The effect of lateral tectonic tilting on fluviodeltaic surficial and stratal asymmetries: experiment and theory

Jessica Kopp and Wonsuck Kim
Department of Geological Sciences and Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, Austin, TX, USA

ABSTRACT
Tectonic influence on deltas has long been recognized for its importance in morphodynamic and stratigraphic development. Here, we explore the control of lateral tectonic tilting on a prograding fluviodeltaic system through six laboratory experiments with a range of tilting rates. Basement tilting was applied along an axis that bisects the centre of the experimental delta, which forced uplift on one half of the basin and subsidence on the opposite half. In the experiments with lower tilting rates, the delta advanced faster in the direction of uplift due to the decline in relative base level. This slow uplift created truncated stratigraphic intervals that were dominated by active channel cut and fill. On the opposite side where subsidence occurred, the shoreline still prograded, but with decreased rates, while the delta topset was deposited thicker, alternating packages of fine and coarse sediments. The fluvial system was active uniformly across the delta in these slow tilting runs and produced asymmetry in shoreline planform geometries. In the experiments with higher tilting rates, deposition quickly ceased on the uplift side and stacked conformable sequences of delta lobes on the subsidence side. The result was an overall lack of progradation in all directions. Progressively greater tilting rates used in these high tilting runs yielded steering of channels towards the direction with higher subsidence and developed even more asymmetrical stratigraphic patterns. Characteristic tectonic and channel timescales applied to the experimental conditions prove to be good predictors of the fluviodeltaic planform and stratigraphic asymmetries. The deltaic asymmetry for the Ganges–Brahmaputra (G–B) system is largely comparable to the experiments with timescale ratios similar to those estimated for the G–B system.

INTRODUCTION
Tectonic steering of channels
Fluviodeltic stratigraphy has been studied for decades as an important indicator of Earth–surface processes during the time of deposition due to its sensitivity to both internal and external signals. These records encompass multiple climate and geological settings, creating a myriad of motivations to study them. Geoscientists have built flume facilities in which three-dimensional experiments make advancing our knowledge in unravelling the controls of environmental forcing, for example, eustasy, tectonics and sediment supply, on surface processes and preserved stratigraphy possible (Paola et al., 2009). Previous studies using physical experiments mostly focused on understanding how individual parameters, for example, base level (van Heijst & Postma, 2001; Paola et al., 2001; Kim et al., 2006b) and tectonics (Kim et al., 2010), change depositional systems and have recently shifted more attention to the interplay between these parameters and the naturally occurring internal (autogenic) processes (Paola et al., 2001; Kim & Muto, 2007; Kim & Jerolmack, 2008; Van Dijk et al., 2009).

Tectonics arouses particular interest because it primarily controls the creation or destruction of accommodation. Field geologists use the sedimentary record as a proxy to determine the size, shape, rate of subsidence and/or uplift, and evolution of basins worldwide under a variety of tectonic settings (see Armstrong, 1978; Nadon et al., 1999; Weissmann, 2005; DeCelles et al., 2007; Engelder et al., 2007; Lamb et al., 2012; Parsons et al., 2012). The importance of linking tectonism with the sedimentary record has been widely recognized since the first quantitative models were introduced in the late 1970’s. Leeder (1978), Allen (1978), and Bridge & Leeder (1979) suggested that the interconnectedness of channel deposits in alluvial systems is controlled primarily by channel avulsion rate coupled with floodplain accretion (or subsidence) rate. Alexander & Leeder (1987) presented the
first analysis of the influence of lateral subsidence motion on interconnectedness of channel deposits and proposed that channels are steered by lateral tilting, leading to an increase in the channel-stacking density over the subsidence maximum area. This idea was built from the contributions of a series of papers proposing a subsurface architecture model, frequently referred to as the ‘Leeder-Allen-Bridge’ (LAB) model, which laid the foundation for quantitative models and corresponding physical experiments.

The general premise set forth by the LAB model (channels are attracted to an area of maximum subsidence, altering channel-stacking patterns) has been countered by theoretical and experimental studies since 1999. Heller & Paola (1996) provided an alternative model to the previous LAB model by considering the three-dimensional geometries of channel-stacking patterns. They found that sediment extraction from the upstream sediment source to the downstream direction results in changes of local sedimentation rate and causes spatial changes in channel-stacking density. Although subsidence may be the primary control on channel-stacking density as well as the interconnectedness of channel sand bodies, it is also important to note that these changes are controlled by secondary factors such as avulsion frequency, sedimentation rate, and channel geometries (Heller & Paola, 1996). Hickson et al. (2005) reported experimental results conducted in 1999 in the Experimental Earth-Scape (XES) basin at the St. Anthony Falls Laboratory, which supported the findings in Heller & Paola (1996). The experiments showed that lateral tectonic tilting does not affect the architecture of the fluvial system with regards to channel-stacking density, but instead results in stratal tilting, where the geometries of beds are inclined towards the area of maximum subsidence. They argued that the primary changes in channel-stacking density are caused by the forcing of primary allogenic controls on the up or down dip migration of facies. The concluding hypothesis stated that it is only possible for the effects of variable subsidence to change the behaviour of a fluvial system if the tilting rate is relatively fast. This closing hypothesis made by Hickson et al. (2005) was explored and reorganized as a problem regarding timescales by Kim et al. (2010). The XES basin was again used to conduct an experiment in 2005 (XES 05) with lateral tilting using a relay-ramp-like geometry. Kim et al. (2010) hypothesized that the channels should feel the effects of the lateral tectons if the timescale in which the differential subsidence acts on the basin is shorter than the timescale in which the channels can re-organize the surface. XES 05 aimed to achieve a shorter tectonic timescale in relation to the channel timescale, that is, a tectonic-dominated system. This produced a higher flow occupation and a higher proportion of sandy deposits towards the lateral subsidence maximum. A recent XES experiment in 2008 (XES 08) conducted with the same relay-ramp-like geometry, achieved a sediment-dominated system due to a shorter imposed channel timescale in comparison to the tectonic timescale (Straub et al., 2013). In both XES experiments, it was demonstrated that the characteristic tectonic and channel timescales determined whether the system was tectonic-dominated vs. sediment-dominated. Elaboration of the characteristic channel and tectonic timescales can be found in the discussion section.

Previous studies, from the early LAB models up until recent series of experiments, have focused on an alluvial river basin setting with a fixed downstream boundary, that is, no lengthening (progradation) or shortening (re-gradation) of the system. These previous models and experiments have worked under the assumption that sediment supplied from upstream is either fully extracted within the basin or bypassed through the system. However, this paper updates the previous findings with data from a new set of experiments that allows a free moving downstream boundary into a fluviodeltaic system and thus shoreline progradation. A range of lateral tectonic tilting rates was applied to experiments conducted in the Sediment Transport and Earth-surface Processes (STEP) basin at The University of Texas at Austin. Through the experimental data here, we examine (1) the effects of lateral tilting on channel steering and associated local shoreline progradation, and (2) sediment volume partitioning onto the relatively uplifted and subsiding area as the delta progrades over the laterally tilting basin.

**Shoreline asymmetry in the Ganges–Brahmaputra delta**

The Ganges–Brahmaputra (G–B) delta displays shoreline asymmetry in planform view (Fig. 1). Changes in the...
morphology and sediment distribution in tidal-dominated environments has been linked to tidal currents and wave action (see Ali et al., 2007). The noted asymmetry in tidal deltas has been studied qualitatively and quantitatively for decades (see Sha, 1989; Gibeaut & Davis, 1991; van der Vegt et al., 2006, 2009; Plink-Bjorklund, 2012), but understanding has primarily focused on processes related to building ebb-tidal deltas and tidal inlets, which are micro- to meso-scale features when compared to the entire G–B delta system. If the asymmetry of the G–B delta cannot be fully explained by the classical idea of tidal currents, then perhaps forcing on a much larger scale, comparable to the scale of the entire G–B delta itself is the explanation centred on the current study. Recently a few papers started to access the potential influence of tectonic subsidence on the sedimentary record and avulsion history of the Ganges–Brahmaputra River (Gupta et al., 2014; Pickering et al., in press). However, the relationship between the shoreline progradation and the G–B tectonic setting has not been adequately addressed. In this paper, we present results from a series of delta experiments that were conducted with a range of tectonic tilting rates. We use theoretical timescales of tectonic subsidence and channel processes to extrapolate our insight from the experiments to understand the cause of asymmetrical shoreline progradation in the G–B delta.

METHODS

Experimental design

A total of six experiments took place in the STEP basin, whose dimensions are 4 m long, 5 m wide, and 1.5 m deep (Fig. 2a). One half of the basin (4 m wide × 2.5 m long) contains a hinged table that can be raised or lowered to create different subsidence patterns depending on placement of the sediment source. The current experiments model a fluviodeltaic system over the flat subsiding table, which acts as the tectonic basement. We set up a Plexiglas perimeter around the basin with the dimensions 4 m wide by 2 m long to build a semicircular delta within the perimeter. A bimodal sediment mixture of 50% fine white sand ($D = 100 \mu m; \rho = 2.65 \text{ kg m}^{-3}$) and 50% very coarse brown sand ($D = 2 \text{ mm}$) by weight was used. The coarse brown sediment is slightly less dense (2.60 kg m$^{-3}$) and transported easier due to better exposure to channelized flow (i.e. pressure forces acting on the surface of grains work effectively compared to the finer grains), thus serving as a proxy for the fine material in nature. Sediment was premixed outside of the basin and stored in a large gravity-driven hopper that can hold over a ½ ton (approximately 0.36 m$^3$) of sediment. The sediment went from the hopper into an auger feeder that was centrally located along an edge of the basin perpendicular to the direction of tilt. In the STEP basin, sea level can be closely monitored and independently controlled to mimic sea-level rise and fall by a computer-controlled weir, which ensures an absolute water height. The basin tilting resulted in basin elevation change; therefore the base-level control accordingly ensured that the relative sea level maintained 5 cm constant at the sediment source (Fig. 2b). Thus, base level remains constant at the sediment source point, with uplift occurring on the left side of the basin and subsidence on the right (Fig. 2b, c).

The six experiments were conducted with a range of different tilting rates (Table 1). The initial control experiment (STEP-12-NON) kept sediment and water discharges constant and had no applied tectonics, and

Fig. 2. (a) Schematic of the STEP basin with dimensions of 5 m long, 4 m wide, and 1.5 m tall. The half of the basin is covered with a subsiding table. Sediment and water are fed at the centre of the short edge of the tank but the long edge of the table. The river right-hand side is uplifted as the base level rises at the half of the uplifting rate, which creates a rotational motion at the centre of the table. (b) Initial and final configuration of the tilting table and base level, viewing from the front of the delta. (c) An image taken at the end of the STEP-12-MAX experiment from an angle.
served as a control case for comparison to find the differences that tectonic subsidence had on the delta. Tectonic tilting was introduced after 1.5 h of run time. By carrying out the initial 1.5 h of run time with no basement motion at the beginning of each experiment, we were able to verify the reproducibility of the experimental results from STEP-12-NON and view the changes that occurred to the already established delta. This is consistent with the idea of ‘Stage 0’ in XES 05 that included an initial period of no changes in subsidence or base level. The initial nontectonic stage in XES 05 served to evaluate the background surface processes of the delta with the intentions of (1) observing the natural surface slope of the delta, and (2) comparing the internal (autogenic) channel timescales when lateral tectonics are active and inactive.

Within a single experimental run, the tectonic rate was held constant, but changed among experiments by several orders of magnitude to encompass a broad spectrum of tectonic rates (Table 1). Each experiment ran for a total of 6 h except for the run with a maximum tilting rate, which had a total duration of 4.5 h. The experimental parameters and associated run names can be found in Table 1.

### EXPERIMENTAL RESULTS

#### Shoreline position

We define the shoreline position as the topset–foreset break, naturally occurring at the sediment–water interface. The delta progrades into the basin at a rate that declines with the cube root of time due to the steady increase in sloped topset area in a radial delta (Powell et al., 2012). In the control run (STEP-12-NON), progradation followed this time dependence, and the shoreline advanced evenly into the basin. The resulting delta was radially symmetric, where the average distance of the right half of the delta from the sediment source to the shoreline was mostly the same distance on the left half of the delta. Throughout the experiment, fluvial sediment storage and release cycles occurred (Kim & Jerolmack, 2008). These autogenic processes released sediment to the shoreline during instances of channelized flow, whereas the storage process caused overland flooding on the fluvial surface, leading to deposition of the brown sand on the subaerial delta plain.

We detected the shoreline using overhead images every 10 min and subdivided the subaerial portion of the delta into halves to track the shoreline downstream location averaged on the uplift ($s_u$) and subsidence ($s_s$) sides of the delta independently. For each half of the basin, distances between the sediment source and the shoreline position across the delta were measured and averaged (Fig. 3).

STEP-12-NON, where no subsidence occurred, showed slight variation (<10 cm) in the shoreline position between the uplift and subsidence halves. This variation was mostly attributed to the avulsion and progradation of individual lobes from channelized flow, and the difference in shoreline position between the two sides of the delta did not exceed 10 cm (Fig. 3a).

Once tectonic tilting was introduced, variation of the averaged shoreline positions in the uplift vs. the subsidence sides occurred beyond the autogenic variability (Fig. 3b–f). Relative uplift reduces water depth at the shoreline, causing accelerated progradation. In the uplift side, the overall progradation rates coincide with tectonic activity: as the rate of differential uplift increases, so does

<table>
<thead>
<tr>
<th>RUN</th>
<th>STEP-12-NON</th>
<th>STEP-12-MIN</th>
<th>STEP-12-LOW</th>
<th>STEP-12-MED</th>
<th>STEP-12-HIGH</th>
<th>STEP-12-MAX</th>
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<tr>
<td>Subsidence (mm s$^{-1}$)</td>
<td>0</td>
<td>0.002</td>
<td>0.01</td>
<td>0.02</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Base Level (mm s$^{-1}$)</td>
<td>0</td>
<td>0.001</td>
<td>0.005</td>
<td>0.01</td>
<td>0.05</td>
<td>0.1</td>
</tr>
<tr>
<td>$Q_u/Q_o$</td>
<td>80</td>
<td>80</td>
<td>80</td>
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the rate of shoreline advancement. This is only nullified when the uplifted portion of the basin becomes inactive (Fig. 3d–f). When comparing the delta on the uplift side vs. the subsidence side, there exists a strong divergence between $s_u$ and $s_s$, that is, the shoreline location begins only after tectonic tilting is introduced. The delay period (time between the onset of tectonic tilting and the divergence between $s_u$ and $s_s$) among the five tectonic experiments decreases as the rate of differential subsidence increases. Under the minimum tectonic tilting condition (STEP-12-MIN), divergence only begins at ca. 230 min, which is a ca. 140-min delay from the onset of imposed tectonics. The same delay trend exists in the low tilting run (STEP-12-LOW), but the delay time until a significant divergence occurs is shorter (ca. 60 min) than that of STEP-12-MIN. The difference in shoreline downstream positions between the uplift and subsidence sides of the delta continuously grows until the end of STEP-12-LOW. For the medium tilting run (STEP-12-MED), the divergence between $s_u$ and $s_s$ begins at 140 min with a delay of ca. 50 min. The shoreline progradation rates on the uplift side in STEP-12-MED are faster than those in STEP-12-MIN and STEP-12-LOW, creating the potential for greater difference between $s_u$ and $s_s$. However, in STEP-12-MED, channels on the uplift side are gradually abandoned starting at ca. 250 min, which decreases the divergence values. The uplifted part of the delta is totally abandoned around 310 min when the shoreline position, $s_u$, plot as a flat line, remaining stationary at one position until the end of the
experiment (360 min). The time delay in shoreline divergence is even shorter in STEP-12-HIGH and almost non-existent in STEP-12-MAX. The shoreline in the uplift side advances even faster in STEP-12-HIGH than that in STEP-12-MED, but the fluvial activity gradually diminishes at ca. 150 min and stops at ca. 250 min entirely due to abandonment. The timing for the onset of shoreline divergence and abandonment of fluvial activity is almost identical in STEP-12-MAX. Landward retreat of the shoreline position on the subsidence side occurs at the onset of tectonic tilting in STEP-12-MAX and the shoreline shows strong autogenic fluctuations in position during relative base-level rise.

**Sediment volume partitioning**

Sediment supply rate was kept constant at 5 cm$^3$ s$^{-1}$ for the duration of each experiment. We tracked how sediment was distributed across the system throughout time as the different rates of tilting were imposed. We captured the total deposit volume using the topographic scans and then divided them in half along the axis of rotation, giving the deposit volume for the uplift, $V_u$, vs. subsidence, $V_s$, portions of the delta. Figure 4 shows deposit volumes normalized with the total delta deposit at the end of each experiment. During the control run where no tectonic tilting occurred, the sediment was delivered equally to each half of the delta as expected (Fig. 4a), with the largest error of unequal sediment delivery being only 7%. STEP-12-MIN shows the difference between $V_u$ and $V_s$ beginning around ca. 300 min, but significant separation between the $V_u$ and $V_s$ values does not really show (Fig. 4b). The difference in deposit volumes fluctuates within 9% compared to the total deposit volume. STEP-12-LOW shows a larger (15%) difference between $V_u$ and $V_s$ (Fig. 4c). However, the uplift side still actively receives sediment and increases $V_u$ throughout the experiment. A clear divergence of these $V_u$ and $V_s$ values occurs in STEP-12-MED (Fig. 4d). Steering of sediment delivery to the subsidence side increases over time and magnifies the difference in deposit volumes between these two regions. This trend remains for STEP-12-MED, STEP-12-HIGH, and STEP-12-MAX (Fig. 5d–f). In STEP-12-MED, divergence does not start until ca. 180 min into the run but sediment is equally distributed to both the uplift and subsidence side for a duration of 90 min after the onset of tectonic activity. As tilting increases, the rate at which the sediment is routed preferentially to the area of the delta undergoing subsidence instead of uplift also increases (Fig. 5e, f), and the preferential routing also starts earlier. Both STEP-12-HIGH and STEP-12-MAX have no delay in transporting sediment preferentially to the subsidence side. Under both high and maximum tilting conditions, the uplift portion of the delta is abandoned and becomes entirely inactive. This inactivity is reflected in the horizontal trend in the total deposit volume for the uplift side, $V_u$, in STEP-12-HIGH and STEP-12-MAX.

There are potential sources of error in measuring the deposit volume. These errors will be further highlighted in the discussion section of this paper.

**Experimental stratigraphy**

Each experimental deposit was sliced vertically normal to the tilting axis after each run and captured with high-resolution images (Fig. 5) (see more details about slicing experimental deposit in Mullin & Ellis, 2008). These sections serve best for comparison of strata between the uplift and subsidence sides of the system because the slicing orientation is parallel to the tilting direction. Here, we focus on analysing slices made at 950 mm away from the sediment source in the experimental runs (see the slice locations in Fig. 3). The section in STEP-12-MAX shown in Fig. 5f was collected at 100 mm upstream compared to other sections and at an oblique angle (45 degrees off from the parallel slice) in the subsiding portion of the delta, because of the smaller overall delta surface. Final deposit sections reveal changes in overall basin stratigraphy on a variety of spatial and temporal scales. The section taken from STEP-12-NON provides a reference for the sections from all other runs (Fig. 5a). The sliced sections are similar laterally, consisting of an initial delta lobe comprised of prodelta foreset avalanche units, laterally accreting channel sands and overbank flood deposits. This is overlain by re-worked channel deposits, as new lobes swept across the previous deposit during an avulsion to that same site or migration over that site via channelized flow. Tongues of highlighted yellow sand packages in Fig. 5 signify a period of a newly active lobe that has migrated laterally across the area while prograding into the basin.

These records of distinct tongues are useful for documenting the stratal asymmetry of the deposit. In STEP-12-NON, the deposit is quite symmetric; therefore, there is no remarkable difference in the stratigraphy as we move equidistantly away from the sediment source in either direction. As tectonic tilting is introduced, a range of changes in the stratigraphy occurs. All sections in Fig. 5 are displayed after rotating the tilting table back to its initial horizontal position. The section taken from STEP-12-MIN begins to show slight changes in the stacking patterns (Fig. 5b), but the section from STEP-12-LOW shows clear distinctions in the stacking patterns as well as sediment partitioning (Fig. 5c). The section from STEP-12-LOW shows more amalgamation of channel sands, with thicker sand bodies that are laterally connected in the uplift side. The subsidence side shows the opposite effect; amalgamation of channels is less common, and aggradation occurs (Fig. 5c). Floodplain deposits interbed these sand packages and isolate them. A more dramatic shift in the stratigraphic asymmetry is observed between STEP-12-LOW and STEP-12-MED. In STEP-12-MED, uplift creates more lateral connectivity within the deposit due to amalgamated channel sands (Fig. 5d). Relatively, more white sediment (medium to coarse sand equivalent) than dark (fine-grained
equivalent) sediment in the uplift portion of the deposit is observed (Fig. 5d). The subsidence portion of the delta consists of an initial prograding lobe of prodelta deposits, clinoforms, and preserved fluvial dominated preserved topsets. Thin channel belts, bounded by erosional and/or nondepositional unconformities, are stacked above the initial deltaic deposit.

As the tilting rate increases further in STEP-12-HIGH and STEP-12-MAX, the overall shoreline progradation rate decreases (see the shoreline data in Fig. 3), which creates more aggradation (instead of progradation) over time. In STEP-12-HIGH, a high stand system tract develops in the subsidence side (Fig. 5e). Progradational stacking of channel belts significantly diminishes along with the concave-up shoreline trajectory (Fig. 5e). STEP-12-MAX shows an immediate retreat of the local shoreline, depositing a back-stepping shoreline (Fig. 5f), and relatively thick delta lobes consisting of lateral accretion packages, floodplain deposits, and avalanche units.

DISCUSSION

Tectonic and channel timescales: theory

In the STEP basin experiments, fluvial channels rework the deltaic surface through channel migration and avulsion (see more description about the fluvial autogenic processes in Kim et al., 2006a; Kim & Muto, 2007; Kim & Paola, 2007; Kim & Jerolmack, 2008; Powell et al., 2012). Systematically, a channel develops in the middle of the delta, which produces a prograding lobe that protrudes beyond the previous shoreline. This channel bifurcates into two channels that laterally migrate away from the original location in opposite directions, reworking the surface of the delta. The lateral migration of the channels delivers sediment from the sediment feeder along with reworked sediment to be deposited at the shoreline, creating progradation. At the end of this cycle, the shoreline is radial and relatively smooth, with no obvious individual lobes. Finally, avulsion will create a new, single channel in the middle of the delta, and the cycle repeats. However, the degree of reworking in the delta plain by channel lateral migration and avulsion is modified by the change in surface slope, which is induced by the active lateral tectonic tilting (differential subsidence). Kim et al. (2010) hypothesized that variations of lateral subsidence could attract channels to areas of high subsidence if the tectonic subsidence was strong enough. They suggested that the reaction of a fluvial system could be predicted based on a ratio between characteristic channel and tectonic timescales. We briefly summarize these two timescales here and then further develop a theory for the current deltaic condition. Kim et al. (2010) stated that channels will only be preferentially steered to the maximum subsidence if the basin surface slope is modified such that

\[
\frac{S_x}{S_y} \leq O(1),
\]

where \(S_x\) is the topset slope in the downstream direction and \(S_y\) is the slope of the topset in the cross-stream direction, and \(O(1)\) indicates an inequality due to natural variation in topography or any variation induced by tectonic
tilting. A timescale over which tectonic movement changes the lateral surface slope to overcome the downdip slope can be written as

$$T_t = S_x \frac{\Delta \sigma}{L_y}$$

where $\Delta \sigma$ is the differential subsidence rate over the lateral distance $L_y$. Channel mobility can be represented as the time required for the internal channel dynamics of the system to rework the sediment surface in the basin:

$$T_c = \frac{B_t - B_w}{v_c},$$

where $B_t$ is the total width of the basin, $B_w$ is the wetted width of the basin, and $v_c$ represents the characteristic channel lateral migration speed. Kim et al. (2010) approximates $v_c = Q_s/h$, where $Q_s$ denotes sediment flux and $h$ is the average channel depth. Equation (3) represents the channel timescale best if the basin width does not vary in the downstream direction (e.g. a river basin confined in a valley) and if the basin length does not change with well-defined fixed upstream and downstream boundaries. This experimental delta is semicircular, therefore the delta plain width increases in the downdip direction and the delta plain length increases as the delta grows. The equation can be slightly modified with a total subaerial surface area to calculate how fast channels rework the whole deltaic surface with the size at the time of calculation as

$$T_c = \frac{A_t - A_w}{Q_s/h},$$

where $Q_s$ denotes the sediment discharge, $A_t$ is the total subaerial delta surface, and $A_w$ is the surface wetted by flow. Here, we calculated the channel and tectonic

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Fig. 5. Final deposit stratigraphy sliced at 1300 mm from the sediment source in (a) STEP-12-NON, (b) STEP-12-MIN, (c) STEP-12-LOW, (d) STEP-12-MED, (e) STEP-12-HIGH, and (f) STEP-12-MAX. The subsiding table was rotated back to be flat before slicing. Sand packages are mapped in all sections. The sections are vertically exaggerated 1.2 times for better presentation.
timescales at the onset of tectonic forcing (i.e. runtime = 90 min) and again at the end of each experiment because the deltaic system strongly progrades and changes the size of the surface area, \( A \). The shoreline downstream position at 90 min is about 0.8 m and the position at the end of the run (except STEP-12-MAX) is about 1.4 m. The down-dip slope, average flow depth, and proportion of the surface inundated by flow are approximated with 0.03, 0.02 m and 5% (at the end of run) – 10% (at the onset of tectonic stage), respectively. Timescales and ratios between the timescales (\( T^* = T_c / T_t \)) are given in Table 2.

The timescale ratio increases with time, due to the tendency of the channel timescale to increase with delta size, whereas the tectonic timescale remains constant regardless of delta growth. As the delta becomes larger, the surface area that needs reworking by the channelized fluvial system increases, requiring more time to travel the whole surface with the given sediment supply and thus lengthening the channel timescale. Since tectonic tilting is uniformly applied to the entire basin regardless of the size of the delta, the tectonic timescale remains constant. The timescale ratio in STEP-12-MIN increases from 0.03 to 0.1 as the average shoreline advances downstream from 0.8 to 1.4 m, but the system remains channel-dominated (i.e. \( T^* < 1 \)). In STEP-12-MIN, the shoreline from both the uplift and subsidence sides continuously prograded, and the sediments were still distributed fairly equally to each side of the basin (Fig. 3b). These results represent that channels take an equal amount of time on both sides of the delta plain and transport sediment freely regardless of the ongoing tectonics. The timescale ratio in STEP-12-MED begins with a value less than unity (i.e. 0.32), and increases to 1.03 at the end of the run. In other words, the system switches from a channel-dominated to a slightly tectonic-dominated system. Sediment volumes deposited on uplift and subsidence sides are equal for the first ca. 90 min after tectonic tilting starts (i.e. runtime = 90 – 180 min) and diverge as the shoreline asymmetry progresses (compare Figs 3d and 4d). STEP-12-HIGH shows a change in the ratio from 1.59 to 5.13. This tectonic dominance yields divergence of sediment volumes in the uplift and subsidence sides at the beginning of the tilting (Fig. 4e). Asymmetrical partitioning of sediment volume to the uplift and subsidence sides likely requires the ratio to be equal to or greater than one. However, the shoreline symmetry is only achieved at a ratio significantly less than unity (i.e. \( T^* < 1 \)). In general, the first-order calculation based on the simple eqns (2) and (4) serve as a good predictor of deltaic sediment distribution to the basin undergoing lateral ground tilting.

We note that the downstream equilibrium slope was approximated to 0.03 and was applied to all calculations, and the characteristic channel depth was set to 0.02 m for all the experiments. The downstream slope could increase significantly on the subsiding side and also, could decrease significantly on the uplift side, however, during the initial pre-tectonic stages, the slopes were approximately 0.03. We note that increasing the slope increased the tectonic timescale and led to a channel-dominated system and vice versa. The sediment supply and water discharge were the same across all the experiments, which support application of the constant channel depth in the timescale calculation. However, experimental channel geometry varied at locations where channels developed under the different tectonic forcings and subsequent shoreline progradation rates. The changes in channel width and depth were less than a few centimetres. Increasing the water depth increases channel timescale, and thus forces the system to become more tectonically dominated. The dynamic responses of channel geometry to tectonics and delta growth is an interesting topic, but out of the scope of this paper.

### Tectonic and channel timescales: experimental stratigraphy

The previous section, ‘Tectonic and Channel Timescale: Theory’, demonstrated the effectiveness that tectonic and channel timescales have in predicting the surface processes and deposit volume partitioning across the uplift
and subsidence sides of the delta. In this section, we used the sliced stratigraphic panels from the six experiments to create a general framework correlating timescale ratios to general stratal architecture on a macro-scale.

There are several important points to consider when observing the sliced sections in regards to timescales: (1) stacking patterns, and (2) spatial variations in sediment type and volume. We noticed no new creation of accommodation by tectonics during the control run (STEP-12-NON). Only thin amalgamated channels are preserved, and lateral changes consist of repetitive coarse to fine sequences due to progradation of new delta lobes. Deposit thickness of the sliced sections thickens to the subsidence side from STEP-12-MIN. The channel timescale in this run is much shorter than the tectonic timescale, and the delta was able to compensate for tectonic tilting in a system. There are limited large-scale changes in the stratarch architecture (the pattern of vertical stacking of channel belts and overland flood deposits) when compared laterally within the STEP-12-MIN section and also if compared with the section taken from STEP-12-NON. This suggests that when the tectonic timescale is greater by an order of magnitude or more than the channel timescale (STEP-12-MIN has a $T_c = 60$ min and a $T_T = 1900$ min), the stratigraphic response to the tectonic influence will be subtle, and determining the actual cause, whether tectonically driven or otherwise, would be difficult. STEP-12-MIN exhibits linkage between channel sands, both vertically and laterally for relatively large distances and more limited flood deposits on the uplift side.

As the tectonic timescale further shortens in STEP-12-LOW, that is, the channel timescale and the tectonic timescales have the same order of magnitude as seen in Table 2, fluvial system is affected enough by tectonics approximating the channel and tectonic timescales. We observe a lateral variation ranging from amalgamated channel sands (uplift) to aggrading channel belts with an increasing presence of fine-grained flood deposits (subsidence). This stratarch asymmetry and more isolated channel-body complex was not easily observed in STEP-12-MIN, suggesting that the timescale ratio is stratigraphically effective when $T^* > ~0.5$ or two timescales are within an order of magnitude.

Increasing the tilting rate even further exaggerates the changes observed thus far. The tilting rate of 0.02 mm s$^{-1}$ in STEP-12-MED forces the theoretical channel to tectonic timescale ratios to values between 0.32 and 1.03. The tectonic forcing leads to routing of a large majority of the sediment to the subsidence area and causes more volume of stacked channel belts (yellow in Fig. 5d) as well as fine grain equivalents, such as flood deposits. Moving laterally from the uplift to subsidence side reveals a drastic change from thin deposits of primarily coarser channel sands to large, isolated volumes of channel sand bodies. Therefore, a clear change in channel-stacking pattern across the basin can serve a useful indication for the presence of differential subsidence ($T^* > ~1$).

In STEP-12-HIGH and STEP-12-MAX, the uplift sides of the deltas are similar in thickness and extent to the runs with lower rates of tilting, but differ greatly in how much surface is reworked. Due to earlier abandonment, there are relatively less amalgamated clean channel sands on the uplift side. On the subsidence side, STEP-12-MAX displays a case of fast relative sea-level rise that outpaces sediment supply likely rivalled in a natural setting by very rapid subsidence that could occur in a pull-apart basin or any active setting that quickly creates accommodation. Under $T^* > ~5$, the fluvial deposit rarely records isolated channel bodies, but is dominated by alternating lateral accretion packages and floodplain deposits.

In summary, careful mapping of stratal asymmetry and channel-stacking patterns can work as a predictor for the timescale ratio, $T^*$. For instance, a delta undergoing relatively low differential subsidence, that is, where the channel timescale dominates by at least an order of magnitude or greater, will display stratigraphic symmetry similar to a basin without lateral tectonics, and minimal vertical stacking across the basin. As the tectonic timescale begins to approach and overtake the channel timescale, there are dramatic differences in the stratigraphic framework across the delta. Tectonic and channel timescales that are within the same order of magnitude produce highly variable stratal architecture across a basin. Amalgamated coarser sediment where less subsidence occurs vs. increased stacking of alternating coarse and fine sequences has more subsidence occurring in most experiments where differential subsidence is present in the basin. The amount of asymmetry (if any) in the stratigraphic record might locally vary due to the lithology and the presence and absence of vegetation, but can be useful to reconstruct basin tectonic history and relative fluvial activity by approximating the channel and tectonic timescales.

Possible sources of error

The tilting table used in the experiments is 4 m long. Over the duration of the 90 min tectonic stage in STEP-12-MAX, one corner was uplifted about 1 m, which shortens the relative length of the experimental table by ca. 0.1 m (Fig. 2b). Because the sediment feeding point is at the centre of the table, the feeding point moved laterally about 0.05 m throughout the STEP-12-MAX experiment. This value decreases in other runs due to their reduction in tectonic tilting rate. Therefore, the shoreline data (based on time-lapse image analysis) and volume calculation (based on the topographic scans) have a slight error associated with the movement of the sediment feeder. However, the sediment and water feeding point moved with the delta deposit and did not disturb the surface processes or the stratigraphic development.

In Fig. 4, the total volume at the end of each experiment is slightly different. The discrepancy among the total sediment volumes is due to (1) different degrees of the feeder movement associated with the imposed tectonic tilting rate, and (2) different amounts of sediment that
was deposited outside of the data collection range. A pre-existing sediment bar along the Plexiglas border was used to create roughness on the upstream wall, and thus preventing faster progradation along the Plexiglas. Erosion of this pre-existing sediment bar transported extra sediment into the measured area, producing error among experiments. Furthermore, the topographic scan was done with a 1 mm × 5 mm horizontal resolution, which may also induce errors when calculating the deposit volume. Finally, the topographic scanner used to measure the delta deposit had a very low tolerance to collecting surface data that is submerged under water. Therefore, only data from the subaerial portion of the delta is accurately recorded, and inundated parts of the system were not scanned effectively.

**Shoreline asymmetry in the Ganges–Brahmaputra delta system**

The G–B delta and submarine system are comprised of over 1.3 × 10⁷ km³ of deposited sediment, currently releasing over 1 billion tons year⁻¹ of sediment (Milliman & Syvitski, 1992; Goodbred & Kuehl, 2000b), making it the largest active depositional system on Earth. It has been active as early as the late Cretaceous, due to subduction of the eastern Indian plate under the Eurasian plate. The majority of sedimentation began with the Oligocene, when the continental portion of the northern Indian–Eurasian collision resulted in the Himalayan orogeny. Very high volumes of sediment were eroded and removed from the Himalayas and Tibetan plateau. The significant amount of continental material that escaped helped accommodate the accretion of new terrain along the western and eastern portions of the Himalayas (Tapponnier et al., 1981). Our area of interest lies where the Ganges and Brahmaputra Rivers join as the primary source of sediment for the delta. The two rivers combined produce a discharge that exceeds 10⁶ tons per year directed in a primarily southward vector into the Bay of Bengal (Allison, 1998). The entire sedimentary system includes the subaerial delta, the subaqueous delta, and the submarine fan (Fig. 1). The subaerial tidally influenced delta is a wedge shaped tract of land above sea level covering ca. 100 000 km² of various deltaic environments (Goodbred et al., 2003), bounded to the west by the Indian continental crust and to the east by the Burma arc. When seen in map view, the subaerial delta appears to have a strong sense of shoreline asymmetry (Fig. 1). We are interested in whether the subaerial delta evolved under conditions of differential subsidence.

Defining the tectonic setting is crucial to understanding the link between the G–B delta and insight gained from the experimental results. The convergence rate of the N–S trending Burma arc is ca. 70 mm year⁻¹ (Tregoning et al., 1994). Increased subsidence in the east and northeast portions of the G–B delta has been attributed to flexural loading in the northeast of the G–B delta (Stanley & Hait, 2000). This subsidence pattern could also be explained from compression of the Indian plate due to the Indo-Burman fold belt and subsequent “downwarping” (Goodbred et al., 2003) along with an increasing subduction angle over time. This increase in the subduction angle is possibly due to the load from the growing accretionary prism (Pal et al., 2003). This down-going subduction angle is roughly perpendicular to the primary direction of sediment transport into the Bengal Basin and creates differential subsidence acting on the delta system. Thus, the delta system experiences different rates of subsidence and subsequent creation of accommodation space depending on the location relative to the ‘tectonic hinge’ (Alam et al., 2003) along which flexure of the plate occurs. Palamenghi et al. (2011) documented differential subsidence in this basin by using C¹⁴ dating of a laterally correlative layer dating from ca. 5000 years ago. On the western side of the basin, these sediments are currently buried at 2 m below the current sea level, whereas the eastern side is buried at 20–30 m deep.

The G–B delta has been heavily influenced by tectonics, despite admittedly being poorly understood with respect to delta evolution (Goodbred et al., 2003). The G–B delta is traditionally considered a tidal delta system (Bhattacharya, 1992; Barua & Kana, 1995; Allison, 1998; Roy et al., 2005; Ali et al., 2007; Fagherazzi, 2008). We acknowledge that tidal and wave dominated deltas can have shorelines that are affected by tidal and wave action, which possibly control the geometry of the shoreline (van der Vegt et al., 2009). Barua & Kana (1995) suggests that tidal action in the eastern G–B delta may encourage a counter-clockwise gyre water motion that re-mobilizes sediment along the coastline, which has a water depth of <10 m. However, the extent of asymmetry seen in the G–B delta is significant and seems too difficult to explain through tidal or wave action alone. The western side of the delta is ca. 75 km further downstream compared to the eastern side. Fitzgerald (1984) showed that for ebb-tidal deltas, morphological influences were focused in the sand bars, spits and shoals, which underwent changes in size and shape due to the changes in current vectors. Tidal currents, coupled with wave action, effectively re-worked the shape and direction of the delta bars (see figure 6 of Fitzgerald, 1984). However, the magnitude of these changes, along with the temporal constraints over which these changes occur, suggests that there may be another factor responsible for the shoreline asymmetry seen at the scale witnessed on the Ganges–Brahmaputra. Fitzgerald (1984) found that these changes occur on small temporal scales (ranging from 4 to 42 years for the Prince Inlet delta, South Carolina, USA) and on smaller scales (metres to hundreds of metres).

The G–B delta is not currently prograding, according to Allison (1998). Lack of obvious progradation suggests that sediment supply is balanced with relative sea-level rise. Using the most conservative estimated values, we approximate the ratio between the channel and tectonic timescales using the updated equations from Kim et al.
(2010). Previous papers (e.g. Palamenghi et al., 2011) on the G–B delta presented a range of subsidence rates that can be used for the timescale calculations, thus we encompassed both conservative and liberal values, that is 2–4 mm year$^{-1}$ to calculate the minimum and maximum possible ranges of these timescales (see Table 3). Applying additional parameters obtained from other studies (Table 3) to eqns (2) and (4) results in $T^* \sim 1$, and thus the tectonic timescale is of comparable magnitude to the channel timescale (Table 2).

Next, we examine if the G–B delta exhibits indications of the fluvial and shoreline processes causing the stratal asymmetry seen in the STEP-12-LOW and STEP-12-MED. The characteristics associated with the timescale ratio are expressed both surficially and stratigraphically in the STEP basin experiments. The primary indicator that we observed as evidence of differential subsidence was the marked asymmetry in the subaerial system. The experimental results give insight into the surface and stratigraphic responses of deltas.

### CONCLUSIONS

We performed a series of six experiments in the STEP basin at The University of Texas at Austin, which introduced a lateral tectonic tilting component to a fluviodeltaic system. The experimental results give insight into the surface and stratigraphic responses of deltas.

### Table 3. The values used in our timescale calculations for the Ganges–Brahmaputra delta. We gathered data from various authors to encompass a range of reasonable numbers

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value(s)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$</td>
<td>2–4 mm year$^{-1}$</td>
<td>(Goodbred &amp; Kuehl, 2000a)</td>
</tr>
<tr>
<td>$A_i$</td>
<td>80 000–200 000 km$^2$</td>
<td>(Alam et al., 2003; Goodbred et al., 2003)</td>
</tr>
<tr>
<td>$A_w$</td>
<td>10$^{10}$</td>
<td>Approx. from Google Earth</td>
</tr>
<tr>
<td>$h$</td>
<td>5–15 m</td>
<td>(Bristow, 1993; Allison, 1998)</td>
</tr>
<tr>
<td>$L_f$</td>
<td>200 km</td>
<td>Approx. from Google Earth, (Alam et al, 2003)</td>
</tr>
<tr>
<td>$Q_i$</td>
<td>12–17 m$^3$ s$^{-1}$</td>
<td>Based on 1 $\times$ 10$^9$ tons year$^{-1}$ (Allison, 1998)</td>
</tr>
<tr>
<td>$S_f$</td>
<td>5.0 $\times$ 10$^{-5}$</td>
<td>Google Earth</td>
</tr>
</tbody>
</table>

(1) Introducing lateral tectonic tilting into an experimental fluviodeltaic system, where uplift occurs on one side of the delta and subsidence occurs on the other, changes the surface process dynamics of the system, resulting in an asymmetric shoreline. The deltaic shoreline position progrades faster under active uplift (relative base-level fall) than a shoreline undergoing subsidence (relative base-level rise). Despite the ability of subsidence to steer channels and distribute more sediment to the subsidence side, shoreline migration rates still do not increase due to an active rise of relative base level, as seen in STEP-12-HIGH and STEP-12-MAX.

(2) A delta undergoing differential subsidence will preferentially route sediment to the area of maximum subsidence. If the difference in subsidence is great enough, the fluvial system will starve and eventually abandon the area of the delta that is undergoing relative uplift and dedicate all of the sediment and water discharge to the portion of the delta undergoing the most subsidence. If the difference in subsidence is comparable to the surface reworking ($T^* \sim 1$), the fluvial channels slightly erode the uplift side and transport larger amount of sediment through the shoreline on the uplift side.

(3) Implications of lateral tectonic tilting can be seen in large-scale basin stratigraphy. When the tectonic tilting rate is large enough to induce changes in sediment volume dispersal, it is also large enough to change the stratigraphic stacking patterns of the deposit. Under no tilting and the minimum rate of tilting, there is little difference in the basin stratigraphy exhibited laterally across the basin. As tilting increases and the timescale ratio nears $T^* \approx 0.5$, it begins to show amalgamated channels where uplift occurs, and slightly aggradational stacking of channel sand bodies. Overland floodplain deposits representing fine material are still present throughout; however, sediment partitioning begins preferentially routing more material towards the area of maximum subsidence. As the tectonic timescale converges with the channel timescale ($T^* \geq 1$), the uplift portion of the delta is re-worked and leaves thin, laterally linked amalgamated channel sands in place, whereas a higher percentage of the sediment volume is deposited to the area of most subsidence. Further relative base-level rise ($T^* \geq 10$), along with the relative increase in sediment discharge in this area, results in an aggradational system at which thin amalgamated channel bodies on the uplift portion shift laterally into stacked sandy channel belts separated by fine overland flood deposits.

(4) The Ganges–Brahmaputra delta system serves as a compelling analogue to the series of lateral tectonic tilting experiments performed in the STEP basin. Differential subsidence (less subsidence or possible uplift in the western portion vs. increases subsidence in the eastern portion of the G–B delta) results in geomorphic and stratigraphic changes in the deposit laterally and vertically throughout geological time. We found that the asymmetry seen in the shoreline of the G–B delta can be better...
explained by the differential subsidence as opposed to tidal effects observed along the delta due to subduction along the Burma Arc. The current G–B delta has $T^* = 0.4–0.8$, similar to STEP-12-LOW and STEP-12-MED. This $T^*$ range is back by the asymmetry observed in the stratal architecture, where sandier channel belt deposits are found in the western delta vs. an increased prevalence of flood deposits in the eastern portion. Shoreline asymmetry, stratigraphic differences and the theoretical timescales all point towards the comparable tectonic movement to the fluvial activity as being the domineering factor shaping the G–B delta.

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