ABSTRACT: Depositional processes interact with mobile substrates in nearly all passive-margin settings throughout the world. The interplay between sedimentation and a mobile substrate (e.g., salt layer) results in a complex stratigraphic record, making it difficult to reconstruct basin-fill history. Herein we investigate the dynamic feedback between sediment loading and substrate deformation to understand morphologic change and stratigraphic development. We used simplified tank experiments of a linked fan and terminal-channel system evolving over a deformable substrate. A series of experiments were conducted with controlling variables including mobile substrate thickness, sediment supply rate, and basin slope. Experimental results indicate: (1) an increase in substrate thickness resulted in increased subsidence around the fan that limited sediment transport to its terminal channels, (2) a higher sediment discharge rate on a substrate resulted in faster fan progradation coupled with relatively less subsidence and more sediment transport to terminal channels, and (3) a higher-slope experiment caused the largest amount of sediment transport downstream, while a decrease in basin slope resulted in a larger number of established channels along with a wider fan surface. An analysis of surface processes is also used to determine the expected stratigraphy between a linked fan and terminal-channel system as it interacted with the mobile substrate. We apply the experimental findings to understand the fluvial-dump–wind-redistribute system deposited on top of the Louann Salt layer in the eastern part of the Late Jurassic Gulf of Mexico basin.

INTRODUCTION

The stratal architecture of depositional basins records the dynamic feedback between deposition and subsidence driven by tectonic movement and/or substrate deformation. A primary goal of stratigraphy is to understand how these processes interact in the development of stratigraphic patterns. Particularly complex stratal architectures develop where the substrate is a viscous layer (e.g., salt) because (1) the substrate deformation is strongly controlled by the temporal and spatial nature of sediment loading, and (2) the sediment transport rate and sedimentary architecture changes as a consequence of the deformation. These bidirectional feedbacks make stratal records associated with a deformable substrate more difficult to interpret. Herein we present a set of physical experiments that were conducted under a range of boundary conditions, which allow better examination of the complex relationship between depositional process and substrate deformation.

Relatively few experimental and theoretical studies have been conducted to understand the interactions between a depositional body of sediment and a pre-existing, deformable, viscous substrate (Hudec et al. 2009; Piliouras et al. 2014; Kopriva and Kim 2015). Each of these studies has revealed the significance of specific variables in controlling the surface morphology and evolving stratigraphy. Piliouras et al. (2014) discovered the importance of substrate thickness in determining the amount of subsidence of an eolian dune and the control of interdune distance on subsidence rate. They suggested that a thicker substrate causes higher subsidence while a longer interdune distance increases salt flow and in turn causes faster subsidence of dunes. Kopriva and Kim (2015) added more insight into the importance of sediment discharge rate and intermittent supply pattern on the geometry (width and depth) of a subsiding minibasin into a salt substrate. A higher sediment discharge rate develops a wider and shallower-depth minibasin, but a low-frequency sediment supply causes a narrower and deeper-depth minibasin. However, these previous experiments were limited to a two-dimensional investigation, and, moreover, the sedimentary transport was driven by grain avalanche, which developed high surface slopes on a triangular sedimentary body. We expand the investigation to a 3-D evolving alluvial fan that feeds into self-organized terminal channels on a mobile substrate.

Our current study is motivated by the dynamic interaction of alluvial fans and their terminal channels with the Louann Salt substrate in the Gulf of Mexico basin. The Upper Jurassic (Oxfordian) Norphlet Formation is a major oil and gas reservoir located in the eastern Gulf of Mexico basin. The stratigraphic unit, reaching over 300 m in thickness, represents the progradation of fluvial systems from the Appalachian Mountains into the early Gulf of Mexico basin, in which the fluvial systems yield basinward to eolian dune fields and sabkhas (Mancini et al. 1985; Mancini et al. 1990; Mancini and Puckett 2003; Ajdukiewicz et al. 2010; Pilcher et al. 2014). The dune fields and related basinal systems, as well as the more distal portions of the fluvial systems, were deposited on the Louann Salt. The Norphlet represents a type of depositional system that can be characterized as “fluvial-dump–wind-redistribute,” in which alluvial fans and channels transported sediment into the basin, but these ended before reaching a body of water. Eolian reworking of the fluvial sediments lead to localized dune fields in the wind-transport direction. Terminal fluvial systems, both with...
and without distal eolian systems, commonly characterize arid or semiarid environments in modern settings and are interpreted in the rock record (e.g., Kelly and Olsen 1993; Nichols and Fisher 2007; Cain and Mountney 2009). Modern examples include the Mojave River Wash and fan systems in Death Valley in California (Tchakerian and Lancaster 2002), and systems adjacent to the Oman Mountains (Glennie et al. 2002) (Fig. 1). Components of terminal fluvial systems are alluvial fans and terminal channels that extend basinward beyond the toe of the fan (Fig. 1). As developed below, the terminal channels are directly linked to the behavior of the fan body, such that the amount of sediment delivered to the channels and channel geometry are closely correlated to the development of the fan body. Given this connection, we herein term these systems as “linked fan and terminal-channel systems.”

This research focuses on the interactions between a linked fan and terminal-channel system with a pre-existing viscous layer (i.e., salt substrate). The objectives of this study are to use 3-D physical tank experiments in order to investigate the factors that are the most significant in controlling alluvial-fan surface morphology and subsidence, initiation and evolution of channels, and terminal-channel geometry. We examined (1) the significance of substrate thickness, sediment discharge, and basin slope on fan morphology and channel geometry, and (2) the sediment distribution between the fan body and the terminal channels. Understanding the main controls on the behavior of terminal channels resting on a viscous layer is significant for determining the local distribution of sands in the fan-terminal channel complex and the larger fluvial-dump–wind-redistribute system.

METHODS

Experimental Design

A three-dimensional basin was used to conduct the experiments; the dimensions of the basin are 120 cm in length, 60 cm in width, and 32 cm in height (Fig. 2). A horizontal flat base was placed inside the tank. Two L-shaped walls were inserted to form a 4-cm-wide inlet channel at the upstream end of the basin. Sediment and water were fed into the inlet channel through a funnel at a constant rate for each experiment. Water was supplied from an external reservoir and was flowed through a rock cage in the inlet channel in order to reduce scouring of the sediment surface by the water influx. The water was dyed blue to visualize the flow. For the sediment, a uniform 100-micron quartz sand was used.

Natural salt was represented by a polymer, which has been tested in many previous studies and found to display several rheological properties in keeping with rock salt (Weijermars 1986; Weijermars et al. 1993). The material is a clear polymer known as PDMS (polydimethylsiloxane) and has a high viscosity \((2.5 \times 10^4 \text{ Pa}s)\). The desired thickness of PDMS was obtained by placing a given amount of PDMS in the basin and waiting until it gravitationally leveled out over the entire flat basin surface. At the start of the experiments the basin was slightly tipped in order to create a slope \((S = 0.013 \text{ or } 0.026)\), which prevented the ponding of water around the fan but that was still an order of magnitude shallower than the fan surface slope. Once the basin had this slight slope, sediment and water were allowed to flow onto the salt layer, creating a prograding fan over time and terminal channels beyond the toe of the fan. The water was recycled from the downstream end back to the water reservoir tank.

We conducted a series of five experiments with different conditions of substrate thickness, sediment supply rate, and basin slope (Table 1). The maximum salt thickness was set at a value higher than channel depth but comparable to the maximum fan-deposit thickness. The basin slopes were explored within a range much smaller than the fan surface slope. The sediment discharges were set within a range that permitted interaction between salt deformation and fan progradation while simultaneously not letting either process dominate.

Data Collection

A camera was placed on the ceiling directly above the basin and connected to a computer that runs a software program (EOS Utility v. 2.10) that digitally captures and saves images of the run. Time-lapse images were taken every 20 seconds during each run. We used images taken at two-minute intervals to make measurements of fan surface area, as well as maximum length and maximum width of terminal channels. A standard lens correction method (Tal et al. 2012) was used to correct for image distortion and perspective.

Directly after a run, the deposit in each individual terminal channel was collected as quickly as possible before the polymer layer further deformed, and width and depth of the channels were recorded every 2 cm along the path of the channel. The sediment from each terminal channel was then dried and the mass for the dry sediment was recorded. The sediment deposited in the fan was also collected and dried for the mass measurement.
EXPERIMENTAL RESULTS

Input sediment and water that flowed through the inlet channel built a radially prograding fan on the basin floor. Figures 3A–C are images taken at 10 min, 30 min, and 60 min of run time in Run 1, the run without a mobile (salt) substrate. The fan grew radially as the channels on the fan surface migrated laterally and underwent nodal avulsions in varying directions across the fan toe. In order to quantify fan planform geometry and compare across the experiments, we calculated the index \( U_F \) as a ratio of maximum width to length of the fan (Fig. 4B). Run 1 shows an average \( U_F \) of 0.94 (higher number indicates wider fan surface, while a lower number indicates a more elongated fan in the down-basin direction). Off the fan in the down-basin direction, a few streams developed to drain water over the sloped basement, but the sediment deposited in the channels off the fan was minimal (Fig. 3A–C).

Run 2 (Fig. 3D–F) was conducted with the same experimental conditions as with Run 1 except that an initial 2-cm-thick polymer substrate was used (see Table 1). As with Run 1, a fan grew radially but over time the fan grew wider than that of Run 1. The fan geometry index \( U_F \) reached 1.32 at the end of Run 2 (Fig. 4B). In addition, the surface area of the fan at the end of the run (60 min) was a smaller than in Run 1 even though the total amount of sediment supplied to the basin was equal in both cases (Fig. 4A). The fan did not prograde faster, but its deposit became thicker as the fan subsided into the salt layer at the same time as the salt slowly flowed outward from underneath the fan. A significant difference we observed in this salt substrate experiment was that sediment-transporting channels developed over the salt surface down-basin of the fan (i.e., terminal channels). Water draining off from the fan toe organized into streams as with Run 1, but in Run 2 sediment was also transported through the channels (Fig. 3D–F). The deposits in the channels caused more subsidence into the salt substrate due to localized loading, and thus accommodated more sediment (Fig. 3F). Each of these terminal channels on the salt surface went through multiple phases of fill and reincision as the sediment sank into the salt substrate and the channel was abandoned and reoccupied. The terminal channel flow was not continuous because lateral migration and avulsion of channels on the fan surface distributed the supplied sediment and water into different terminal locations cyclically (Fig. 3E, F). This is discussed in more detail in the Interpretation section.

FIG. 2.—Diagram of 3-D basin used for physical experiments. Constant rates of sediment supply and water flowed through the inlet and created a fan with terminal channels. A polymer covered the base of the basin and acted as a proxy for a mobile salt substrate over which the fan prograded.

### Table 1.—Experimental parameters.

<table>
<thead>
<tr>
<th>Date</th>
<th>Run Name</th>
<th>2015-05-28</th>
<th>2015-05-11</th>
<th>2015-03-25</th>
<th>2015-04-17</th>
<th>2015-04-08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qs (g/s)</td>
<td>Run 1</td>
<td>2.12</td>
<td>2.12</td>
<td>2.12</td>
<td>1.79</td>
<td>1.79</td>
</tr>
<tr>
<td>Qw (ml/s)</td>
<td>Run 2</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
<td>14.5</td>
</tr>
<tr>
<td>Total Run Time (min)</td>
<td>Run 3</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Salt Thickness (cm)</td>
<td>Run 4</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flume Slope (O)</td>
<td>Run 5</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.026</td>
</tr>
<tr>
<td>Sediment</td>
<td>Run 1</td>
<td>Quartz</td>
<td>Quartz</td>
<td>Quartz</td>
<td>Quartz</td>
<td>Quartz</td>
</tr>
</tbody>
</table>


Salt Substrate Thickness

The impact of salt substrate thickness on fan development was investigated by varying polymer thickness in Runs 2 (2 cm) and 3 (3 cm), which otherwise had an identical set of parameters (Table 1). The area of the fan surface at the end of Run 3 was smaller than in Run 2 (Fig. 4A). Since both Runs 2 and 3 used the same total amount of sediment, subsidence in Run 3 should be larger in comparison to Run 2. This is also consistent with the theoretical model presented in Piliouras et al. (2014); the subsidence rate scales with the substrate thickness to the third power. In

Fig. 3.—Images comparing a run without a mobile substrate (Run 1) to a run with a mobile substrate (Run 2). Images were taken at A) 10 minutes, B) 30 minutes, and C) 60 minutes in Run 1, and at D) 10 minutes, E) 30 minutes, and F) 60 minutes in Run 2. Direction of flow is indicated by the arrow at the top of the image.
FIG. 4.—Variations in salt thickness. A) Calculated fan surface area of Run 1, Run 2, and Run 3. Note that fan surface area decreased as thickness of the mobile polymer substrate increased. B) Index for fan planform geometry ($\Phi_f$) as a ratio of maximum width to length of the fan for Run 1, Run 2, and Run 3. The index for planform geometry indicates if the fan surface is more laterally dominated (higher $\Phi_f$) or if the fan surface is more elongated (lower $\Phi_f$) in the downbasin direction. Overall, $\Phi_f$ increases in experiments with a mobile substrate layer, and the ratio increases with a thinner layer. C) Final image of Run 2 showing the larger number of channels that are strongly connected to the fan body as well as the distance downstream that sediments were transported. D) Run 3, showing the formation of lakes along the fan fringes, the pinch-outs of terminal channels at the salt forebulges, and the smaller number of terminal channels.
Run 3, the faster subsidence combined with a salt forebulge in front of the fan to produce “fringe” lakes and/or playas near the fan toe (Fig. 4D). The lakes grew as the fan received more sediment, which subsequently pushed salt from underneath the fan to the front and caused a higher salt bulge around the fan. The depth of the lakes changed locally with time and was dependent on the amount of sediment that was delivered by channels on the fan, which actively migrated laterally and avulsed. The presence of the lakes resulted in a retreat of the fan–lake boundary along the fan body as a greater amount of the fan subsided into the mobile substrate and resulted in overall less surface area (Fig. 4A, D).

Both of the fans in Run 2 and Run 3 created terminal channels on the salt layer. However, a larger number of channels were generated in Run 2 (Fig. 4C) and there was about a five-fold increase in the amount of sediment deposits in channels (Table 2) that extended greater distances downstream (Fig. 5A, B). In Run 3, because of the development of lakes along the fringes of the fan, sediment transport off the fan toe to the terminal channels was not continuous. In addition, the terminal channels began to be pinched off from the fan as the salt bulge grew wider and higher down-basin (Fig. 4D). In this stage, water was transported only intermittently from either updip knickpoints on the fan or from lakes that overflowed into a terminal channel. The flow from a lake to a terminal channel often showed a tributary pattern in comparison to a distributary pattern developed upstream where the fan prograded toward the lake. Most terminal channels in Run 3 were disconnected from the fan at the end of the run and developed pinch-offs, typically near the toe of the fan (Fig. 4D). The tributary–distributary transition and the channel pinch-off are discussed further in the Interpretation section.

### Sediment Supply Rate

Manipulating the sediment supply rate in Run 2 and Run 4 created different fan planform geometries and terminal-channel results (Fig. 6A, B). A higher sediment discharge rate with Run 2 ($Q_s = 1.79$ g/s) resulted in a faster progradation rate of the fan body, which produced a larger fan surface area (Fig. 6C). The increased progradation rate did not allow the sediment to sink into the mobile substrate as fast as with the lower sediment discharge rate ($Q_s = 1.22$ g/s) in Run 4. This slower subsidence associated with the higher sediment-discharge condition is clear when the surface area is compared to the total amount sediment supplied to the basin in Runs 2 and 4. Run 2 at runtime = 50.7 min used the same amount of sediment as Run 4 at runtime = 60 min. Figure 6C shows that Run 2 was still larger at runtime = 50.7 min than that in Run 4 at runtime = 60 min, which represents less subsidence and more progradation. Both runs showed an increase in $\Phi_F$ over time. However, Run 2 had an index of approximately 1.2 or higher (i.e., wider in planform), which indicated a stronger radial progradation (Fig. 6D).

Both runs developed five terminal channels on the salt layer surface, but the channels in Run 2 were more widely distributed across the fan toe (Fig. 6A, B). The amount of sediment transported off the fan into terminal channels in Run 2 almost doubled that in Run 4 (Table 2). Individual channels were also wider and more sinuous, channel depth was only slightly greater than in Run 4 (Fig. 5A, C). Pinch-outs at the upstream ends of terminal channels were limited to channels at the sides of the basin.

### Basin Slope

The overall area of the fans in Run 4 (Fig. 7A) and Run 5 (Fig. 7B) was not significantly different (Fig. 7C) even though their basin slopes were set differently at 0.013 and 0.026, respectively. However, the fan–geometry index for the length and width changed noticeably (Fig. 7D). The fan surface geometry in Run 5 (doubled slope) was longer and narrower, while the fan in Run 4 was wider and more radially symmetric (Fig. 7D). Only Run 5 developed a fan that had a larger maximum down-basin length as compared to maximum cross-basin width (average $\Phi_F = 0.8$), with the exception of the control run.

The distribution of sediment into the terminal channels was also affected; a smaller number of channels were established in Run 5 in comparison to the lower-slope experiment, but the amount of sediment being transported off of the fan was remarkably similar (Table 2). These terminal channels on the salt substrate developed primarily at the fan center and transported sediment the farthest downstream distance in comparison to all other runs (travelled 36 cm from the fan toe) (Fig. 5D). Most channels in all other runs were also consistently wider and deeper closest to the fan toe. Run 5 developed more variability in width and depth of the terminal channels, suggesting more lobate structures forming in the channels over time. These widening and narrowing, as well as deepening and shallowing, channel cycles occur with longer wavelengths in this run compared to others (Fig. 5D).

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**Table 2.—Sediment distributions between fan and terminal channels.**

<table>
<thead>
<tr>
<th>Run Name</th>
<th>Mass (g)</th>
<th>C Total</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 2</td>
<td>7000</td>
<td>367</td>
<td>22.6</td>
<td>38.4</td>
<td>89.9</td>
<td>139.8</td>
<td>66.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Proportion</td>
<td>95.0</td>
<td>4.99</td>
<td>0.31</td>
<td>0.52</td>
<td>1.22</td>
<td>1.90</td>
<td>0.91</td>
<td>0.13</td>
</tr>
<tr>
<td>Run 3</td>
<td>7134</td>
<td>76.9</td>
<td>13.2</td>
<td>63.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion</td>
<td>98.9</td>
<td>1.06</td>
<td>0.18</td>
<td>0.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 4</td>
<td>6100</td>
<td>189.1</td>
<td>39.5</td>
<td>58.3</td>
<td>38.2</td>
<td>28.8</td>
<td>22.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Proportion</td>
<td>97.0</td>
<td>2.97</td>
<td>0.58</td>
<td>0.93</td>
<td>0.61</td>
<td>0.46</td>
<td>0.36</td>
<td>0.025</td>
</tr>
<tr>
<td>Run 5</td>
<td>6200</td>
<td>172.4</td>
<td>87.7</td>
<td>53.3</td>
<td>31.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proportion</td>
<td>95.5</td>
<td>2.65</td>
<td>1.35</td>
<td>0.82</td>
<td>0.48</td>
<td></td>
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Fig. 6.—Variations in sediment supply rates. Final images of A) Run 2 and B) Run 4. C) Calculated surface area over time for Run 2 and Run 4, showing that Run 2 (greater sediment discharge rate) has a larger fan surface area in comparison to Run 4 throughout the course of the run. D) Index for fan planform geometry ($\phi_F$) for Run 2 and Run 4; Run 2 shows a higher ratio, indicating a stronger lateral progradation than Run 4.
SUMMARY AND INTERPRETATION

Dynamic Interactions between Sedimentation and Salt Deformation

Mathematical and experimental modeling studies of salt deformation under sand dunes (e.g., Piliouras et al. 2014) indicate a strong correlation between the initial salt layer thickness and the subsidence rate. Salt flows faster in a thicker layer because a larger proportion of the layer is free from the friction acting on the boundaries. Varying the salt layer thickness in these experiments produced a similar result. The thicker salt layer in Run 3 subsided faster and resulted in a thicker deposit, thus resulting in a smaller fan area developed in the same total run time as compared to experiments with a thinner salt layer (Figs. 4, 8).

Manipulating the sediment supply rate also affected the morphology of the fan body and its interactions with the mobile substrate. A smaller rate of sediment supply in Run 4 allowed more time for the salt substrate to flow outward from underneath the fan. This caused a relatively localized area of high subsidence, which reduced the progradation rate of the fan (Figs. 6, 8).

In the case of no salt substrate (Run 1), the fan surface area is a function of the basin slope because as the basin slope increases toward a value near that of the fan surface slope, the fan deposit thins and thus elongates significantly in the down-basin direction. However, in the experiments with a salt substrate the basin slope has less effect on the fan surface area, as shown in the similar overall area growth between Run 4 and Run 5 (Fig. 7C). The higher basin slope in Run 5 increased the salt flow down the basin, and thereby increased the accommodation space in the proximal part of the system, which diminished the effect of slope on the fan surface area (Figs. 7, 8).

Fan surface geometry is dependent on the relative rates between deposition and subsidence. This is most evident in the runs with a mobile substrate present, beginning with Run 2. In Run 1 (no salt layer present) the fan shape quickly stabilized and then maintained a constant shape with only minor fluctuations (Figs. 3A–C, 4B). However, all runs with a salt substrate showed dynamic changes in the planform pattern over time, ranging from a more elongated to a radially round shape. This change in the fan planform geometry over time was caused mainly by the decrease in salt substrate underneath the fan. The initial elongated shape in Run 2 (Figs. 3D, 4B) could be maintained by high subsidence where a thick-enough salt layer still existed under a fan. As the fan subsided and the salt layer decreased in thickness, the subsidence rate reduced significantly, but the channels varied in depth and width downstream. The variability in deposit thicknesses is the result of the salt interacting with the sediments and the other established channels. Widely distributed channels across the basin typically developed wider channel widths because the larger space between the channels allowed the channels to grow as well as allowing salt to easily flow upward between channels (e.g., Run 2). Narrowly distributed channels, however, could not develop exceptional width, and these were mostly associated with the conditions of higher salt bulges (e.g., Run 3 and Run 4).

Connecting Surface Processes to Stratigraphy

The current experiments used a uniform grain size in order to isolate the controls of the mobile salt substrate on the evolving linked fan and terminal channel system. Because of the uniform sediment size, clear stratigraphic layers could not be resolved in sections taken at the end of the experiments. However, we are also able to reconstruct stratigraphic horizons using time-lapse images and final topographic surfaces. Here we provide two examples from Run 3 and Run 4.

The first reconstructed stratigraphy consists of a sequence of terminal-channel evolution with a channel lateral migration on a fan (Fig. 9). The channel was active on the river left-hand side of the fan, and during this period the terminal channel on the river far right-hand side did not receive any sediment (Fig. 9A). The channel gradually migrated to the river right-hand side of the fan and started to flow into the terminal channel (Fig. 9B). The flow generated scour at the tips of patched deposits (bars) in the channel (Fig. 9B) and transported sediment to thicken and widen the terminal channel deposit (Fig. 9C, D). Once the channel started to migrate back to the river left-hand side of the fan, a minimal amount of flow and sediment could be transported to the terminal channel (Fig. 9E). The terminal channel on the river far right-hand side was abandoned within approximately 6–7 minutes of the depositional event, and the other terminal channels began to receive sediment (Fig. 9F). Therefore, the depositional cycle in a terminal channel was linked to the time that it takes the channel to laterally migrate on the source fan and return to the original location (i.e., autogenic channel timescale). In general, the autogenic timescale for channel avulsions on a fan scales with the total volume of a channel divided by sediment supply rate; this calculates the time it takes to fill a channel at a given sediment discharge rate (Kim and Jerolmack 2008; Reitz et al. 2010; Powell et al. 2012). In the case of a fan on a salt substrate, the autogenic channel timescale would be longer due to subsidence. Subsidence would be higher where more sediment loading is focused along channels, which likely delays channel filling and new avulsions. Therefore, the fluvial autogenic cycle and terminal channel activation should be less frequent.

Figure 9G shows a stratigraphic section along the terminal channel reconstructed from the observed surface processes in Figure 9A–F. The terminal-channel deposit starts with an erosional surface around a salt high and gradually fills in the overall surface as a sediment wedge or bar. The terminal channel will then subside at differing rates depending on the thickness of the new deposit until a new depositional event begins. A new set of layers associated with the autogenic cycle described above will develop as long as there is remaining salt underneath the channel to generate subsidence.

An initially thick salt substrate produced high subsidence. In this condition the supplied sediment could not keep up with the subsidence rate in order to continually expand the fan. The fan toe retreated and lakes developed around the fan toe (e.g., Run 3). The lake development in this depositional environment does not necessarily indicate changes in the subsidence rate or in the sediment supply to the system. As the fan evolved, more salt flowed out to the front of the fan and mounded; the local base level autogenically increased due to this salt upwelling and created lakes. These lakes caused shifts in the depositional setting from an alluvial fan to a lake delta in the depositional cycle. An example is shown in Figure 10;
FIG. 7.—Variations in basin slopes. Final images of A) Run 4 and B) Run 5; the fan body is noticeably wider, and five channels were established in Run 4 while a narrower, more elongated fan body and 3 channels were developed in Run 5. C) Calculated surface area over time for Run 4 and Run 5; the overall fan surface area for Run 5 is larger than Run 4. D) Index for fan planform geometry ($\Phi_F$) as a ratio of maximum width to length of the fan for Run 4 and Run 5. Run 4 consistently maintained a higher $\Phi_F$ value than Run 5. The fan surface for Run 4 grew more laterally, while Run 5 produced a more elongated fan shape, resulting in a smaller $\Phi_F$ value.
Run 3 developed lakes around the fan. Channels were active at the river left-hand side in 49.3 min (Fig. 10A). These fan channels migrated to the river right-hand side, advanced the shoreline, and filled the local lake (Fig. 10B, C). Because of lake development, no sediment could be effectively transported to the terminal channels. Only a small portion of the sediment could be deposited in the terminal channels and at a low rate. However, when the delta prograded far enough to fill the lake, the upstream sediment source was linked to the terminal channel, and it provided sediment to build a thick terminal-channel deposit (Fig. 10D). Interestingly, the transition from a distributary to a tributary system developed at this downstream boundary within a short distance. The fan and/or delta distributed sediment into the lake, and the terminal channel received sediment and water through a tributary developed over the topographic high that resulted from the salt upwelling (Fig. 10E). The stratigraphic
reconstruction (Fig. 10F) shows the transition between fan and delta deposits as a result of lake development and local shoreline progradation.

Both cases in Figures 9 and 10 visualize the strong connection between the source fan and terminal-channel evolution. The frequency of fan-channel lateral migration is directly related to the terminal-channel deposition. The frequency may decrease due to subsidence acting on the fan, which reduces fan progradation but potentially enhances episodic sedimentation. The autogenic lake development also caused dynamic changes in the depositional environment from fan to lake delta and limited the connection between fan and terminal channel, thus potentially causing a significant delay in sediment delivery to the terminal channels.

**Applications to the Jurassic Norphlet Sandstone**

The Jurassic Norphlet Formation is an exceptionally complex major oil and gas reservoir developed from fluvial and eolian depositional systems in the early Gulf of Mexico basin. Many petroleum traps in the Norphlet correspond with the halokinesis of the Louann Salt layer; these traps involve salt anticlines, faulted salt anticlines, and extensional fault traps (Mancini et al. 1985; Kugler and Mink 1999). The combined effects of continental collision and later extension resulted in a unique basement structure, which influenced the deposition of the Louann Salt layer. These two tectonic factors are generally accepted as the main controls in determining the location of salt diapirs, fold belts, and subcanopy hydrocarbon prospectivity, and play types (Hudec et al. 2013). The relative salt thickness deposited underneath the Norphlet, especially the updip portion of the system, could control the thickness of the fan deposits, which then could influence the amount of terminal-channel deposit. If fans developed on a paleolow location, a thick accumulation of alluvial-fan sediments would be expected in combination with minor transport processes moving sediment off the fan body. This would imply that terminal-channel deposits on the mobile substrate would be minimal in this region, but a small planform area and thick layers of fan deposit are expected to alternate with lake-delta sequences. Under the assumption that the sediment deposited off the fan into the channels served as the source for the nearby eolian dune field, if the eolian deposits are thinner, this could be the result of a lack of sediment supply from the interactions between the upstream-fan–terminal-channel systems. A known paleotopographic high implies less salt accumulation; this would result in a thinner and wider fan body deposit and a larger amount of terminal-channel deposits. The availability of sediment to be reworked into the dune...
system is greater, suggesting thicker accumulations of dunes nearby fans deposited on a thinner amount of salt. A decrease in salt-layer thickness toward proximal areas where fans develop potentially enhances sediment distribution to distal areas and would trap thicker deposits in terminal channels. Fans that are situated near the up-basin salt pinch-outs would grow more radially and create a large number of terminal channels. The downstream increase in salt thickness aids in subsidence to produce deep channels with less lateral mobility, which will trap more sediment that can be used for a local sediment source for eolian reworking.

The northeastern region of Norphlet deposition in the Gulf of Mexico experienced extension of 24–39 km downdip and formed rafts (Pilcher et al. 2014). The original low-relief deposition of the Louann Salt resulted in thick deposits throughout the basinal area. However, the distribution of the salt sequence is strongly dependent on basin architecture and is subject to change over time with differential loading (Dobson and Buffler 1997). The basin slope in the experimental tank was a simple representation of the basin architecture. The planform geometry (i.e., the width-to-length ratio) of the fan body and the distance the sediments were transported into the basin can provide geologists with a tool to find the relative steepness of slope of the basin and gain more insight into the sediment transport in the system. A substantially narrower fan with sediments far downstream through terminal channels would imply a steeper slope off of a known topographic high. A lower slope inhibits sediment travel downstream and deposits sediments in a less condensed pattern. Dispersed channel locations with smaller sediment deposits would suggest a lower slope and less efficient transport processes into the basin. Dynamic interactions between sedimentation and substrate deformation cause complicated geomorphic and stratigraphic patterns. Due to the lack of accessible data, we could not directly apply our modeling results to the field. The spatial distribution of the Louann Salt layer associated with the paleo-basinal topography and the spatial depositional patterns of the Norphlet sand related to the thickness of the salt layer would be an exciting future study. However, insight from the current experiments conducted to isolate each control (e.g., salt thickness, sediment supply, and basin slope) on a linked fan and terminal-channel system can aid in achieving better stratigraphic interpretation in field cases.

**CONCLUSIONS**

Based on the analysis of surface processes and feedback interactions between the linked fan and terminal-channel system and a mobile...
substrate, we are able to evaluate the potential relationships of substrate thickness, sediment supply rate, and basin slope with morphology and stratigraphy. Furthermore, we are able to determine the experimental stratigraphy expected. Our series of experiments show: (1) a larger substrate thickness results in more available accommodation space and therefore more volume for the fan to sink and cut off transport to terminal channels beyond the toe of the fan, (2) a higher sediment supply rate creates a higher progradation rate and less local subsidence for a given sediment volume, while a smaller sediment supply rate produces a smaller fan body and more locally high subsidence for a given sediment, and (3) basin slope determines the capability of the channels to transport sediment; the higher the basin slope, the greater the sediment transport downstream. These three variables altered fan body morphology and downstream sediment transport processes over the course of the experimental runs. It is clear that subsidence rate and slope of the basin strongly control fan size and morphology, and also the efficiency of sediment moving into the terminal channels. Sediment discharge correlates with the progradation rate, and the rate at which the fan body progrades determines the subsidence rate and, therefore, fan surface area.

Depositional cycles and stratigraphy in this system provide insight into the unique dynamics between a mobile substrate and differential loading of sediment. The depositional cycle in a singular terminal channel is linked to the autogenic timescale of channels in the source fan. In general, the autogenic cycle of the fan channel systems with an underlying salt substrate was less frequent than where salt was absent because of active subsidence of the fan into the salt. Timing for reactivation of terminal channel deposition should be correlated with the slower channel timescale for the source fan.

In a fast-subsidence condition, the fan evolved into a lake delta as the salt bulge prevented sediment and water from being transported downstream, effectively ending transport to the terminal channels. This condition resulted in a different stratigraphic configuration as compared to a system with strongly connected channels and continual sediment supply to streams. This study provided a process understanding of each control on the dynamic interactions and potential applications to future studies of the depositional environments in the Jurassic Norphlet and/or other similar field cases.

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