005). For example, Rojas and Le Roux measured the processes on a small active delta in Chile during calm conditions and storm events. During storms, offshore-directed wave-driven and river-driven currents transported clasts towards the delta front where they avalanched to the foot of the delta. In waning storm these clasts were covered by suspension fall-out from the river, causing a couplet of coarse and fine sediment. Such wave modifying processes may be relevant for basin depths up to 20 m with enough fetch length to generate the waves. However, the point illustrated by the experiments is that the cyclicity is not a unique signal for changes in the (allogenic) boundary conditions but can easily be generated autogenically. Consequently, some of the (quasi-)cyclic deposits interpreted to be the result of allogenic change may need to be reinterpreted as being the result of autogenic processes. Such a reinterpretation would require careful reconsideration of all clues in the data on the origin of topsets and foresets.

The remainder of this discussion is devoted to generalising the different processes to other delta experiments within the framework of the classification of Postma (1990). Two questions are addressed: when the feeder is a line or a point source, and the effect of the sediment transport mode (bedload, suspended load) on the delta architecture. The delta classification is based on the feeder system and the relative water depth of the feeder system compared to the basin depth (Postma, 1990). The feeder system types are A: steep debris or alluvial fans with unstable bedload channels, B: steep bedload-dominated multiple channels (e.g. braid plains) delivering sediment in a laterally uniform rate to the basin margin (line feeder) by continuous avulsion, C: less steep and more stable channelised feeder system with well-defined outlet points (point feeders) and D: low gradient alluvial systems with highly stable channels and dominant suspended sediment transport. The relative depth classes are shallow shoal-water type deltas, Gilbert-type deltas and deep water deltas. The experiments reported here mostly concern the prototype deltas 4, 9 and 11 of Postma (1990, 1995, Fig. 2 in both papers), which are intermediate to deep basin-depth deltas with point or line feeders, ranging from bedload- to suspended load-dominated conditions.

4.1. Line or point source

The first question revolves around whether the feeder is a line source or a point source or series of point sources. The sediment sorting within the channels and on floodplains may cause quasi-cyclic deposition in the foresets as demonstrated in the D experiments. Given a poorly sorted feed sediment, the width–depth ratio W/h_1 of a channel determines the plan form and potential for sorting (Bridge, 2003). Narrow channels ($W/h_1 < 5$–10) commonly have bedforms such as dunes (or small bedload sheets in this case) which are associated with vertical flow turbulence structures and vertical bedload sediment sorting. This is illustrated by the experiments of Jopling (1965) and Termes (1986, also see Kleinhans, 2004) which had similar W/h_1 ratios as the present experiments and had bedforms but no alternating bars. Wide channels ($W/h_1 > 5$–10) commonly have side bars and even mid-channel bars (grading into a braided river plan form) which are associated with horizontal flow turbulence structures and horizontal bedload sediment sorting ('bend sorting'). The transition between narrow and wide is obviously gradual and superposition of dunes on bars is common, but the bars dominate. Since the wide feeder systems develop lateral sediment transport non-uniformities because of the bar formation process and the sorting pattern therein, the wide systems also develop the lateral foreset sediment patterns. Such channel bar sorting has for example been recognised by Nemec and Postma (1993). In the presence of migrating alternating bars these patterns will cause quasi-cyclic foreset patterns as observed in the experiments. In addition, the whole sediment mixture is deposited in coarse and fine patches as observed in the large standard deviations of the topset (Fig. 4) in contrast to the narrow delta which deposited only sand in the topset and bypassed the gravel to the foresets. Even the topset may show some quasi-cyclic stratification due to the migration of the deepest part of the channel.

Bowman (1990) found cyclic fine and coarse gravelly couplets in the topset of a Gilbert structure at Wadi Mor in Israel. Bowman attributed the topset stratification of sand and gravel layers to climatic effects on sediment supply and calibre, but it may thus be an autogenic feeder effect as in the experiments. More detailed characteristics of the topset strata would help to decide between the two hypotheses: if bar deposits or channel fills are found that can be related to the alluvial system on the topset of the delta, then it is conceivable that the sorting was created by migrating bars. If, on the other hand, the cyclic couplets have a different length scale than the channels and bars of the feeder system, then it is conceivable that the boundary conditions of the feeder system really changed (cyclically), which could be indicative of climatic change.

The channel sorting (width–depth) effect probably applies to small deltas fed by a relatively simple system as in the present experiments, but needs modification for large deltas with a very large depth ratio (h_0/h_1), as in the prototype deltas 5 and 6 of Postma's (1990) classification. (Note that Jopling (1965) uses the inverse of this depth ratio.) In that case, the sediment is delivered to the basin margin by an alluvial fan or a braided river plain consisting of many channels. If these channels have a small depth compared to the basin depth, their time scale of avulsion is smaller than the time scale of oversteepened slope failure. Consequently, the sediment is still delivered laterally uniform to the basin margin averaged over a time period that is insufficiently long to produce significant delta progradation with lateral sediment non-uniformity. For example, a braided river plain with rapidly migrating channels (prototype 6) effectively provides a line source of sediment, if the time scale of channel shifting is indeed smaller than the time scale of the gravitational slope processes. However, a meandering river with cohesive and vegetated banks (prototype 9 or 10) provides point sources of sediment, leading to non-uniformity of slope processes on the delta foreset. Quasi-cyclic avulsion of such channels may then lead to quasi-cyclic foreset deposition and sorting in very deep basins. For interpretation of the foreset deposits it is therefore necessary to assess the feeder type on the topset as well.

For example, Horton and Schmitt (1996) studied a 1600 m thick succession of a Miocene lacustrine fan–delta system in Nevada, USA. Within the subaqueous fan–delta facies association the gravity flows were dominant: they found conglomerates created by subaqueous debris flows, interbedded sandstones created by high- and low-density turbidity currents and interbedded mudstones created by suspension fall-out. These different deposits provide alternations of coarse and fine sediment, which, together with small-scale characteristics of the facies, such as dewatering structures and mud cracks, were interpreted as relatively quiet periods between successive gravity flows. Although the lateral continuity of the deposits was up to hundreds of meters, it is not inconceivable for this large system that the coarse sediments originated from channel sediments and the fines from suspended sand mud transported over the floodplains during floods. The subaerial facies association consisted of ungraded and normally graded conglomerates and sandstones, which were only laterally continuous for tens of meters and had channel fills. Although fluvial stream-channels were rare, the subaerial fan was probably dominated by gravity flows. It is not likely that these were spread uniformly over the fan; rather they would have shifted over the fan during the build-up (Parker, 1999). In short, the alternation of fine and coarse sediment might be due to the autogenic shifting of feeders over the delta plain, providing different sediments to the foresets of the delta at different times. This suggests that the low- and high-energy conditions inferred by Horton and Schmitt (1996) might have occurred simultaneously as a spatial sequence rather than a periodic sequence of events.

4.2. Mode of transport

The second question refers to the mode of transport in the feeder system. This is specifically important for shallower basins. In a shallow basin, only bedload transport will lead to a Gilbert-type steep foreset, because suspended sediment settles over a longer path and would therefore create low-sloping foresets of sigmoidal shape (Jopling, 1965; Endo et al., 1996; Sohn et al., 1997). If the relative basin depth is very small then the flow velocity is still large over the toe of the delta (conservation of momentum), and the sediment will be transported downstream for a large distance before it settles out. Consequently, suspended sediment is deposited all over the delta slope as in Jopling's (1965) experiments, or, when the sediment concentration is large enough, a turbidity current commences as in the Kostic and Parker's (2003) experiments. Prototypes 1, 2, 7 and 8 (shallow basins, ranging from bedload to suspended load-dominated streams with stable banks) of the Postma classification must therefore be suspension-dominated, contrary to the typification of 1 and 2 as bedload rivers. If bedload were dominant, prototypes 1 and 2 would still have developed steep foresets even in basins that are only marginally deeper than the feeder channels as demonstrated in many experiments. In the case of a hyperpycnal plume, sediment settles over a large (horizontal) distance. In other words, oversteepening and slope processes leading to steep foresets will only occur if this settling distance is still much smaller than the length of the delta slope. The sediment transport mode and the settling path length can be evaluated with the ratio u/w_s of depth-averaged current velocity u (or, better, shear velocity u^*) and the settling velocity w_s of the sediment (Jopling, 1965). The sorting of the feed sediment provides an additional control: fine sediment suspended above a coarse bedload feed will lead to a mix of stratification, with coarse sediment in the steep foresets grading into fine sediment in sigmoidal sets or toesets.

The effect of the h_0/h_1 ratio is already obvious for the limited range of the present experiments: the fining-upward grading is much clearer in the largest delta D5, where the feeder sediment deposits mostly on the top of the slope, than in the smallest deltas D2, D3 and D4, in which suspended sediment settles over most of the foreset slope (Fig. 4). This continuum between grain flows and turbidity currents may in general correlate well with the continuum between gravel and sand or mud-dominated systems. It is, however, well possible to have grain flow-dominated Gilbert deltas in noncohesive silt if the water and sediment discharge of the feeder system is small and the basin depth is large. In short, it is the sediment mobility and the depth ratio that determine whether a steep Gilbert-type foreset is generated with potentially fining-upward gradation. Again, for the interpretation of foreset deposits it is necessary to investigate the nature of the feeder in the topset as well.

In summary, the present experiments represent deltas with point and line feeders with small and somewhat larger width–depth ratios. Also, the experiments represent large basin-channel depth ratios and small suspension numbers, as both bedload and suspended load sediment of the feeder are deposited mostly on top of the delta foreset. As a result, the steep Gilbert-type foreset slope is developed with the potential for fining-upward gradation. The line feeder, finally, produces a rather regular upward fining, whereas the point feeder produces quasi-cyclic foreset sorting caused by the sorting processes in the feeder channel. Cyclicity in foreset sorting may be caused by seasonal or diurnal cycles in water and sediment supply, but in the case of point feeder channels the cyclicity may well be due to autogenic processes.

5. Conclusions

Simple experiments of fluvial flow and sediment feeding to a basin demonstrated the effect of line feeder systems with small width–depth ratios versus (channelised) point feeder systems with larger width–depth ratios. A uniform distribution over the width of the delta of flow and sediment transport leads to grain flows depositing as laterally uniform fining-upward foresets. When the flow is channelised and side bars emerge, the sediment supply to the basin margin becomes laterally non-uniform. As a result, laterally non-uniform topset and foresets are created. These foresets are still fining-upward but less so than in the uniform case. Viewed in a longitudinal section, the foresets cycle between coarse and fine as a result of the laterally migrating channel outlet. These variations do not represent diurnal, seasonal or climatic change-driven water or sediment supply variations in the source area since the experimental boundary conditions were kept constant.

In addition, even with a constant basin water level the fluvial topset is aggrading, because the fluvial system maintains a constant slope as a result of the constant discharge and sediment input rates. Finally, these and other experiments demonstrate that the delta classification of Postma (1990) based on relative basin depth and line versus point feeders can be refined by incorporating the ratio of flow velocity and sediment settling velocity. For horizontal settling path lengths that are smaller than the delta foreset slope, oversteepening occurs and a Gilbert-type steep foreset may develop with potentially fining-upward grading.

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