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Investigating the autogenic process response to allogenic forcing: experimental geomorphology and stratigraphy

WONSUCK KIM*, ANDREW PETTER†, KYLE STRAUB‡ and DAVID MOHRIG*

**Department of Geological Sciences, Jackson School of Geosciences, University of Texas at Austin, Austin, 78712 TX, USA (E-mail: delta@jsg.utexas.edu)*

†St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN 55414, USA

‡Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA 70118, USA

ABSTRACT

Decoupling the preserved signal of environmental (allogenic) forcing from those of internally generated (autogenic) processes is at the centre of understanding the evolution of the Earth's surface preserved in the sedimentary record. A major stumbling block for distinguishing between allogenic versus autogenic signatures in the stratigraphic record is the lack of quantitative understanding of autogenic processes and their interactions with allogenic forcing. Physical experiments with moving sediment and water construct topography through dynamic self-organised fluvial systems, thus providing an opportunity to investigate autogenic processes under controlled boundary conditions (e.g. sediment supply and tectonics). This paper presents a set of tank experiments that are used to examine quantitatively 1) the autocyclic storage and release of sediment in the delta top surface associated with river-pattern changes between channel and sheet flow and 2) changes in fluvial autocyclic behaviour driven by external forcing (e.g. sea-level change and tectonics). The time and event scales of the autogenic processes observed in the experiments conducted without external forcing have provided the first-order quantitative understanding of the autogenic processes. Changes in the frequency of autogenic processes through base-level changes and lateral ground tilting have provided a new view into the coupled allogenic and autogenic controls on stratigraphic development. Coupled experiments that test the effects of allogenic forcing on autogenic process are presented here: one experiment was conducted with constant external forcing and the other was conducted with cyclic changes in external controls. This review provides 1) quantitative measurements of fluvial autogenic processes and thorough comparisons of cyclic strata attributed to allogenic versus autogenic controls and 2) suggestions for future experimental studies of fluvial autogenic processes that will enhance our ability to interpret the mixed signals of environmental variation and internal dynamics in the sedimentary record.

Keywords: Autogenic process, stratigraphy, experiment, geomorphology, shoreline.

INTRODUCTION

Sedimentary deposits in basins are sensitive indicators of environmental variations, e.g. global sea-level change, river floods, coastal storms and earthquakes. These environmental conditions exert a crucial influence on the shape of Earth's surface which, in turn, influences the development of subsurface architecture (stratigraphy). Decoupling the products of environmental (allogenic) forcing from the internally generated (autogenic) 'noise' written in the sedimentary record remains as a fundamental goal of sedimentary geosciences. Classically allogenic deposits have been recognised by their cyclic nature. Their cyclicity is interpreted as the signature of periodic changes in climate, base-level, sediment supply, and/or tectonics. On the other hand, it has also been generally accepted that nonlinearity in sediment transport (e.g. delta lobe switching, channel avulsion) results in random or scale-free (fractal) deposits, i.e. autogenic-driven deposits (Jerolmack & Paola, 2007; Jerolmack &

From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin, First Edition.
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Paola 2010; Jerolmack & Swenson, 2007; Kim & Jerolmack, 2008).

Even with current advanced technology for imaging the subsurface in high-resolution and more than a half-century of research aimed at developing techniques to disentangle autogenic noise from allogenic signals in stratigraphic data, accurate reconstruction of allogenic variations preserved in the stratigraphic record remains challenging. An important foundation for many steps to overcome this challenge is actually quantitatively understanding the 'noise' of autogenic processes (Jerolmack, 2011). This includes the understanding of 1) the autogenic processes and their stratigraphic products and 2) complicated reactions of the autogenic processes to basinal forcing and the effects of these interactions on stratigraphic products. A fundamental understanding of autogenic processes and their stratigraphic products that are isolated from external controls should be achieved first and then changes in autogenic processes due to external controls imposed on the system should be investigated systematically. These steps will facilitate the decoupling of stratigraphic signatures into allogenic and autogenic components in basin interpretations. Field studies always deal with geological data that record multiple environmental controls and must deduce palaeo-environmental changes from a complicated mixture. This traditional method of interpreting basin history will be significantly improved by the quantitative understanding of individual causes (external basin controls) and effects (stratigraphic products composed of autogenic and allogenic signatures) under controlled conditions through physical tank experiments.

This paper presents a review of the previous experimental studies. Firstly, fluvial autogenic processes isolated from the effect of basin forcing (i.e. no sea-level change or tectonic activities) are introduced. Then, a set of tank experiments that were conducted with changes in basin forcing is reviewed. This paper also presents two experiments that both show similar cyclic sedimentation; although one is caused by autogenic fluvial cycles under a steady tectonic forcing and the other is caused by cyclic tectonic variations. Finally, suggestions for potential studies using physical and mathematical experiments, to enhance the current results and understanding of the autogenic processes, are discussed.

QUANTIFYING FLUVIAL AUTOGENIC PROCESSES

Recent experimental studies with sediment and water (Fig. 1) clearly demonstrate self-organisation due to internally driven sediment transport processes (e.g. Ashworth *et al.*, 2004; Bryant *et al.*, 1995; Cazanacli *et al.*, 2002; Heller *et al.*, 2001; Hickson *et al.*, 2005; Jerolmack & Mohrig, 2005; Kim & Jerolmack, 2008; Kim & Muto, 2007; Kim & Paola, 2007; Kim *et al.*, 2006a; Muto & Steel, 2001; Paola, 2000; Paola *et al.*, 2001; Paola *et al.*, 2009) and suggest an opportunity to investigate quantitatively the morphodynamic and stratigraphic representations of autogenic processes. The current advancement in experimental technology allows for better control in boundary conditions; and therefore a simpler mixture of autogenic processes with environmental variations for investigation. This section details previous experimental studies that focus on autogenic processes under either no or minimal external controls (i.e. base-level change and tectonic variation).

Fluvial autogenic sediment storage and release

Recent publications in tank experiments have observed strong landward-to-seaward fluctuations in shoreline position from an overall progradational experimental delta under both constant

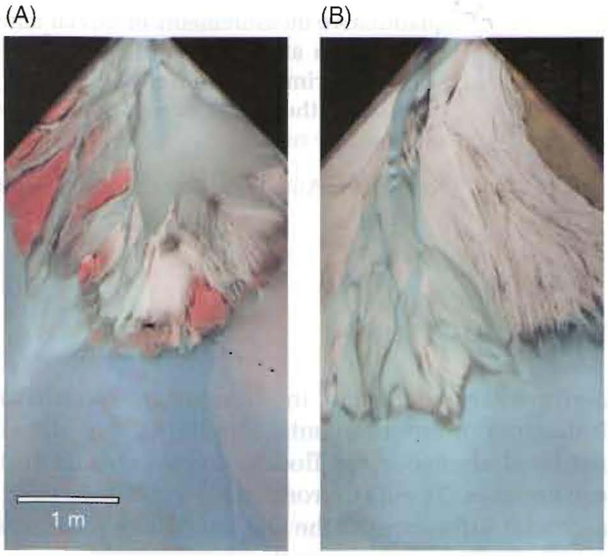

Fig. 1. Experimental fluvial surface taken during XES 02 showing (A) a sheet-flow dominated sediment storage event and (B) strong channelisation with a release event.

sediment supply (Q_s) and water discharge (Q_w) with either no or slight relative sea-level changes (e.g. Kim & Jerolmack, 2008; Van Dijk *et al.*, 2009). These shoreline fluctuations were caused by autocyclic fluvial sediment storage and release associated with changes in the fluvial planform pattern between channelised flow and sheet flow (Fig. 1). Sheet flow covers most of the delta top surface and forces strong aggradation of the fluvial system as hardly any sediment gets delivered to the shoreline. Channelisation is initiated by focusing flow in a narrow corridor on the delta top. As a result, transport capacity increases due to increase in both channel depth and flow velocity. Supplied sediment, as well as eroded sediment from the channel bed, is transported to the shoreline, thus producing a strong pulse of shoreline regression. Quantitative measurements of 1) the time frequency of the autogenic process and 2) magnitude of the autogenic shoreline fluctuation (i.e. shoreline signature of the fluvial autogenic process) have been reported (e.g. Kim & Jerolmack, 2008; Van Dijk *et al.*, 2009).

Autogenic shoreline fluctuation

Two sets of experimental data are presented in the current analysis. One set is from the eXperimental EarthScape (henceforth XES) facility at St. Anthony Falls Laboratory, University of Minnesota and the other is from the Eurotank Flume facility at Utrecht University. The individual results have been published (Kim & Jerolmack, 2008; Van Dijk *et al.*, 2009), so only a brief summary is given below.

Kim & Jerolmack (2008) used data from two experiments in XES. The XES basin is 6 m long, 3 m wide and 1.5 m deep. A detailed description of the XES facility can be found in Paola *et al.* (2001). The experiment conducted in 2002 (XES 02) had roughly five times greater sediment discharge than the second experiment conducted in 2005 (XES 05). However, both experiments had roughly the same sediment to water supply ratio (Q_s/Q_w) at 0.01 in volume influx. Both experiments used a sediment mixture with roughly 70% quartz sand (D = 110 μm) and 30% coal sand (bimodal D = 460 and 190 μm). The coal sediment is much less dense than the quartz sediment and thus works as a proxy for fine material. Sediment supply and water discharge were kept constant during the experiments. Data used for the analysis were taken from the initial stages of the two experiments (10 to 18 hours of experimental run time in XES 02 and 80 to 100 hours in XES 05), during which the shorelines in both experiments prograded 20 to 40 cm basinward (Fig. 2). The overall lengths of both deltas were around 3 m but XES 02 had a ~ 10 cm water depth and XES 05 had ~ 0.5 cm water depth in front of the deltas.

Autogenic sediment storage and release events in the fluvial surface were observed twice during the period that data were collected. During the sediment storage events on the fluvial surface associated with sheet/widespread flows, the shoreline migration was reduced to a rate below the long-term averaged progradation rate. However, the shoreline rapidly advanced during release events by strong channelisation. When the surface is degraded and the shoreline progrades basinward enough to decrease the topographic slope, a new storage process is reinitiated. Autogenic processes in XES 02 showed the shoreline migration with high frequency and high magnitude fluctuations (even with a deeper water depth at the delta front) in comparison to the XES 05, which showed low frequency and low magnitude shoreline fluctuations (Fig. 2).

Three experiments conducted in the Eurotank Flume facility at Utrecht University also exhibited autocyclic incisions by channelised flow that were then progressively backfilled by sediments in the incised channels (Van Dijk *et al.*, 2009). Two of the three experiments were conducted side by side with the same Q_s but different Q_w values. As a result, the sediment to water discharge ratio in these two experiments varied between 0.002 (A004-1) and 0.003 (A004-2). For these experiments the sediment mixture was composed of grains with D = ~200 to 250 μm and the deltas were built in a basin with a total size of 2.7 m × 2.7 m. The decrease of Q_w in A004-2 resulted in higher topographic slopes than in the A004-1 experiment, which reduced overall progradation of the shoreline in A004-2. Roughly, A004-1 had a range of delta-top slopes between 0.02 and 0.06 but A004-2 had a range between 0.04 and 0.07. The high Q_w experiment shows more distinct shoreline regression periods (total shoreline distance travelled during each release event is longer) than those periods shown in the low Q_w experiment (See Fig. 7 in van Dijk *et al.* (2009)), which would be caused by more channelised incisions.

Reitz *et al.* (2010) reported a smaller-scale tank experiment (3 m length × 1 m width × 1 m depth)

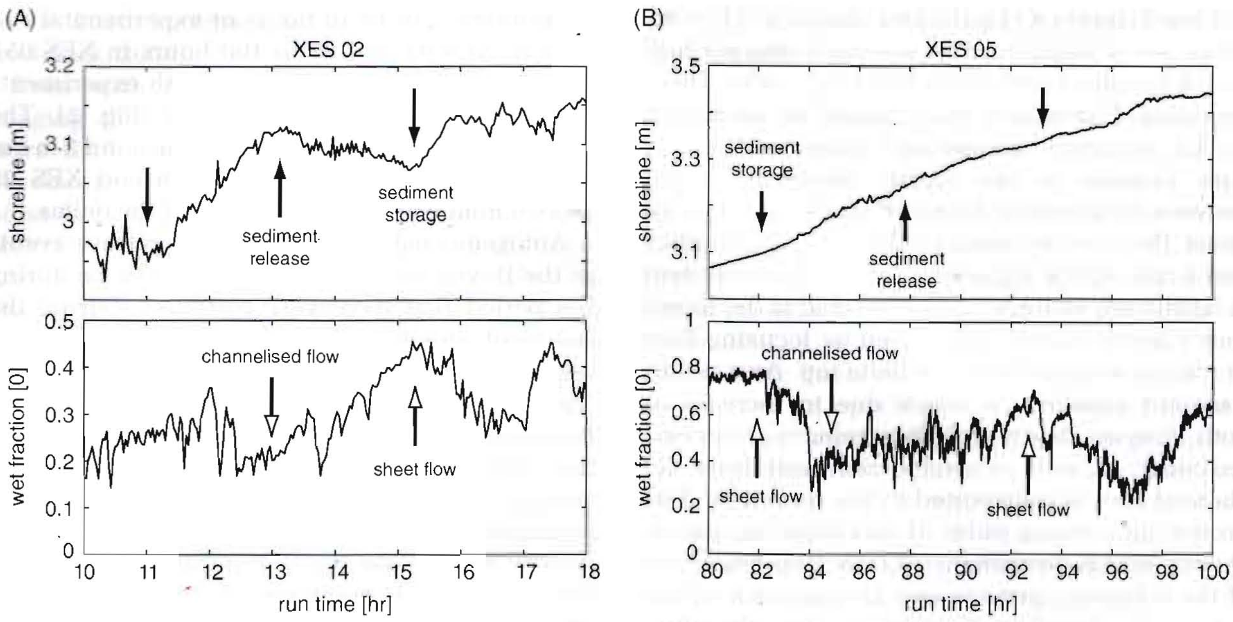

Fig. 2. Time series data of shoreline migration (top panels) and wetted fraction of the deltaic surface (bottom panels) in (A) XES 02 and (B) XES 05.

using a bimodal sediment mixture at the University of Pennsylvania. The sediment mixture is composed of 80% acrylic sand (D = 300 μm) and 20% granite chips (D = 2 mm). This bimodal mixture was designed to maximise the contrast between grain size and density, thus enhancing the threshold effect for sediment transport. Fluctuation in the wetted fraction associated with strong channelisation and backfilling in the fluvial surface is consistent with the other experiments presented above. The time necessary for the surface to reorganise through refilling incised channels and searching for new paths was shown to scale with the following form (Reitz *et al.*, 2010):

$$T_{ap} \sim \frac{HBs}{Q_s} \tag{1}$$

where T_{ap} denotes the characteristic avulsion (autogenic process) time scale, H is the vertical length of alluvial cutting by the release events, which can be roughly scaled with flow depth, B is the horizontal length of basin, scaled with total channel width, s denotes the downstream shoreline position as a function of time equivalent with the basin size in the downbasin direction and Q_s is sediment supply. This time scale captured the sediment storage and release cycles in their experiment as well as correctly predicting autogenic frequencies in the XES 02 and 05 experiments. The XES 02 experiment had five times greater sediment supply, which would cause a shorter time duration between the autogenic cycles, than that shown in XES 05. XES 02 showed an increase in the wetted fraction over 2 to 3 hour backfilling/storage events whilst the XES 05 shows 8 to 10 hour events (Fig. 2).

The sediment to water discharge ratios for the XES 02 and 05 experiments were kept constant at ~0.01, which generated similar delta top surface slopes of 0.036 and 0.048, respectively. However, this small increase in delta topset slope induces a fair decrease in the size of the fluvial sediment buffer (i.e. potential volume capacity to hold sediment during a storage event) and forces less sediment on the topset potion of the delta to be accommodated and released to offshore (Kim & Jerolmack, 2008). Direct and indirect measurements for the slope fluctuations in XES 02 and 05, due to the fluvial autogenic processes, indicate averaged 0.004 and 0.0027 slope changes across the basin, respectively (11% and 6% changes compared to the averaged topset slopes), to account for the observed shoreline fluctuations. The amount of sediment that is either stored or released in the delta top surface thus defines the magnitude of the shoreline fluctuation over the autogenic process (Kim & Jerolmack, 2008). XES 02 shows a larger amount of sediment reworked during the storage and release events, in comparison to XES 05. The high water discharge in XES 02 also took a relatively longer period for channelisation and led to larger degradation in the delta top surface. More symmetrical cycles of the wetted fraction were shown in XES 02 while asymmetrical (positively skewed) fluctuations were dominant in XES 05, which indicates a relatively different period for the release event. XES 05 shows quicker release of sediment and a longer period for sediment storage, whilst XES 02 shows a very symmetric distribution of times for storage and release events (Fig. 2).

Suggestions for further work

The experimental studies discussed above provide a suite of quantitative measurements of autogenic processes; however, more thorough investigations are required to understand the physical links between the sediment and water discharge conditions and autogenic processes. The experimental studies discussed above dealt with 1) the same Q_s/Q_w ratio but different absolute amounts of sediment and water (Kim & Jerolmack, 2008) and 2) changes in Q_w whilst keeping Q_s the same (Van Dijk *et al.*, 2009). However, experiments dealing with changes in Q_s while keeping Q_w constant are missing. Additionally, 1) the current suite of experiments was limited to only a few cycles of the autogenic events; and 2) the effects of different grain sizes, sediment mixture with multiple grain sizes and cohesiveness have not been thoroughly tested yet. More experiments should be done with experimental duration sufficient enough to capture events with ranges of Q_s and Q_w, over which the experiment can produce enough numbers of the autogenic events for a meaningful statistical analysis, multiple grain-size mixtures and cohesiveness. These experiments will provide insight into quantitative understanding of the fluvial autogenic processes and implications to field-scale stratigraphy.

CONTROLS OF ALLOGENIC FORCING ON AUTOGENIC PROCESSES

Basin response time scale and high-frequency stratigraphic signals

Sedimentary systems are sensitive to environmental changes. Changing architectural-stacking patterns in stratigraphy have generally been accepted as signatures of palaeo-environmental variations. The causes of these changes are frequently inferred from episodic active tectonics separated by relatively quiescent periods (e.g. Blair & Bilodeau, 1988; Dorsey *et al.*, 1997), climatically controlled variation in sediment yield (e.g. Smith, 1994), sea-level change (e.g. Posamentier *et al.*, 1988; Posamentier & Vail, 1988) and global climate changes by the Earth's orbital cyclicity (e.g. House, 1985) and solar and oceanic variations (e.g. Roth & Reijmer, 2005).

However, stratigraphic interpretations of high-frequency signals have been questioned in the rock record. It has been argued that depositional systems might not fully record high-frequency external changes in the stratigraphy if the time that sedimentary systems need to respond to the external changes is longer than the period over which the external forcing cycles. It has also been argued that depositional systems might exaggerate high-frequency autogenic signals in the stratigraphy, depending on the nature of the external forcing. A characteristic response time for depositional basins was first theoretically derived by Paola *et al.* (1992) and Paola (2000) and implications of this scaling to natural systems and flume analogues were further discussed in Postma *et al.* (2008). The basin equilibrium time serves to define what 'high frequency' is here; high-frequency external controls are environmental basin forcing that cycles over a smaller time period compared to the basin equilibrium time-scale. This time scale takes the following form:

$$T_{eq} = \frac{L^2}{\upsilon} \tag{2}$$

where L is the length of the depositional system and υ is the diffusivity coefficient. Castelltort & Van Den Driessche (2003) applied this basin diffusional relaxation time to modern worldwide rivers and reported that the basin response time scale ranges from 10^4 to 10^6 years. Allen (2008) conducted a similar analysis on large Asian rivers and suggested that this time scale is in the range of 10^5 to 10^6 years. Large river systems with extensive floodplains therefore tend to buffer any external variations when the external forcing period is less than the response time scale. The basin response time scale overlaps with the time scales for many geological processes, e.g. Earth orbital cycles, which calls into question the origin and interpretations of high-frequency patterns in stratigraphic architecture.

The following sections describe the complex responses of autogenic processes to external forcing (i.e. base-level change, tectonic tilting) in physical experiments. Both time scale and event size of the fluvial autogenic processes are different when base-level and tectonic controls are manipulated in the experiments compared to those conducted without the external forcing. Some elongated and magnified internal processes observed from the previous studies suggest stratigraphic signals exhibiting periodicity close to or longer than the equilibrium time scale could also be attributed to autogenic processes that have comparable stratigraphic results to allogenic controls.

Base-level change

Changes in the magnitude of autogenic fluctuations in shoreline migration rates during base-level rise and fall were first quantified in Kim *et al.* (2006a) using the XES 02 experiment. The deltaic shoreline responded to multiple sinusoidal base-level cycles applied in the experiment and exhibited high-frequency shoreline fluctuations superimposed over long-term responses (see studies about stratigraphic (allogenic) responses to the base-level cycles in Kim *et al.* (2006b) and Martin *et al.* (2009a)). The first base-level cycle started at 26 hours in run time and lasted for 108 hours which is a longer duration than a rapid cycle that was applied for 18 hours after the initial slow cycle. The amplitude of the first slow base-level cycle was 0.11 m, which is ten times larger than the averaged channel depth in the experiment. In the study, shoreline migration rates were calculated using 10 min laterally averaged downstream positions of the shoreline and roughly show a 3-fold increase in autogenic variability during the base-level rise than that during the base-level fall (Fig. 3).

Topographic scans reveal that the slope of the delta top surface varies cyclically during the autogenic processes: The slope decreases during release events and increases during storage events. This slope fluctuation is casted in a geometric model in Kim *et al.* (2006a), the results of which

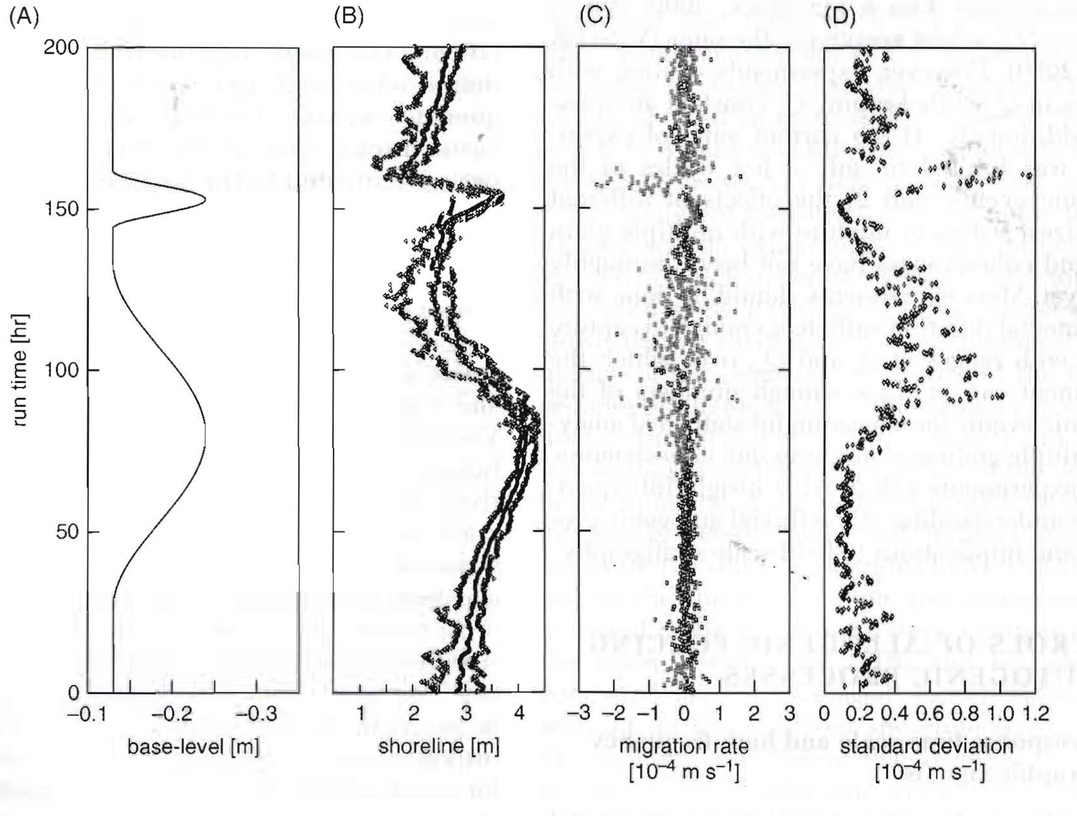

Fig. 3. Shoreline data in XES 02 (note that the time series includes only the first 200 hours of the total 310 run time). (A) Imposed base-level cycles; (B) maximum, minimum and laterally averaged shoreline downstream positions; (C) migration rate calculated using the averaged shoreline positions; and (D) standard deviations of the shoreline migration rates.

accounted well for the difference in variability in the shoreline migration rate observed during the falling and rising rims of the sinusoidal base-level cycle (see Fig. 11 in Kim *et al.* (2006a)). In the model, the magnitude of the slope increase within a single modelling time step during the storage events are constrained by the supplied sediment discharge; and thus the slope increment is smaller for a larger delta. A fraction of the topset slope averaged over the total experiment (i.e. 1% to 4% in XES 02) was given to limit the total range of the slope fluctuation in the model. The modelling results show that autogenic event signatures (i.e. variability in shoreline migration rate) differ according to the direction of base-level change even though the autogenic process size (i.e. the range of topset slope fluctuation between maximum and minimum threshold slopes) is assumed to be constant. Base-level fall enhances the sediment release process, forcing the shoreline seaward migration, but regression is inevitable in this setting, thus diminishing the effect on varying the shoreline migration. However, a sediment release event during overall transgression easily reverses the direction of shoreline migration because the delta front develops over the shallow submerged topset surface. In the Kim *et al.* (2006) study, it is clear that the delta geometry plays a role in the footprint of the shoreline autogenic fluctuation during base-level rise and fall but it is not clear if the event size (angle between threshold maximum and minimum topset slopes) varies by the direction of the base-level change due to the lack of high-res (in time) topographic scans. The following experiments address in part how autogenic event size varies during base-level rise and fall.

A research team in the ExxonMobil Upstream Research Company conducted a series of experiments using a sediment mixture with a polymer that improves deposit cohesiveness (Hoyal & Sheets, 2009; Martin *et al.*, 2009b). This sediment mixture restricts both channel sidewall erosion and channel widening, thus allowing for relatively stable, distributary channel networks to form, in contrast to the typical braided system in other experiments discussed in this paper. Martin *et al.* (2009b) produced a cohesive delta in an experiment with two stages: stage 1 without base-level rise; stage 2 with base-level rise. In the second stage, the rate of base-level rise was kept constant at a rate designed to nearly maintain the same size of the delta top surface (i.e. strongly aggrading delta with minor progradation). The base-level rise in the second stage forced a two-fold increase in fluvial deposition and caused a two-fold increase in frequency of the fluvial autogenic process compared to the first stage. Roughness of the shoreline along the experiment was also measured and characterised, thus showing statistical saturation at an opening angle $\theta = 16.5°$ (distributary lobes are scaled with 2θ). These shoreline roughness and lobe scales are consistent across both the delta progradation (with no base-level rise) and aggradation stages (with base-level rise), supporting the two-fold increase in the autogenic channel time scale due to enhanced fluvial deposition of the supplied sediment. High-resolution topographic data are still missing in this experiment, which might allow for detecting changes in the threshold slopes due to base-level forcing in more detail. However, the consistent roughness in the shoreline across the two stages of constant base-level and linear rise of base-level hints that no major changes in the autogenic event size occurred due to the base-level control.

The migration of the upstream end of the experimental deposit in these experiments (XES 02 and Martine *et al.* experiment) is restricted due to the vertical tank wall. As a result, the upstream boundary at the transition between alluvium and bedrock exposure (henceforth alluvial-bedrock boundary) could not migrate freely. Kim & Muto (2007) presented a series of experiments that allowed for free migration of the upstream end of the deposit. An isolated delta free from the tank walls developed over a sloped non-erodible basement in each of their experiments. The basement slope was set at a higher slope than the steepest delta topset slopes so that sediments bypassed the exposed upstream bedrock surface. Either constant base-level rise or fall was applied over the last half of an experiment after the first half of stationary base-level. The overall trend of the variability change in the shoreline migration rate during base-level rise and fall is in good agreement with the previous results: that is maximised when the mean shoreline migration direction is against the base-level change, but minimised if they are aligned. Thus there is no difference in the process for sediment internal buffering by allowing a free moving alluvial-bedrock boundary. However, the amplitude of the autogenic signal in migration rate of the alluvial-bedrock transition increases during base-level fall and diminishes during base-level rise, which is the opposite trend to that at the shoreline. This change in amplitude of the autogenic variability is mainly controlled by changes in the axial length of the alluvial system, i.e. shortening the length results in a decrease in the alluvial-bedrock transition autogenic variability; and vice versa. A simple geometric, mass-balance model similar to one in Kim *et al.* (2006a) was also employed in this study. The model again used varying fluvial slopes to express sediment transport efficiency in the fluvial system and captured the patterns of the autogenic signature in the both moving boundaries. The dimensionless variability of the shoreline and alluvial-bedrock boundaries, enhanced by the base-level forcing, indicated that the autogenic response has the same order of magnitude as the allogenic response. This suggests the possibility of overlap in time and event scales across the autogenic and allogenic stratigraphic products, even though the allogenic signal is mostly expected to be coherent over much longer length and time scales.

Tectonics: Lateral ground tilting

The response of rivers to tectonic activity is generally accepted as a key control for spatial distribution of the subsurface channel sandbodies. Stacking density of channel deposits therefore has been used to infer changes in 1) tectonic activity and 2) sediment supply (as a proxy for climate changes) from catchments (e.g. Alexander *et al.*, 1994; Alexander & Leeder, 1987; Allen, 2008; Bridge, 1993; Bridge & Leeder, 1979; Heller & Paola, 1996; Kim *et al.*, 2010; Leeder, 1978; Leeder *et al.*, 1996). However, stratigraphic evolution in active tectonic basins cannot be properly understood without consideration of the dynamic interactions of autogenic process with tectonic forcing. The following experimental example shows a complex autogenic response to tectonic activity.

The XES 05 experiment further considered the influence of subsidence on autogenically-driven stratigraphy. XES 05 had an initial stage with no tectonic component, in which the results for quantifying the autogenic process were presented in the previous sections. The experiment was composed of two separated normal fault segments that set up a relay-ramp. Constant fault slip rates were applied to both faults in the experiment (Kim *et al.*, 2010). Topographic displacement occurred across the upstream footwall and downstream hangingwall basins, which substantially lengthened the time for the fluvial channel system to redistribute sediment and to reach a quasi-steady-state landscape. Analysis using time integrated maps of wetted surface by channel flow in the tectonic stage (Fig. 4) indicates an increase in the characteristic time scale of the fluvial autogenic variation from 13 hours (non-tectonic stage) to 65 hours (tectonic stage) (Kim & Paola, 2007).

The five-fold increase in the autogenic time scale (i.e. slow channel lateral migration) caused temporal variation in sediment supply to the position of the maximum subsidence in the hangingwall basin. The slow redistribution of

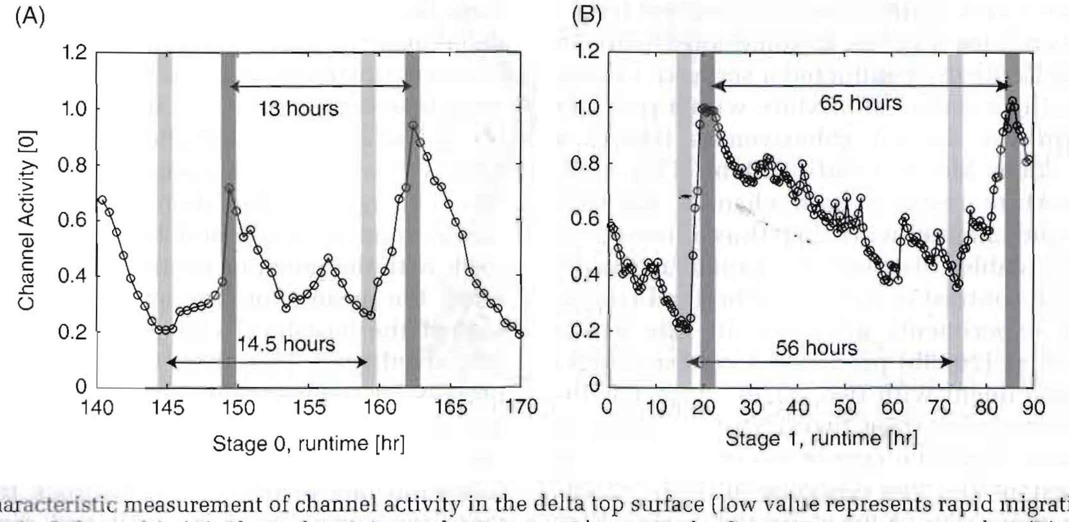

Fig. 4. Characteristic measurement of channel activity in the delta top surface (low value represents rapid migration (and/or avulsion) of channels). (A) Channel activity cycles every ~ 13 hours in the first non-tectonic stage, but (B) the cycle period increases to 65 hours due to lateral ground tilting imposed during the second tectonic stage.

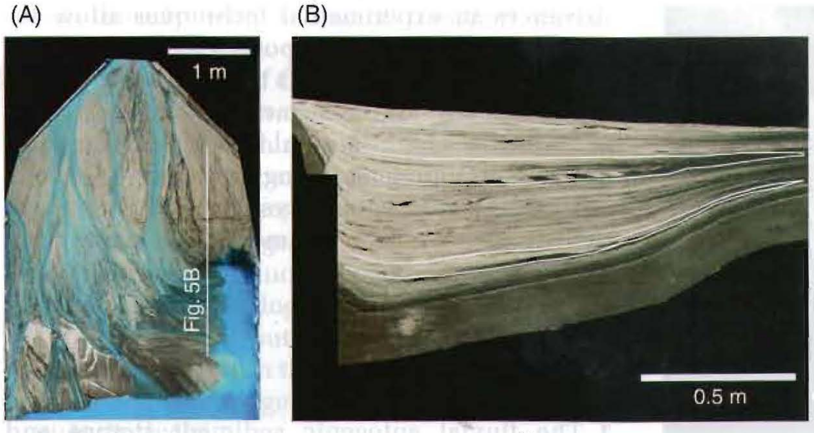

Fig. 5. (A) Surface Image taken from XES 05 when the hangingwall basin developed a lake autogenically. (B) A sliced dip section (location is indicated in (A)) across the footwall and hangingwall showing cyclic sedimentation between fluvial and lake facies (bounded by white lines).

sediment over an area with variable subsidence rates allows enough time to develop a tectonic depression in the surface topography, causing periodic opening of a lake (Fig. 5A). Opening and closing of the autogenic lake cycled twice in XES 05. During the opening of the lake, the channels flowed away from the hangingwall basin, whereas the channels flowed into the hangingwall basin around and across the fault during the closing period. Cyclic alternation between foreset and fluvial stratification was observed in sliced deposit sections, which developed even without time variations in tectonic controls (i.e. no changes in fault slip rate or sediment supply from the upstream source) (Fig. 5B).

These experimental results can be extrapolated to field conditions using scour depths as a reference scale. During the 60 hour exchange period between foreset and fluvial deposits, about 20 scour-depths (1 scour depth ≅ 2 cm) developed in the subsidence maximum. Assuming a 5 m scour depth in natural depositional basins and a sedimentation rate of 0.001 m/yr, the record of the full 60 hour autogenic event would be equivalent to 50 to 100 m thick strata and the entire autogenic cycle time would be approximately 10^5 years (Kim & Paola, 2007). This unexpected modification of scale of the internal process suggests the possibility of very long-period, high-magnitude autogenic variability associated with the coupling of channel reorganisation and active tectonic deformation.

Suggestions for future work

The Earth's surface is active over all time scales due to external perturbations and internally organised dynamics. In nature, depositional systems respond actively to multiple external controls with a wide range of time and space scales. The complex mixture of allogenic and autogenic signatures recorded in sedimentary records presents a puzzle; whose pieces consist of the causes and effects responsible for basin-fill history. Physical experiments in sediment transport and sedimentary basin evolution for understanding the relationship between external and internal changes along with associated stratigraphic architecture have advantages over numerical modelling and field study because 1) the depositional system in experiments naturally self-evolves and 2) precise managing of key external controls and monitoring of basin evolution can be achieved.

Initial efforts should focus on isolating individual causes and examining the complex effects associated with autogenic dynamics. Studying the modification of time and event scales by autogenic processes from linear external controls (e.g. Kim & Muto, 2007; Martin *et al.*, 2009b) should be continued in order to define their fundamental relationship under simple conditions. High-resolution topographic measurements in time and space should be taken for robust investigation of event size of autogenic processes. Coupled allo-autogenic study should also be expanded to investigating 1) the effect of base-level change over a wide range of rates, 2) various tectonic styles such as passive-margin and foreland basin styles and 3) long-term increase and/or decrease in sediment supply.

One of the hurdles to overcome for improving our ability to decouple allogenic signals from the rock record is the suppression of signals that come from external controls in stratigraphy. An experiment in the XES basin was performed in 2008 with an identical tectonic geometry as

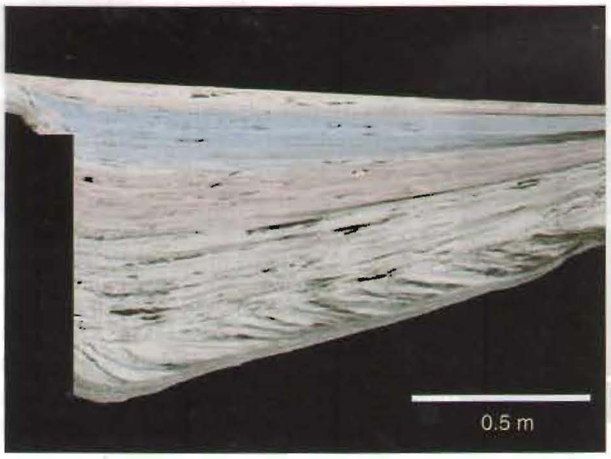

Fig. 6. A sliced dip section across the footwall and hangingwall in XES 08. The blue and top yellow layers were developed during the 4th stage with two tectonically quiescent periods.

the XES 05 experiment but with cyclic variations of the fault slip rate in time. Unlike the XES 05 experiment, the XES 08 experiment did not develop clear cyclic patterns for tectonic variation in the strata (Fig. 6). The 4th stage of the XES 08 experiment was composed of three substages with two tectonically quiescent periods in the first (16 hours) and last (24 hours) stages and a middle tectonic stage. The middle tectonic stage was applied for 6 hours with a slip rate almost double that of the other stages, both in the XES 05 and 08 experiments (Straub *et al.*, 2009). However, the 6 hour duration (cf. 65 hours modified autogenic channel time scale in XES 05) was too short to develop a topographic low significant enough to be recorded in the final deposit and the two 16 and 24 hour non-tectonic stages had long enough duration (compared to the 13 hour autogenic frequency in XES 05 non-tectonic stage) to reorganise the tectonically deformed surface.

A numerical rice-pile model in Jerolmack & Paola (2010) demonstrated a damping of cyclic sediment (rice grains) input signal in the output flux at the downstream end. Cyclic input applied at the upstream end, with a time period less than a characteristic relaxation time, is shredded through the rice-pile transport system, unless the magnitude of the perturbation is very large (Fig. 4 in Jerolmack & Paola (2010)).

Stratigraphic products attributed to periodic changes in base-level, tectonic movement and sediment supply should be better examined. Advances in experimental techniques allow for more complete tests of hypotheses related to sensitivity of transport systems to imposed frequency of external forcing. Experiments with a wide range of frequencies in the basinal forcing will provide a fundamental understanding of origin of cyclic sedimentation in natural systems and thus a way to better decouple environmental signatures from rock records.

CONCLUSIONS

1 The fluvial autogenic sediment storage and release process occurs naturally and periodically changes transport rates in fluvial systems. Channel patterns alternate between strong channelisation and sheet flow to modulate fluvial sediment transport processes. The characteristic time for this internal alternation is scaled with the sediment supply rate, basin length, flow depth and width, as shown in equation (1).
2 Moving boundaries, such as the shoreline and alluvial-bedrock transition, records internal variability. Experiments with base-level change produce increase in the variability in the shoreline migration rate for base-level rise and decrease in the variability of the shoreline migration rate for base-level fall. The variability in the alluvial-bedrock transition shows an opposite trend to the base-level forcing.
3 Lateral tectonic tilting lengthens the autogenic channel time scale by decreasing the channel lateral migration rate. An experiment with a lateral subsidence variation slows down the fluvial reorganisation process and induces long-term cyclic sedimentation without time-varying allogenic controls.
4 Cyclic changes in basinal forcing at a frequency less than the characteristic relaxation (equilibrium) time in equation (2) were significantly blurred during the stratal development in sedimentation.
5 Future projects should be specifically designed to measure quantitatively the fluvial autogenic processes and investigate associated stratigraphic products under precisely controlled boundary conditions (tectonic subsidence rate, sediment and water supplies etc.). The level of contribution of autogenic processes to stratigraphic development almost certainly varies

non-linearly with sediment transport conditions and mixings with basinal forcing; and thus the control of fluvial autogenic processes on the resulting strata can be more significant than what has been normally accepted. Results of the previous experiments and proposed next steps will fundamentally improve the understanding of autogenic processes and their stratigraphic products. Further investigations of the coupled allogenic-autogenic signatures in experiments, but starting with simplified external controls in the experiments, will aid in disentangling allogenic and autogenic effects quantitatively.

REFERENCES

Alexander, J., **Bridge, J.S.**, **Leeder, M.R.**, **Collier, R.E.L.** and **Gawthorpe, R.L.** (1994) Holocene meander-belt evolution in an active extensional basin, southwestern Montana. *J. Sed. Res.*, **64**, 542–559.

Alexander, J. and **Leeder, M.R.** (1987) Active tectonic control on alluvial architecture; Recent developments in fluvial sedimentology. In: *Third International Fluvial Sedimentology Conference, Fort Collins, CO, United States, Aug. 1985* (Eds F.G. Ethridge, R.M. Flores, M.D. Harvey and J.N. Weaver), **39**, 243–252, United States (USA).

Allen, P.A. (2008) Time scales of tectonic landscapes and their sediment routing systems. *Geol. Soc. London Spec. Publ.*, **296**, 7–28. doi: 10.1144/sp296.2.

Ashworth, P.J., **Best, J.L.** and **Jones, M.** (2004) Relationship between sediment supply and avulsion frequency in braided rivers. *Geology* (Boulder), **32**, 21–24.

Blair, T.C. and **Bilodeau, W.L.** (1988) Development of tectonic cyclothems in rift, pull-apart and foreland basins: Sedimentary response to episodic tectonism. *Geology*, **16**, 517–520.

Bridge, J.S. (1993) Description and interpretation of fluvial deposits – a critical perspective. *Sedimentology*, **40**, 801–810.

Bridge, J.S. and **Leeder, M.R.** (1979) A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 617–644.

Bryant, M., **Falk, P.** and **Paola, C.** (1995) Experimental study of avulsion frequency and rate of deposition. *Geology* (Boulder), **23**, 365–368.

Castelltort, S. and **Van Den Driessche, J.** (2003) How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sed. Geol.*, **157**, 3–13.

Cazanacli, D., **Paola, C.** and **Parker, G.** (2002) Experimental steep, braided flow: Application to flooding risk on fans. *J. Hydraul. Eng.*, **128**, 322–330.

Dorsey, R.J., **Umhoefer, P.J.** and **Falk, P.D.** (1997) Earthquake clustering inferred from Pliocene Gilbert-type fan deltas in the Loreto Basin, Baja California Sur, Mexico. *Geology* (Boulder), **25**, 679–682.

Heller, P.L. and **Paola, C.** (1996) Downstream changes in alluvial architecture; an exploration of controls on channel-stacking patterns. *J. Sed. Res.*, **66**, 297–306.

Heller, P.L., **Paola, C.**, **Hwang, I.-G.**, **John, B.** and **Steel, R.** (2001) Geomorphology and sequence stratigraphy due to slow and rapid base-level changes in an experimental subsiding basin (XES 96–1). *AAPG Bull.*, **85**, 817–838.

Hickson, T.A., **Sheets, B.A.**, **Paola, C.** and **Kelberer, M.** (2005) Experimental test of tectonic controls on three-dimensional alluvial facies architecture. *J. Sed. Res.*, **75**, 710–722.

House, M.R. (1985) A new approach to an absolute time-scale from measurements of orbital cycles and sedimentary microrhythms. *Nature*, **315**, 721–725.

Hoyal, D. and **Sheets, B.A.** (2009) Morphodynamic evolution of experimental cohesive deltas. *J. Geophys. Res.*, **114**, 18. doi: F0200910.1029/2007jf000882.

Jerolmack, D.J. (2011) Causes and effects of noise in landscape dynamics. *Eos*, **92**, 385–386.

Jerolmack, D.J. and **Mohrig, D.** (2005) Frozen dynamics of migrating bedforms. *Geology*, **33**, 57–60.

Jerolmack, D.J. and **Paola, C.** (2007) Complexity in a cellular model of river avulsion. *Geomorphology*, **91**, 259–270.

Jerolmack, D.J. and **Paola, C.** (2010) Shredding of environmental signals by sediment transport. *Geophys. Res. Lett.*, **37**, L19401. 10.1029/2010gl044638.

Jerolmack, D.J. and **Swenson, J.B.** (2007) Scaling relationships and evolution of distributary networks on wave-influenced deltas. *Geophys. Res. Lett.*, **34**, 23402.

Kim, W. and **Jerolmack, D.J.** (2008) The Pulse of Calm Fan Deltas. *J. Geol.*, **116**, 315–330. doi: 10.1086/588830.

Kim, W. and **Muto, T.** (2007) Autogenic response of alluvial-bedrock transition to base-level variation: Experiment and theory. *J. Geophys. Res.*, **112**. doi: 10.1029/2006JF000561.

Kim, W. and **Paola, C.** (2007) Long-period cyclic sedimentation with constant tectonic forcing in an experimental relay ramp. *Geology*, **35**, 331–334.

Kim, W., **Paola, C.**, **Swenson, J.B.** and **Voller, V.R.** (2006a) Shoreline response to autogenic processes of sediment storage and release in the fluvial system. *J. Geophys. Res.*, **111**. doi: 10.1029/2006JF000470.

Kim, W., **Paola, C.**, **Voller, V.R.** and **Swenson, J.B.** (2006b) Experimental measurement of the relative importance of controls on shoreline migration. *J. Sed. Res.*, **76**, 270–283. doi: 10.2110/jsr.2006.019.

Kim, W., **Sheets, B.A.** and **Paola, C.** (2010) Steering of experimental channels by lateral basin tilting. *Basin Res.*, **22**, 286–301.

Leeder, M.R. (1978) A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness; Fluvial sedimentology. First international symposium on fluvial sedimentology, Calgary, Alberta, Canada, Oct. 20–22, 1977, 587–596.

Leeder, M.R., **Mack, G.H.**, **Peakall, J.** and **Salyards, S.L.** (1996) First quantitative test of alluvial stratigraphic models: southern Rio Grande Rift, New Mexico. *Geology*, **24**, 87–90.

Martin, J., **Paola, C.**, **Abreu, V.**, **Neal, J.** and **Sheets, B.** (2009a) Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base-level. *AAPG Bull.*, **93**, 503–533.

Martin, J., **Sheets, B.**, **Paola, C.** and **Hoyal, D.** (2009b) Influence of steady base-level rise on channel mobility, shoreline migration and scaling properties of a cohesive experimental delta. *J. Geophys. Res.*, **114**, F03017. 10.1029/2008jf001142.

Muto, T. and **Steel, R.J.** (2001) Autostepping during the transgressive growth of deltas; results from flume experiments. *Geology* (Boulder), **29**, 771–774.

Paola, C. (2000) Quantitative models of sedimentary basin filling; Millennium reviews. *Sedimentology*, **47**, Suppl. 1, 121–178.

Paola, C., Heller, P.L. and **Angevine, C.L.** (1992) The large-scale dynamics of grain-size variation in alluvial basins; 1, *Theory. Basin Res.*, **4**, 73–90.

Paola, C., Mullin, J., Ellis, C., Mohrig, D.C., Swenson, J.B., Parker, G.S., Hickson, T., Heller, P.L., Pratson, L., Syvitski, J., Sheets, B. and **Strong, N.** (2001) Experimental stratigraphy. *GSA Today*, **11**, 4–9.

Paola, C., Straub, K., Mohrig, D. and **Reinhardt, L.** (2009) The "unreasonable effectiveness" of stratigraphic and geomorphic experiments. *Earth-Sci. Rev.*, **97**, 1–43.

Posamentier, H.W. and **Vail, P.R.** (1988) Eustatic controls on clastic deposition; II, Sequence and systems tract models. In: *Sea-Level Changes: An Integrated Approach* (Eds C.K. Wilgus, B.S. Hastings, C.A. Ross, H.W. Posamentier, J. Van Wagoner and C.G.S.C. Kendall), **42**, pp. 125–154, Houston, TX, USA.

Posamentier, H.W., Jervey, M.T. and **Vail, P.R.** (1988) Eustatic controls on clastic deposition; I, Conceptual framework. In: *Sea-Level Changes: An Integrated Approach* (Eds C.K. Wilgus, B.S. Hastings, C.A. Ross, H.W. Posamentier, J. Van Wagoner and C.G.S.C. Kendall), **42**, pp. 109–124, Houston, TX, USA.

Postma, G., Kleinhans, M.G., Meijer, P.T. and **Eggenhuisen, J.T.** (2008) Sediment transport in analogue flume models compared with real-world sedimentary systems: a new look at scaling evolution of sedimentary systems in a flume. *Sedimentology*, **55**, 1541–1557.

Reitz, M.D., Jerolmack, D.J. and **Swenson, J.B.** (2010) Flooding and flow path selection on alluvial fans and deltas. *Geophys. Res. Lett.*, **37**. doi: 10.1029/2009GL041985.

Roth, S. and **Reijmer, J.J.G.** (2005) Holocene millennial to centennial carbonate cyclicity recorded in slope sediments of the Great Bahama Bank and its climatic implications. *Sedimentology*, **52**, 161–181.

Smith, G.A. (1994) Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona. *Geol. Soc. Am. Bull.*, **106**, 1212–1228.

Straub, K.M., Paola, C., Kim, W. and **Sheets, B.** (2009) Controls on steering of channels in laterally tilting basins: an experimental study: Eos Trans. *AGU*, **90**, no. 52, Fall meet. suppl., Abstract EP53A-0612.

Van Dijk, M., Postma, G. and **Kleinhans, M.G.** (2009) Autocyclic behaviour of fan deltas: an analogue experimental study. *Sedimentology*, **56**, 1569–1589.