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SEDIMENT STORAGE PARTITIONING IN ALLUVIAL STRATIGRAPHY: THE INFLUENCE OF DISCHARGE VARIABILITY

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ABSTRACT: **Numerical models of formation of alluvial stratigraphy often specify, either explicitly or implicitly, the proportion of channel and overbank sediments that are deposited during a given interval of time. However, little is known about the factors that affect the partitioning of sediment between channels and the overbank environment over long time intervals, and the fidelity with which that partition is preserved in the stratigraphic record. Here we use physical experiments to investigate the role that discharge variability plays in this partitioning in fluvial stratigraphy. We find that channels formed under constant flow conditions have low lateral mobility and act mostly as conduits for sediments to reach the shoreline. The bulk of the aggradation in this case is derived from sediment-laden flow that escapes the main channels. By contrast, including floods increases channel lateral mobility, and this change is recorded in stratigraphy as an increased proportion of channel deposits relative to overbank deposits. When variable flow is included as an input condition a large volume of in-channel deposition occurs, rendering the channels substantial contributors to stratigraphic volume on their own. The increase in channel deposit volume is driven mainly by a threefold increase in the average time that a location is subject to in-channel aggradation. Other factors include a slight increase of in-channel aggradation rates, and an increase in erosion of the overbank environment that results from energetic overbank flows. Our study shows that the character of a river's hydrograph exerts a significant influence on the proportion of channel to overbank sediment bodies in alluvial successions, which is an unexamined source of uncertainty in common stratigraphic models.**

INTRODUCTION

Our eyes and attention are more easily drawn to a river's channel than to the sodden swamps that surround it, but most lowland rivers are embedded in a dynamic overbank environment that plays an important role in managing the channel (Mohrig et al. 2000; Aalto et al. 2003; Hajek and Edmonds 2014). Deposition in the overbank environment, which receives overflow from the main channel as well as from breaches and crevasses in the channel margins, is documented to influence channel behavior through a variety of mechanisms: Overbank environment topography and depositional dynamics are known to be important, because avulsion timing and location can be influenced by regional slopes (Slingerland and Smith 1998), by local features associated with both active and relict channels (Mohrig et al. 2000; Slingerland and Smith 2004; Jerolmack and Paola 2007), and by the ability of flow to cause erosion (Hajek and Edmonds 2014). Bank strength, which is affected by the characteristics of the overbank sediments (Caldwell and Edmonds 2014) and by vegetation patterns (Tal and Paola 2007; Nardin and Edmonds 2014), plays an important role in setting the lateral mobility of channels. And in turn, channel lateral mobility is thought to affect whether a river forms a single-thread channel or a branching network (Jerolmack and Mohrig 2007), implying that the dynamics and composition of the overbank environment play a fundamental role in setting the morphodynamic style of a river, and in the formation of alluvial stratigraphy.

Our analysis centers on the fundamental process linking channels and the overbank environment: floods. Specifically, we are interested in the degree to which the character of a river's hydrograph influences the partitioning of sediment between channel and overbank deposits, and the long-term storage in either environment. Our research is grounded in the field of quantitative stratigraphy, with a specific eye on improving the process basis for stratigraphic models of filling of alluvial basins, such as the well-known Leeder–Allen–Bridge models (Allen 1978; Leeder 1978; Bridge and Leeder 1979) and their derivatives. However, improving our understanding of sedimentary function in overbank environments is an important goal across a variety of disciplines. Information about temporal trends in the channel to overbank sediment ratio of a river's deposit can provide important context to stratigraphic reconstructions across climate boundaries (e.g., Foreman et al. 2012), and could factor in to global predictions of fluvial response to climate change (Toonen et al. 2017). Further, sequence stratigraphic reconstructions of alluvial successions along continental margins (e.g., Huerta et al. 2011; Marenssi et al. 2015) will be improved by considering hydrograph variability in the context of the existing allogenic forcings of accommodation and sediment supply. We also note that the role of overbank environments as sinks for fine-grained sediments makes them important to the global carbon cycle (Sutfin et al. 2016), and our results imply that changes to regional precipitation patterns

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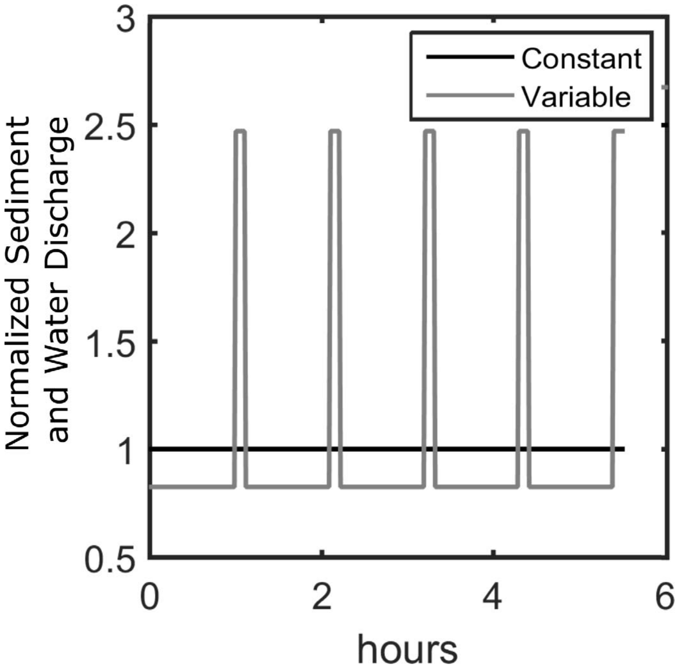

FIG. 1.—Experimental sediment and water discharge. Sediment and water discharge for the constant-flow experiment does not vary. Sediment and water discharge during the high flow periods in the variable-flow experiment are three times that of the low-flow periods, while their time integral is equal to that of the constant-flow experiment. Values shown here are normalized by the values from the constant-flow experiment.

in response to global climate change (e.g., Scholes et al. 2014) could influence terrestrial carbon budgets.

While we are unaware of any study that ties the channel/overbank partition to the character of a river's floods, recent years have seen a deluge of interest into whether and how information about flood intensity is transmitted into the stratigraphic record, from the scale of regional channel avulsions (Chatanantavet et al. 2012; Ganti et al. 2014; Plink-Björklund 2015) to that of bar dimensions and bedforms (Sambrook Smith et al. 2010; Van de Lageweg et al. 2013; Shaw and Mohrig 2014; Nicholas et al. 2016). Much of the research into the stratigraphic signature of variable flow has thus far focused on defining sedimentary structures and the geometry of the channel deposits. One point that is often overlooked is that the influence of floods is felt just as keenly in the floodplain as it is in the channel. We present data from two physical basin experiments. One of our experiments features a variable hydrograph, and the other was run with constant water and sediment input. We compare the surface dynamics and stratigraphy of the two experiments to test the hypothesis that floods influence channel lateral mobility, and that this plays a role in partitioning sediments between channel deposits and overbank deposits. Our analysis is relevant to any fluvial environment that is subject to regular variations in discharge.

EXPERIMENTAL PROCEDURE

We compare results from two physical experiments that were conducted in the Tulane Delta Basin, which is 4.2 m long, 2.8 m wide, and 0.62 m deep. Sediment is fed with a commercial sediment feeder into a funnel that sits above the delta basin, where it is mixed with water and then flows by gravity into the basin. Water drains through a weir on a computer-controlled vertical slide at the downstream end of the basin. The two experiments differed only in that one was run under constant flow conditions (constant- discharge case) (Straub et al. 2015; Li et al. 2016) while the other featured a hydrograph (variable-discharge case). Our variable-discharge experiment was conducted so that the average discharge of sediment and water was the same as in the constant-discharge experiment, but that the discharge at flood was three times that at base-flow (Fig. 1). This discharge ratio is in the range of large rivers in temperate climates like the Mississippi River, but lower than what would be expected in a monsoonal climate (Allison et al. 2013; Plink-Björklund 2015). Sediment-to-water ratio was held constant between flood and base-flow conditions. While sediment-to-water ratio typically varies seasonally in natural systems, we chose to hold it constant in order to clarify the analysis. The sediment mixture used in both experiments is based on the cohesive mixture developed by Hoyal and Sheets (2009), and contains silica flour, quartz sands, bentonite, glass beads, cat litter, and a polymer that increases sediment cohesion. The increase in sediment cohesion adds bank strength that enables single-thread channels with sandy beds to form at subcritical Froude numbers, and the large proportion of fine sediment is intended to result in a large and dynamic overbank environment. The sediment mixture used here is the "strongly cohesive" mixture used by Straub et al. (2015). Basin dimensions and a background rate of sea-level rise (0.25 mm/hr), which promoted conditions of net deposition, were constant between the experiments (Table 1).

The constant-flow experiment was paused every 60 minutes to collect topographic and co-registered RGB data of the delta surface with a FARO laser scanner (dry scan). In order to locate flow paths a second scan (wet scan) was taken near the end of each run hour while the experiment was running, with the water dyed blue. Data collection during the variable-flow experiment differed in that RGB data were collected with a digital camera mounted above the basin, and that RGB data were collected once at the end of the run cycle (dry photo), once during the flood (flood photo), and once during low-flow conditions (low-flow photo). As with the constant-flow

TABLE 1.—*Delta parameters. Forcing conditions and measured morphological parameters for the constant-discharge and variable-discharge experiments. Sediment and water inputs in the variable discharge experiment are set such that the high discharge is three times the low discharge, and their time integral is equal to that of the constant-discharge experiment.*

		Constant Discharge	Variable Discharge, Low	Variable Discharge, High
Input Conditions	Q_s (kg/s)	3.91×10^{-4}	3.23×10^{-4}	9.68×10^{-4}
	Q_w (m^3/s)	1.72×10^{-4}	1.42×10^{-4}	4.25×10^{-4}
	sea-level rise rate (mm/hr)	0.25	0.25	0.25
	cycle time (min)	60	59	7
	Total run time (hr)	900	186	
Calculated Parameters	maximum channel depth (mm)	15–20	10–12	
	Terrestrial growth rate (mm^3/hr)	2.40×10^5	4.70×10^5	
	Average delta top area (m^2)	0.9	1.6	
	T_5 (hr)	64	19	

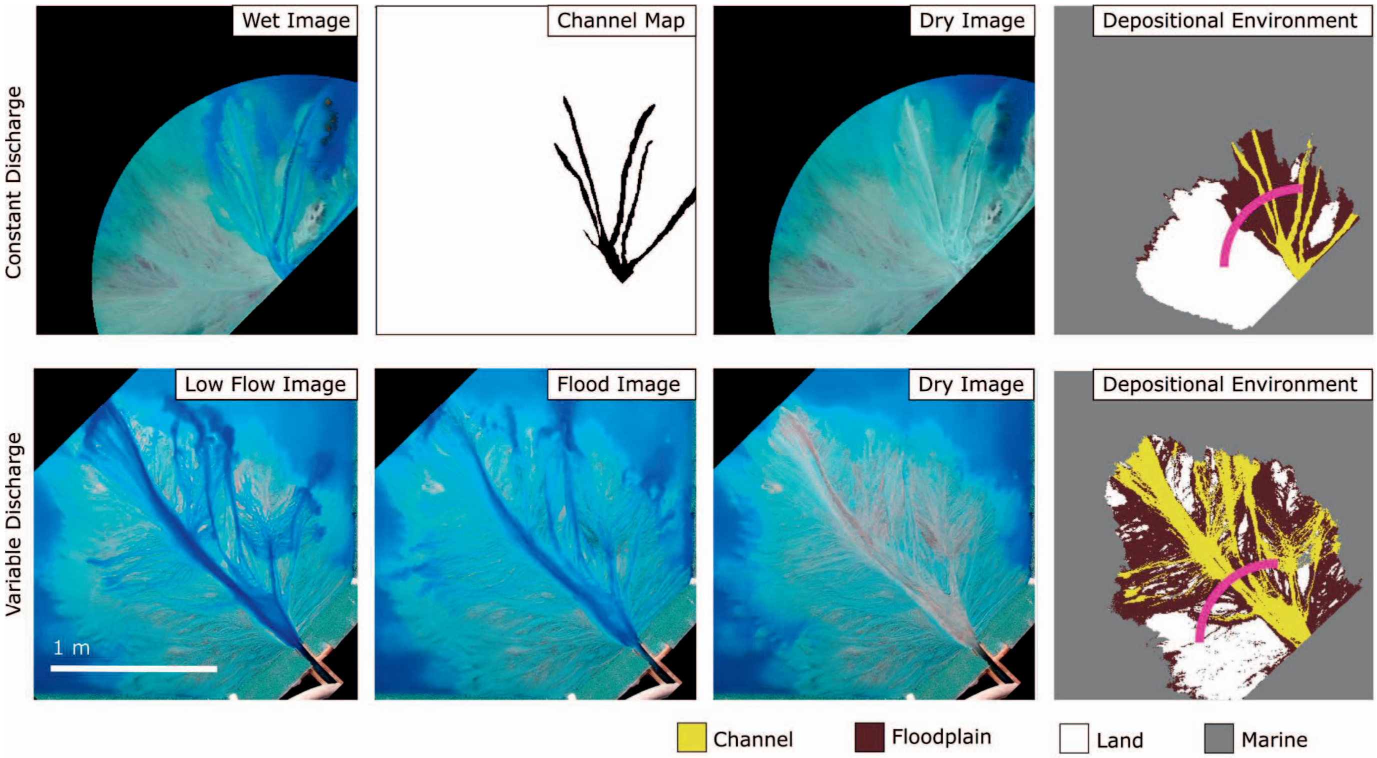

FIG. 2.—Depositional environments. Maps of depositional environments were generated for each delta using the RGB data, the handpicked channel maps (constant flow only), and topographic data collected with the FARO laser scanner, of which examples are displayed here. The locations of cross sections shown in Figure 7 are marked by magenta lines. Note the small linear features present in the variable-discharge overbank environment but absent in the constant-discharge case. The constant-discharge data shown here are from the cycle ending at hour 452, and the variable-discharge data are from the cycle ending at hour 535.4.

experiment, topographic data were collected with the FARO at the end of the run cycle. In both experiments the FARO data were interpolated horizontally to a 5 mm by 5 mm grid. The vertical resolution on the laser scanner is approximately 1 mm. The position of the camera used in the variable-flow experiment ensured minimal lens distortion on the delta top, and the photographs were latched to the FARO coordinate system with a nonreflective similarity transform and resampled. The image transform was assessed visually to match the scan data within the 5 mm pixel resolution. Each cycle of low and high-water conditions in the variable flow experiment lasted 66 minutes, with 7 minutes at flood and 59 minutes at base flow (Fig. 1, Table 1). The timing of the flood within each cycle was set so that the delta would be in flood for approximately 10% of each cycle. The length of the cycle is set so that there would be a large number of cycles in the time necessary to aggrade, on average, a single channel depth everywhere on the delta top, which has been shown to be an important timescale of autogenic activity. The total experimental run time was long enough to aggrade several channel depths, which allows us to assume that the time-series behavior of the system parameters that we measure is statistically stationary (Straub et al. 2009; Wang et al. 2011).

We used RGB images, topographic data, and visual assessments to classify each pixel as one of four depositional environments: ocean, channel, active overbank, or dry land (Fig. 2). To do so we first made wet–dry maps by applying a threshold to the ratio $\frac{(blue-red)}{(blue+red)}$ at each pixel for each image. The technique is similar to the Normalized Difference Vegetation Index (NDVI) measurement (Tucker 1979) used to identify vegetation in remote-sensing applications, and minimizes the effects of uneven lighting across the delta, and of inconsistent lighting between images.

Because we had both high-flow and low-flow images from the variable-discharge experiment we were able to set an aggressive threshold that confidently identified deep water in the low-flow image, and a less stringent threshold to distinguish land from any water in the flood images. Any pixel that was wet during both high and low flow conditions was considered to be a channel, while pixels that were wet only at high flow were marked as active overbank, and pixels that were not wet at all during the cycle were marked as land. We defined ocean as pixels that were wet during all three images, or which had an elevation below the current imposed sea level. The redundant method of defining the ocean results in a shoreline that is always the most conservative. Any pixel that did not fall into one of these defined categories (for example, a pixel that was wet at low flow but not at high flow) was discarded as spurious.

In the constant-flow experiment, where we had a single wet image from each cycle, we were thus not able to use an aggressive color-ratio threshold. In practice this meant that the active overbank environment could be distinguished from land with a threshold as above, but channels had to be picked by hand (see Fig. 2 for an example of a picked channel map, and the source photograph). Once the channel maps were defined, the process of defining depositional environments was identical to the variable flow experiment. Slight variations in the basin water-surface elevation between high and low flow conditions in the variable-flow experiment caused errors in interpreting the depositional environment near the shoreline. To avoid this problem we restricted our analysis, including all figures and all calculations, to pixels that were terrestrial (i.e., non-ocean) more than 50% of the time for both experiments.

RESULTS

We use our depositional-environment maps coupled with our time series of topography to focus our analysis on the role that variable flow plays in channel mobility, and in the partitioning of sediment between channel deposits and overbank deposits. Our first task then was to quantify the

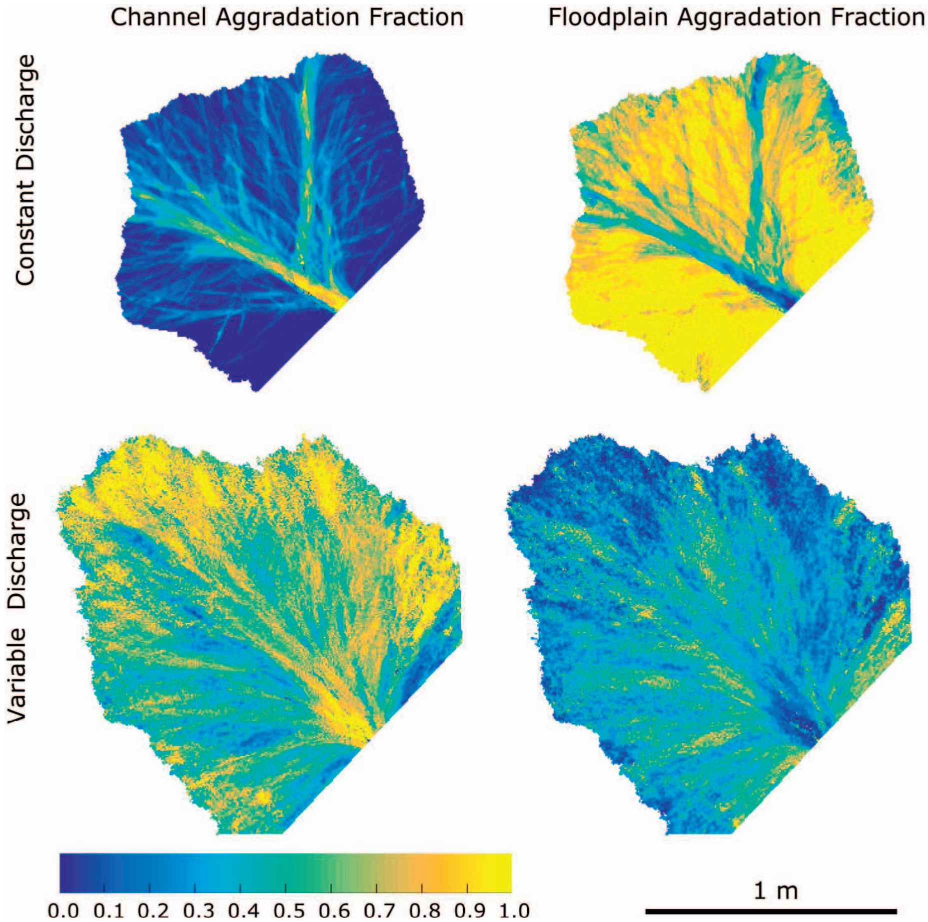

FIG. 3.—Aggradation fraction. Maps showing the fraction of the total thickness attributable to channelized or overbank deposition. Overbank deposition dominates the constant-flow case, but in the variable-flow case the observed trend is reversed.

deposit volume that is stored in each depositional environment during the experiment. By assigning the aggradation during a timestep in a pixel to the appropriate depositional environment and removing eroded volume, we generated synthetic stratigraphy for the entire delta deposit. We then calculated the fraction of the thickness of each deltaic deposit that is attributable to channel deposits or to overbank deposits. This calculation (Fig. 3, Table 2) shows that 76% of the constant discharge stratigraphy is composed of overbank deposits, and only 11% is channel deposit. The remaining 13% is marine deposition or deposition in pixels characterized as land, which occurs occasionally by flows that were not active at the time that the overhead photograph was taken. By contrast, in the variable-flow delta the overbank and channel deposit fractions are closer together at 39% and 43%, respectively. The maps of depositional environment and aggradation at each timestep will form the basis for the remainder of our analysis. With the long-term average sediment partition established, we used the maps to investigate the transition from short-term sediment partitioning to long-term, as a function of channel mobility and rates of vertical change (aggradation or erosion) in the channel and overbank environments.

In depositional systems where mobile channels are present, channels that migrate through the overbank environment rework sediments that have been deposited there. Some of the reworked sediment will be removed from the overbank environment entirely, implying that the volume of sediment stored in the floodplain should decrease with increasing measurement interval. To investigate the timescales that are relevant to sediment partitioning, we calculated the fraction of the sediment input that was stored in channel and overbank deposits as a function of the temporal measurement interval, shown in Figure 4. For these calculations the total measured change in delta deposit volume was calculated for each possible time interval and divided by the volume of sediment that was input to the basin over that interval. Conversion from sediment mass input (Table 1) to volume input was achieved using a deposit porosity of 53% and a sediment density of 2650 kg/m^3. The sediment porosity of this sediment mixture was

TABLE 2.—*Aggradation calculations. Table showing the deposit volume fraction and occupied time fraction for channel and overbank environments. These values are spatial averages of the data shown in Figures 3 and 5. Effective aggradation rate is derived from deposit volume fraction and occupied time fraction. Note that deposit fractions do not sum to unity. The remainder in each deposit is composed of ocean deposition or deposition in pixels classified as land.*

		Channels	Overbank
Variable discharge	Deposit volume fraction (–)	0.43	0.39
	Effective aggradation rate (mm/hr)	0.76	0.20
	Occupied-time fraction (–)	0.22	0.43
Constant discharge	Deposit volume fraction (–)	0.15	0.76
	Effective aggradation rate (mm/hr)	0.68	0.43
	Occupied time fraction (–)	0.07	0.42

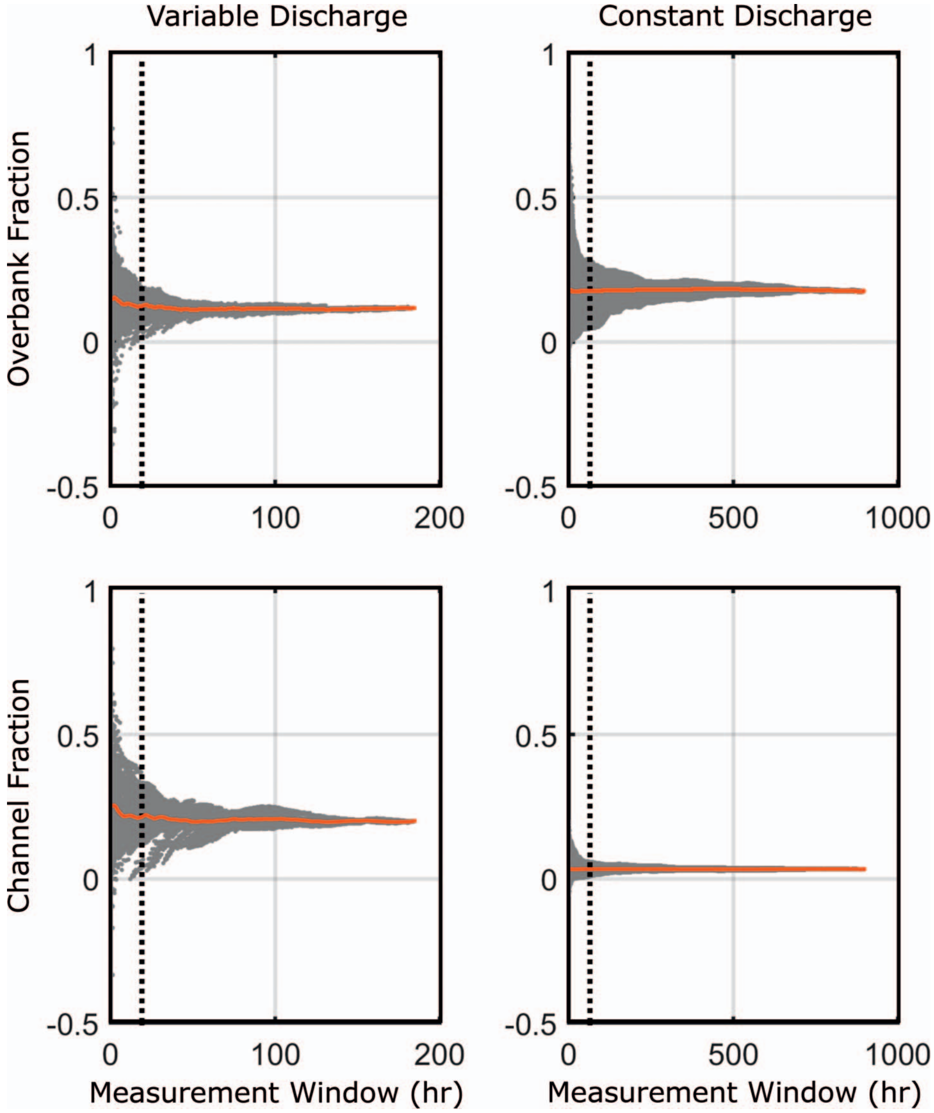

FIG. 4.—Delta deposit fraction. The overbank and channel deposit fraction for each delta, displayed as a function of measurement interval. Each gray dot represents the fraction of the total sediment input to the basin during a time period that is preserved as the given deposit type. The average for each measurement window is shown as an orange line. Values below zero indicate net erosion for that environment. The T_5 statistic (Fig. 6) is shown as a dotted black line. Because these data are calculated as a fraction of sediment input to the basin rather than sediment deposited in the delta top, the magnitudes are lower than those shown in Table 2.

measured by Straub et al. (2015), where it is referred to as the strongly cohesive mixture.

We also compute the time of occupation for channel and overbank environments, shown in Figure 5. The overbank environment in each experiment occupied the entire delta area with similar frequency, but the pattern of channel occupation was different. The constant-flow case shows a small number of channel locations surrounded by a high proportion of delta-top area that was never or very rarely occupied by a channel. In the variable-flow delta almost every spot on the delta was occupied by a channel for a significant amount of time. This is an indication of high mobility of the variable-flow channels, which is discussed further below.

To investigate rates of vertical change, we follow the technique of Sheets et al. (2002) and calculate the effective aggradation rate of channel and overbank environments by dividing the total aggradation attributable to one environment at a given location by the occupation time of that same environment. The result of this calculation, displayed in Table 2, shows that channels in the variable-flow experiment aggrade only slightly more rapidly than those in the constant-flow experiment, but that a location on the variable-flow delta top is subject to channel aggradation for an average of 22% of the time, which is more than three times as long as the 7% experienced by a location in the constant case. Locations on both deltas are subject to overbank aggradation for approximately the same fraction of time, but the overbank effective aggradation rate is fast in the constant-discharge delta (0.43 mm/hr) relative to the variable-discharge delta (0.2 mm/hr). Time that is not spent as overbank or as channel is spent as either a dry land or a marine environment. The effective aggradation rates shown in Table 2, and discussed thus far, are net rates that implicitly include erosion. In Table 3 we decompose the effective aggradation rates into pure aggradation and erosion. In this way we see that erosion affects the overbank environment in both experiments, but that erosion in the variable-discharge overbank environment takes place slightly more often (17% of the time, compared to 13%) and operates at substantially higher rates (0.52 mm/hr, compared to 0.27 mm/hr) than in the constant-flow case.

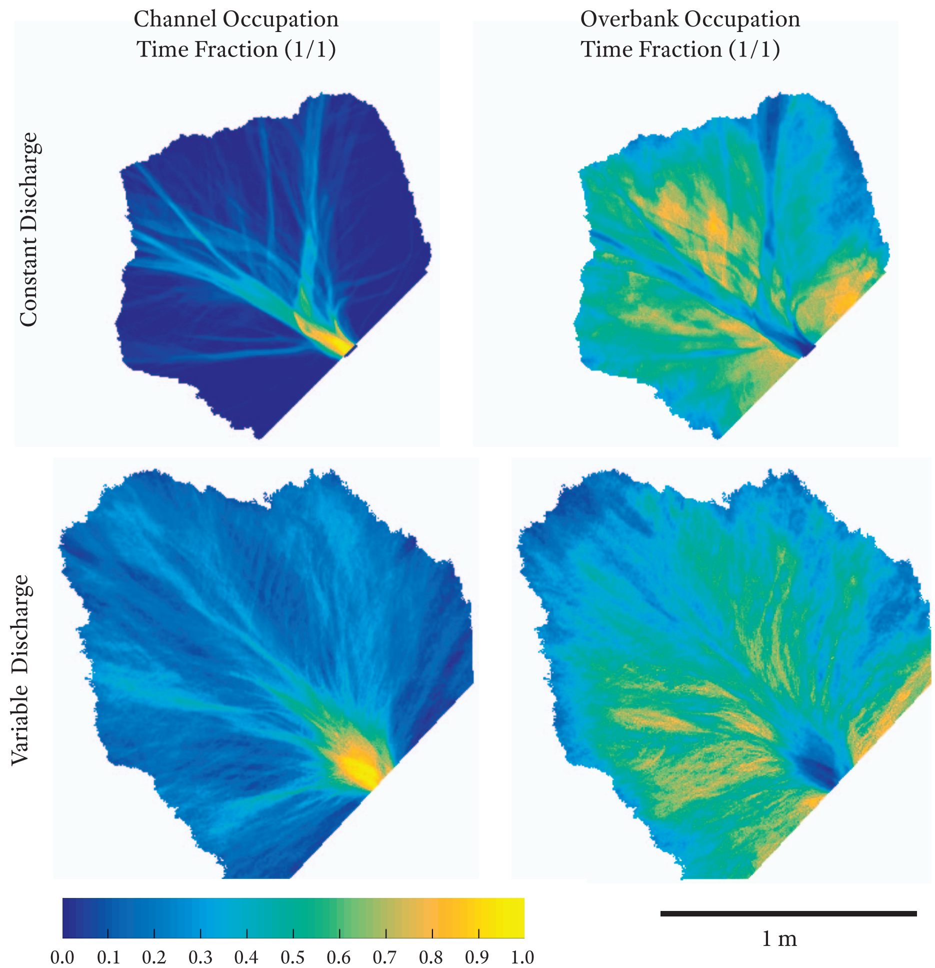

FIG. 5.—Occupation time. Maps showing the fraction of total run time spent as a channel or as overbank. The variable-discharge maps show the entire run time of 186 hours. We used a 186-hour-long portion of the constant-discharge experiment (hours 500 to 686) for consistency.

Finally, we quantify channel mobility with the normalized overlap statistic introduced by Wickert et al. (2013) (Fig. 6). This technique measures the amount of time necessary for the channel network to change such that no information about the initial channel pattern is preserved. The key calculation is to compute the number of pixels that have changed between channel and non-channel environments from an initial timestep to a future timestep. We then compute the number of changed pixels that would be expected if the equivalent channel and non-channel areas were randomly distributed in the map of each timestep. A ratio near 1 of the number of pixels that were changed to the number that were expected to be changed randomly indicates that very little information has been preserved, and achieving such a value in a small number of time steps indicates high channel mobility. This ratio, subtracted from 1, is referred to as the normalized overlap statistic. As suggested by Wickert et al. (2013), we perform this calculation beginning at each timestep, and measure the average number of subsequent timesteps necessary to get 95% of the way towards no retained information, which we call T_5 (Table 1). The T_5 for the constant-flow channel network is 64 hours, and is 19 hours for the variable-flow case, confirming that the constant-flow channels are less mobile, and it therefore takes much longer for their networks to decorrelate.

Our results connect the partitioning of channel deposits vs. overbank deposits to the morphodynamics of the channels. Channels in the constant-flow experiment tend to remain in place for long periods of time (Fig. 5, serial images in SI), resulting in isolated, vertically aggrading channels. These isolated channels are evident in the preserved stratigraphy (Fig. 7), as are the natural-levee deposits that flank them and the overbank sediments beyond the levees. In this scenario channels act mostly as conduits for sediments to reach the shoreline; the bulk of the aggradation that occurs on the delta top is derived from flow that escapes the main channels. As in the constant-flow experiment, the channels in the variable-flow experiment aggrade rapidly compared to the overbank environment. However, the channels also move rapidly across the delta top, allowing their deposits to be spread widely. The lateral migration is evident in the

TABLE 3.—*Aggradation Breakdown. The effective aggradation rate decomposed into the amount of time spent aggrading or eroding, and the respective rates.*

		Channels	Overbank
Variable discharge	aggradation rate (mm/hr)	1.32	0.74
	aggradation time fraction (–)	0.16	0.26
	erosion rate (mm/hr)	0.61	0.52
	erosion time fraction (–)	0.06	0.17
Constant discharge	aggradation rate (mm/hr)	1.03	0.78
	aggradation time fraction (–)	0.05	0.29
	erosion rate (mm/hr)	0.42	0.27
	erosion time fraction (–)	0.02	0.13

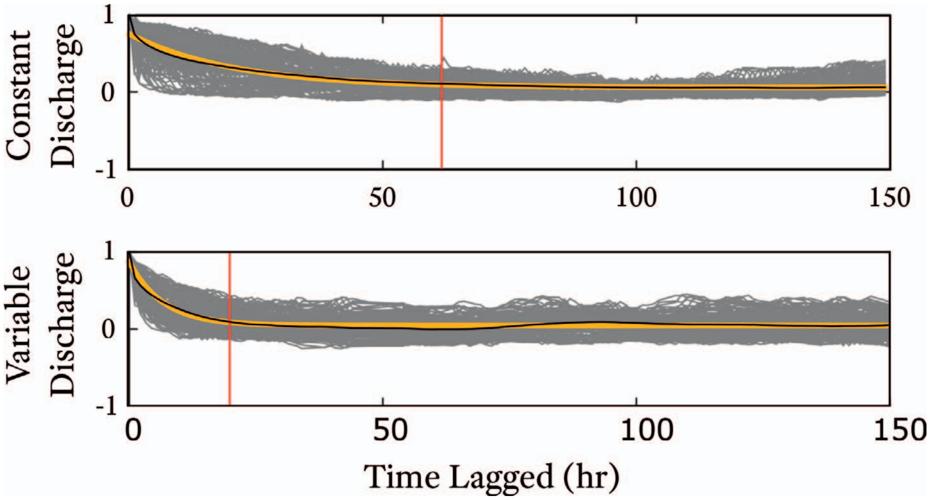

FIG. 6.—Channel mobility. Normalized overlap decay curves, following Wickert et al. (2013). Gray lines are the decay curves described in the text, the black line is the average of the gray lines, and the orange line is the best-fit exponential decay to the black line. The vertical red lines, calculated from the orange best-fit curves, indicate the T_5 measurement that is shown in Figure 4.

map of occupation time (Fig. 5), and in the channel forms preserved in stratigraphy (Fig. 7). As a result of this migration, channels in the variable-flow experiment leave sediment behind as they move across the delta, and are therefore substantial depositional contributors to stratigraphic volume. The contrast in channel function (conduit vs. depositional contributor) results in more sediment being retained on the delta top in the variable-discharge experiment than in the constant-flow experiment. We can use our aggradation maps to calculate that the constant flow experiment retains $2.4 \times 10^5 \frac{mm^3}{hr}$ in terrestrial deposits, which is approximately half of the $4.7 \times 10^5 \frac{mm^3}{hr}$ measured in the variable-flow experiment. The fact that the variable-flow case has a higher sediment retention efficiency and a higher proportion of channel deposits implies that its channel bodies are composed of a lower sand fraction than the constant-flow case, though measurements of the channel deposits would be needed to confirm this.

DISCUSSION

As shown in the Results section, differences in channel mobility lead to the differences in sediment partitioning that we observe between our two experiments. The changing flow conditions in our variable-discharge experiment ensure that the channel geometry is never in equilibrium with its input. The result is an aggrading channel bed that forces the channel to regularly overflow and invade the adjacent areas. This mechanism, which depends on variable flow and sediment that resists erosion, allows for a rapidly moving channel that does substantial aggradation on the delta top, but little erosion (though still more than in the constant-flow overbank environment), and results in a deposit that is dominated by broad, laterally continuous channel bodies (serial images in SI, Fig. 7). By contrast, the channels in the constant-flow experiment lose flow, resulting in the formation of well-developed levees, but the channels are relatively stable and more efficiently pass their sediment from the input all the way to the ocean. The lack of well-developed levees in the variable flow experiment led to channels that were shallower (Table 1) and wider (Fig. 2) than their counterparts formed under constant-flow conditions. The contrast between our two experiments is therefore enabled by the cohesive sediment that we use, which allows levees and strong banks to form if energetic flows do not overwhelm them.

This level of long-term process detail is difficult to observe in field-scale systems, so the influence of discharge variability on stratigraphic architecture is not well quantified. Facies models often emphasize planform morphology, but several recent reviews (e.g. Plink-Björklund 2015; Fielding et al. 2018) have used modern deposits to make a convincing case that the stratigraphic signature of discharge variability is best defined at the scale of bedforms and sedimentary structures. For example, Plink-Björklund (2015), offers a set of diagnostic sedimentary structures that indicate seasonally intense monsoon precipitation. However, as Fielding et al. (2018) point out, in systems where flow variability is expressed mainly as seasonal fluctuations—the type of variability that we study in our experiments—the rate of change means that bedforms are not necessarily in equilibrium with the flow. Bedforms in such situations are not always reliable gauges of transport processes. Our work points the way towards a theory of preservation potential as a function of depositional environment and discharge variability, and therefore represents something of a bridge between the emerging process-based understanding of variable flow in stratigraphy and traditional facies models.

In this context it is interesting to consider our results, from experiments with cohesive sediment and strong banks, in the context of two recent studies that examined the impact of flooding on channel form in braided streams with relatively weak banks. Sambrook Smith et al. (2010) present DEMs collected before and after a large flood (40-year return period, $\sim 10\times$ mean flow conditions) in the South Saskatchewan River. Their data show that the flood significantly altered the planform morphology, but that the new channels were not deeper, nor were the new bars thicker. Because the floods did not alter the total relief in the system, the induced morphological changes would not be easily recognizable in the stratigraphy, implying that floods would not be important to include in forward stratigraphic models of a similar system. The reason the flood was not effective enough to be preserved, Sambrook Smith et al. (2010) found, is that all floods above a certain magnitude lose flow to the overbank environment, resulting in a reduction in stream power. This same line of reasoning should hold with more frequent floods, making it extremely difficult to distinguish flood intensity by preserved hydraulic geometry alone. Van de Lageweg et al. (2013) confirm experimentally that channel depths and bar thicknesses are not statistically different between a braided stream subject to repeated floods and one with a constant discharge.

Unlike the braided-stream deposits in the Van de Lageweg et al. (2013) and Sambrook Smith et al. (2010) studies, the stratigraphic products of our two experiments are easily differentiated by the mobility evident in the channel bodies and by the proportion of channel deposits. The contrast between the two results suggests that information about river dynamics is better preserved in single-threaded systems with cohesive banks than in braided streams in noncohesive material. This knowledge can be used to select field sites that are likely to yield the most informative data. For example, a stratigrapher interested in a regional shift in precipitation patterns might look for a volumetric change in the density of channel bodies in a single-threaded system. But if only braided streams in noncohesive material whose deposits are

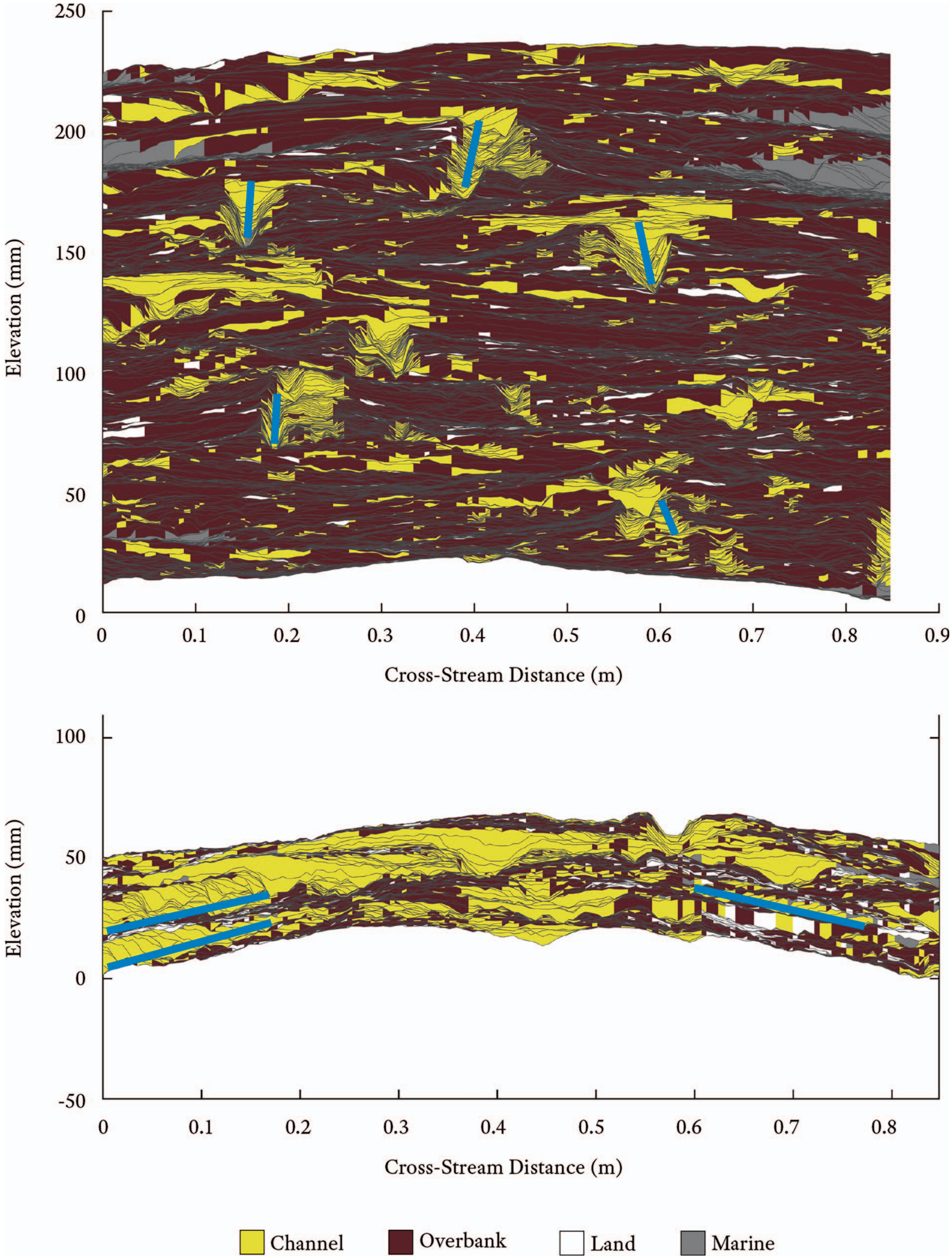

FIG. 7.—Cross sections. Synthetic stratigraphic cross sections colored by depositional environment. Note the channel thalweg trajectories indicated with blue bars. Cross-section locations are shown in Figure 2. The constant discharge stratigraphy is in the top panel, and the variable discharge stratigraphy is on the bottom.

dominated by channels are available, such an investigation might not be worth undertaking.

The principal result of the current study is that floods influence channel lateral mobility, which in turn alters the partitioning of sediments between channelized and overbank deposits. This result should hold for any net-depositional environment where regular floods are a driver of channel mobility. That the channels are more mobile in the variable-flow experiment can be seen in the statistical evaluation (via T_5, Fig. 6) as well as by visual examination of the stratigraphy (Fig. 7) and of the time-lapse imagery of the delta (see SI). The increased mobility has a counterintuitive consequence: the deposit of the delta created with floods has a lower proportion of overbank deposits than the one created under constant flow conditions. This is a result with potentially broad implications. As noted by Jerolmack and Paola (2007), surprisingly little is known about the dynamics of floodplain sedimentation over long timescales. Our investigation identifies the intensity of a river's hydrograph as an important parameter that influences sediment export from the channel to the overbank environment. Users of models that derive from the Leeder–Allen–Bridge family can incorporate this information to better ground their model inputs to fluvial processes. For example, the data in Figure 4 show that any measurement of channel-to-overbank deposit ratio from a time interval that is longer than T_5 should be very close to the long-term mean. In our experiments the partitioning of channel and overbank deposition was highly variable over time scales less than T_5. The mean partitioning over these short time scales, however, was close to the long-term mean, which suggests that the movement of channels in our experiment was not associated with significant erosion of overbank strata. This might be due to the enhanced deposit cohesion achieved with our sediment mixture. In many systems, erosion of overbank strata, which occurs as a result of channel lateral migration (van de Lageweg et al. 2014) or incisional avulsions (Hajek and Edmonds 2014), is common. Significant removal of overbank strata and replacement with channel sediments, from the processes mentioned above, would only further tilt the long-time-scale partitioning of sediment towards channelized strata.

The ratio of channel to overbank sediments deposited in a sedimentary basin has long been an important, though implicit, parameter in models of fluvio-deltaic stratigraphy. Some of the earliest models (Allen 1978; Leeder 1978; Bridge and Leeder 1979), function by adding a specified volume of channel and overbank sediments to an alluvial succession at each time step. The specific volume added of each is determined by the width of the channel belt, the width of the basin, the depth of the channel, the basin-wide aggradation rate, and the spatial relationship of aggradation relative to the channel belt, but is consistent for a given model initialization. Postdepositional compaction of fine sediments and erosion by channel-belt avulsion events can subsequently alter the ratio of channel to overbank sediment volume that is transferred into stratigraphy. In some cases this alters the topography and dynamically interacts with channel path selection. An important result, consistent through all such models, is that high channel mobility on the surface is associated with high channel-body interconnectedness in the deposit. But decreasing the width of the alluvial plain relative to the channel belt—effectively increasing the volume fraction of channel sediment input to the system at each timestep—is also associated with increased channel-body interconnectedness. It is therefore important to understand the factors that influence sediment partitioning in order to distinguish between the two similar effects.

The basic framework set forth by the Leeder–Allen–Bridge models—that of a linked channel–floodplain system where channel path selection is driven by floodplain topography, and floodplain deposition is related to channel location—is still in common use in contemporary studies. Törnqvist and Bridge (2002) use field data from the Rhine–Meuse and Mississippi Deltas to fit an exponential decay to overbank deposit thickness as a function of distance from the channel-belt edge, and apply this result as an input parameter to a 3D model of alluvial stratigraphy (Mackey and Bridge 1995). Including realistic topography in this way improves the model, but as with earlier models the channel-to-overbank deposit proportion input at each timesetep in the Mackey and Bridge (1995) formulation is determined at the model initialization. This is because, while some variation in the partition of deposit volume is possible due to the geometry of the channel within the computational domain, a given decay constant approximately specifies the channel-to-overbank deposit ratio. The channel-to-overbank input ratio in Leeder–Allen–Bridge models is heavily dependent on geometric constraints but does not easily consider process. Our work provides an opportunity to incorporate fluvial processes into such formulations, and thus improve the mechanism for determining appropriate model input parameters.

CONCLUSIONS

Intuition might lead to the assumption that the volume of overbank strata in an alluvial basin increases with the intensity of the floods in the catchment. Results from this study challenge this assumption and suggest that floods can increase channel lateral mobility, which increases the proportion of channel deposits relative to overbank deposits preserved in stratigraphy. We also find that the variable-discharge experiment retained more total sediment on its delta top than the constant-discharge experiment. We tie this result to the observation that the channels in the constant-discharge delta were stable for long periods of time, during which they functioned as efficient conduits of sediment to the ocean.

The T5 statistic, which measures the approximate time necessary for channels to occupy the entire delta top, provides a useful timescale to determine the time interval over which a measurement of channel-to-overbank sediment partition is representative of the long-term average. Measurements from intervals that are shorter than T5 are likely to have an elevated proportion of overbank sediments relative to the long-term average. These observations represent an advance in our understanding of the rules that govern long-term sediment storage in floodplains, and will be useful to formulate rules-based models formation of alluvial stratigraphy.

Our results differ from those found in studies of braided streams with noncohesive sediment in which no information about hydrograph shape was transferred to the stratigraphy. In contrast to braided systems, where the greater part of the preserved deposits result from channel processes, we find that single-threaded streams in cohesive sediment preserve recognizable flood signals in their ratio of preserved overbank deposits to channel deposits.

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SUPPLEMENTAL MATERIAL

Data from the constant-discharge and variable-discharge experiments (TDB_12_1, and TDB_15_2, respectively) have been uploaded to the Sustainable Environment–Actionable Data (SEAD) project data repository in collaboration with the Sediment Experimentalist Network. All data can be accessed through the Tulane Sediment Dynamics and Quantitative Stratigraphy Group's collection, at the URL below.

https://sead2.ncsa.illinois.edu/collection/596d28c5e4b05e3417b2096f.

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