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The Effect of a Pre-deposited Mobile Substrate on Terminal Fan Evolution: Tank Experiments

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The Effect of a Pre-deposited Mobile Substrate on Terminal Fan Evolution and Channel Organization: Tank Experiments

by

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Thesis

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Dedication

I would like to dedicate this thesis to several people. First, to my dad, for being my biggest fan and supporting my move to Austin to follow my dreams. Second, I would like to dedicate this to my mom for always being there and loving me unconditionally. I would also like to dedicate this to my aunt and my grandparents, who have been such a big part of my life.

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Abstract

The Effect of a Pre-deposited Mobile Substrate on Terminal Fan Evolution and Channel Organization: Tank Experiments

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The University of Texas at Austin, 2016

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Depositional processes and interactions with a mobile substrate are seen in passive margins throughout the world. The interplay between brittle stratigraphic layers and a deformable substrate resulted in a complex stratigraphic record due to dynamic feedback influences. During the Late Jurassic, a fluvial-dump-wind-redistribute system deposited sediment on top of the pre-deposited Louann Salt layer in the eastern part of the early Gulf of Mexico basin. By using simplified, scaled-tank experiments we are able to investigate the evolution of a linked fan and terminal channel system in response to subsidence in a mobile substrate. A series of experiments were conducted with controlling variables including salt substrate thickness, sediment supply rate, and basin slope. Fan surface area and morphology, number of terminal channels, channel longevity, and geometry were measured along each experiment. 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 thin substrate resulted in faster fan progradation coupled with less subsidence and more sediment transport to terminal channels, and (3) a higher-sloped 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. Furthermore, we utilize the experimental findings to improve the current depositional model for the Jurassic Norphlet Sandstone.

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Introduction

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 aeolian dune fields, sand sheets and sabkhas (Mancini et al. 1985, 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 upon a salt substrate formed by the Louann Salt. The Callovian Louann Salt was deposited during early rifting of the Gulf of Mexico via an inferred connection to the Pacific Ocean (Salvador 1991). The Louann Salt, which is dominated by halite in the central basin and anhydrite in more peripheral areas, may have been originally 3-4 km thick and was possibly deposited within 1-2 My (Hudec et al. 2013). Loading of the salt with deposits from Norphlet fluvial and aeolian systems, the subsidence of these sediment bodies into the salt, and later salt tectonics have resulted in a very complex stratigraphic architecture of the Norphlet in the subsurface. Opening of the Gulf of Mexico and connection to the early Atlantic Ocean during the later Oxfordian (Salvador 1987; Mancini et al., 1984) caused a rapid, low-energy flooding of the dune fields with partial preservation of dune topography (Story 1998; Ajdukiewicz et al. 2010;

Pilcher et al. 2014). Continued marine transgression allowed for widespread deposition of the carbonate Smackover Formation overlying the Norphlet Formation.

The Norphlet represents a type of fluvial system that can be characterized as "fluvial-dump-wind-redistribute," in which alluvial fans and channels transported sediment into the basin, but these terminated before reaching a body of water. Aeolian reworking of the fluvial sediments lead to localized dune fields in the wind transport direction. Terminal fluvial systems, both with and without distal aeolian systems, commonly characterize arid or semi-arid 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 and Singhvi 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 behavior of the channels is related to the development of the fan body. Given this connection, we herein term these system as "linked fan and terminal channel systems."

The added complexity in the Norphlet example is the progradation of the fluvial systems and development of dune fields over the deformable Louann Salt substrate. 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 et al. 2015). Each of these studies, however, has revealed the significance of specific variables in controlling the morphology and evolving stratigraphy in experimental settings and how these apply to real world basinal settings. Piliouras et al. (2014) discovered the importance of substrate thickness in determining the amount of subsidence of a dune and the control of interdune distance on subsidence rate. Kopriva et al. (2015) added more insight into the importance of sediment discharge rate on the geometry (width and depth) of a subsiding minibasin.

This research focuses on the interactions between a linked fan and terminal channel system with a pre-existing viscous layer (i.e., salt substrate) in order to better understand the Norphlet Formation in the eastern Gulf of Mexico basin. The objectives of this study are to use 3D 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. The findings from these experiments are then explored within the context of the Norphlet Formation. Understanding the main controls on the behavior of terminal channels resting upon on a viscous layer is significant for determining the local distribution of sands within 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 flat level 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 forced to flow through a rock cage in the inlet channel in order to reduce scouring of the sediment surface by the water influx. In order to visualize the flow, the water was dyed blue. For the sediment, a uniform 100-micron quartz sand was used.

The polymer used in the experiments works as a proxy for natural salt; it has been tested in many previous studies and is widely accepted as a representative for natural rock salt (Weijermars 1986; Weijermars et al. 1993). The material is a clear polymer known as PDMS (polydimethylsiloxane) and has a high viscosity (2.5e4 Pa•s). A desired thickness of PDMS was obtained by placing a given amount of PDMS in the basin and waiting until it leveled out over the entire basin. At the start of the experiments the basin was slightly tipped in order to create a slope (S = 0.013 or 0.026), which prevented the ponding of water around the fan but that was much 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 fan that prograded over time and created terminal channels beyond the toe of the fan. The water was recycled from the down-basin 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). Substrate thicknesses were set at 0 cm in Run 1, 2 cm in Run 2, and 3 cm in Run 3. We used a sediment supply rate of 2.12 g/s in Run 2, and 1.79 g/s in Run 4. For the basin slope, a slope of 0.013 was used in Run 4, and 0.026 in Run 5.

DATA COLLECTION

A camera was placed on the ceiling directly above the basin and connected to a computer that runs a software program 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 2-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 prospective.

Directly after a run, the deposit within each individual terminal channel was removed as quickly as possible, and width and depth measurements were recorded every 2 cm along the path of the channel. The sediment from each terminal channel was then dried and the mass was recorded. The sediment deposited in the fan was also collected and dried for the mass measurement.

Experimental Results

General Linked Fan and Terminal Channel System on a Mobile Substrate

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. We calculated the index for fan planform geometry (Φ_R) as a ratio of maximum width to length of the fan (Fig. 4B). Run 1 shows an average Φ_R 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 no significant sediment transport occurred.

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. As with Run 1, a fan grew but over time the fan grew wider than with Run 1. The fan geometry index Φ_R 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. Water draining off from the fan toe organized into streams as with Run 1, but in Run 2 sediment was 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 re-incision as the sediment sank into the salt substrate. Furthermore, the sediment and water delivered from the fan to the terminal channels were not continuous because lateral migration and avulsion of channels on the fan surface distributed the supplied sediment and water into different locations cyclically (Fig. 3E- F).

SALT SUBSTRATE THICKNESS

The impact of salt substrate thickness on fan development was modeled by varying polymer thickness in runs Run 2 (2 cm) and Run 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) because the amount of subsidence in Run 3 was larger in comparison to Run 2. In Run 3, the faster subsidence combined with a salt forebulge in front of the fan to produce ‘fringe’ lakes/playas near the fan toe (Fig. 4D). The lakes grew as the fan received more sediment that 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 upon 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 receding shoreline 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). The lakes interacted with the fringes of the fan, limiting fan growth downstream and laterally (Fig. 4D).

Both of the fans in Run 2 and Run 3 created terminal channels on the salt layer. However, a larger number of channels were organized in Run 2 (Fig. 4C) and there was about a five-fold increase in the amount of deposits within 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 was not continuous. In addition, as the salt bulge grew wider and higher down-basin, and the terminal channels began to be pinched off from the fan (Fig. 4D). In this stage, water was transported only intermittently from either updip knick points 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).

SEDIMENT SUPPLY RATE

Manipulating the sediment supply rate in the 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 = 2.12 g/s) resulted in a faster progradation rate of the fan body, which produced a relatively larger fan surface area (Fig. 6C). The increased progradation rate did not allow for the sediment to sink as fast into the mobile substrate as with the relatively lower sediment discharge rate (Q_s = 1.79 g/s) in Run 4. Both runs showed an increase in Φ_R 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 to accommodate larger deposits than those in Run 4(Fig. 5). Although the channels were 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

When comparing two identical experiments except for a change in slope between 0.013 in Run 4 (Fig. 7A) and 0.026 in Run 5 (Fig. 7B), the overall area of the fan was not significantly different (Fig. 7C), although 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 3 was wider and more radially symmetric (Fig. 7D). Only Run 5 developed a fan that had a larger maximum down-basin length instead of maximum cross-basin width (average Φ_R = 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 sloped 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 furthest downstream distance in comparison to all other runs (travelled 36 cm from the fan toe) (Fig. 5D). Most channels were also consistently wider and deeper closest to the fan toe. Run 5 developed more variability in width and depth, 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).

Discussion

Dynamic Interactions between Sedimentation and Salt Deformation

The experimental results from this suite of experiments provide insight into the controls of substrate thickness, sediment supply rate, and basin slope in a linked fan and terminal channel system. In regards to the fan body, we focused on fan growth rate, fan planform geometry and lake development. For the terminal channels, we focused on the number of channels, amount of deposition within the channels, and channel width and depth geometry.

Previous modeling studies of salt deformation under sand dunes (Piliouras et al. 2014) indicated a strong correlation between the initial thickness of salt layer and subsidence rate. A similar result occurred with these experiments where the thickness of the salt layer was varied. The thicker salt layer in Run 3 resulted in faster subsidence and a thicker deposit, thus resulting in a smaller fan area developed within the same total run time and with the same sediment influx as compared to experiments with a thinner salt layer (Fig. 4).

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 for 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 (Fig. 6).

In the case of no salt substrate (Run 1), a steeper basin slope may significantly change the fan surface area because as the basin slope increases toward a value near to that of the fan surface slope, the fan deposit thins and thus elongates significantly in the down-basin direction. However, the experiments with and without a salt substrate resulted in similar overall area growth with time (Fig. 4A). 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 (Fig. 7).

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 mainly caused 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, which aided in transporting more sediment laterally on the fan (Figs. 3E-F, 4B). For example, a fan that subsided faster could maintain a narrower shape along with lower Φ_R values (Fig. 7D). On the other hand, a fan that received a higher sediment supply became wider and produced higher Φ_R values (Fig. 6D). A similar trend was also seen in the runs with different substrate thicknesses. The thicker substrate in Run 3 produced higher subsidence and developed a narrower fan. Run 3 also did not show a strong change in Φ_R values over time (Fig. 4B). The lakes that were developed in Run 3 fostered progradation uniformly across the fan and thus maintain a similar Φ_R value.

Each experiment showed a range of two to five terminal channels that were established on the salt substrate. The number of terminal channels is strongly correlated with lateral distribution of sediment within a fan. If a fan developed in a narrow shape, only a small number of channels formed (Fig. 7A-B), but if a fan could distribute sediment laterally more effectively, a higher number of channels developed (e.g., Run 2). Therefore, the factors that cause a narrower fan (i.e., smaller sediment discharge, higher slope, and thicker salt substrate) could also cause a relatively smaller number of terminal channels, and vice versa. The proportion of sediment deposited within the terminal channels relative to fan body deposits generally followed the trend in the number of channels. In Run 2, in which five channels formed, about 5% of the total sediment mass was transported to the terminal channels, while the two channels in Run 3 received only 1% of the total sediment. The depth of the channels was highly limited to the initial salt layer thickness, 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 5).

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. Using a grain-size mixture would be an interesting next step in the future experiments, but here we are also able to reconstruct stratigraphic horizons using time-lapse images and final topographic surfaces.

Figure 8 shows a sequence of terminal channel evolution with an event associated with a channel lateral migration on a fan. A 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. 8A). The channel gradually migrated to the river right-hand side of the fan and started to flow into the terminal channel (Fig. 8B). The flow generated scours at the tips of patched deposits (bars) in the channel (Fig. 8B) and transported sediment to thicken and widen the terminal channel deposit (Fig. 8C-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. 8E). 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. 8F). Therefore, the depositional cycle in a terminal channel was linked to the timescale of the channel system on the source fan. In general, the timescale for channel avulsions on a fan scales with the total volume of a channel divided by sediment supply rate; this calculates the time that it takes to fill a channel at a given sediment discharge rate. In the case of a fan on a salt substrate, the timescale would be longer due to subsidence. Therefore, the fluvial autogenic cycle and terminal channel activation should be less frequent.

Figure 8G shows a stratigraphic section along the terminal channel reconstructed from the observed surface processes in Figures 8A-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 will develop in cycle 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 9; Run 3 developed lakes around the fan. Channels were active at the river left-hand side in 49.3 min (Fig. 9A). These fan channels migrated to the river right-hand side, advanced the shoreline, and filled the local lake (Fig. 9B-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. 9D). Interestingly, the transition from a distributary to a tributary system developed at this downstream boundary within a short distance. The fan/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. 9E). The stratigraphic reconstruction (Fig. 9F) shows the transition between fan and delta deposits as a result of lake development and local shoreline progradation.

Both cases in Figures 8-9 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 fan-terminal channel connection, 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 aeolian depositional systems in the early Gulf of Mexico basin. The major petroleum traps in the Norphlet directly 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 presence of the Louann Salt layer and the paleogeographic framework were the two main controls on Jurassic sedimentation (Tew et al. 1991). 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 factors are generally accepted for the main controls in determining the location of salt diapirs, fold belts and subcanopy hydrocarbon prospectivity, and play types (Hudec et al. 2013). However, the dynamic interactions between the Norphlet sedimentation and the Louann Salt deformation have not been thoroughly discussed.

Previous models have focused on the depositional environments seen in the stratigraphy of the Jurassic Norphlet primarily at a macroscopic scale. As put forth by Mancini et al. (1985), the depositional environment is a fluvial-dump-wind-redistribute system, but the morphological and sedimentological interactions between a linked fan and terminal channel system and the pre-deposited Louann Salt layer have not been previously investigated. Significantly, only in experiments using a salt substrate did sediment-transporting terminal channels extend basinward beyond the toe of the fan. These sand channel deposits, once the channels are abandoned, work as a local source and are distributed by aeolian processes. The results of this research improve the understanding of how substrate thickness, overall basin slope, and sediment supply to the basin affect the morphology and stratigraphic development of a fan and terminal channels.

Past studies have shown that basinal areas received a higher accumulation of salt while the salt is thin or absent in paleohighs (Mancini et al. 1985; Tew et al. 1999; Kugler et al. 1999; Obid et al. 2005; Hudec et al. 2013). The relative thickness of the salt deposited underneath the Norphlet, especially the updip portion of the system, controled the thickness of the fan deposits, which then controlled 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 would alternate with lake delta sequences. The sediment deposited off the fan into the channels served as the source for the nearby aeolian dune field; if the aeolian deposits are relatively 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 up-basin areas where fans develop potentially enhances sediment distribution down-basin 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 local sediment source for aeolian reworking after all.

Presently, the northeastern region shows 24-39 km of extension (Pilcher et al. 2014). The original low-relief deposition of the Louann Salt resulted in thick deposits throughout the basinal area from the sediment source. However, the distribution of the salt sequence is strongly dependent on basin architecture and is subject to change over time with differential loading (Dobson et al. 1997). The results from this study signify the importance of understanding the slope of the system at the time of the Norphlet deposition. Since there are multiple fans in this system (bajada), determining the location of channels along the fan-sides might be difficult to find in the stratigraphy. The planform geometry (i.e., the width to length ratio) of the fan body and the distance the sediments into the basin can provide geologists with a tool to find the overall 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 relatively lower slope inhibits sediment travel downstream and deposits sediments in a less condensed pattern. Dispersed channel locations with relatively 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. However, insight from the experiments conducted to isolate each control (e.g., salt thickness, sediment supply, and basin slope) on a linked fan-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 determine the significance of substrate thickness, sediment supply rate, and basin slope in this system. Furthermore we are able to determine the experimental stratigraphy expected and apply findings to a field case. Our series of experiments show: (1) a larger substrate thickness results in more available accommodation space and therefore more area 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 faster progradation rate and less subsidence, while a smaller sediment supply rate produces a smaller fan body and more subsidence, 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 within this system provides 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 all channels connected to the source fan. The autogenic cycle of the fan channel systems with an underlying salt substrate should be less frequent than where salt is absent because of active subsidence of the fan into the salt. Terminal channel activation should follow the same trend. 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 also leads to the improvement of the current understanding of the depositional environments of the Jurassic Norphlet by providing a process-understanding of each control on the dynamic interactions.

Appendix A: Figures

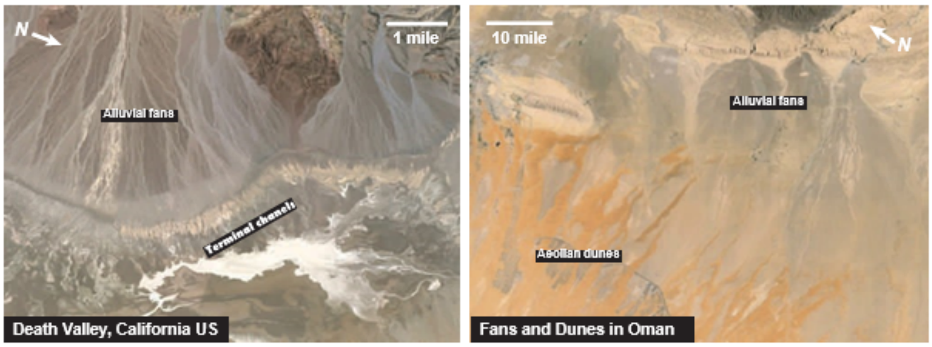


Figure 1. Modern examples of terminal fans. (A) Image of Death Valley, CA and (B) the Oman Dune Field. Modern examples of a fluvial-dump-wind-redistribute systems in semi-arid and arid environments. Terminal fans and linked channels are labelled in these images, showing the changes from a topographic high to a topographic low.

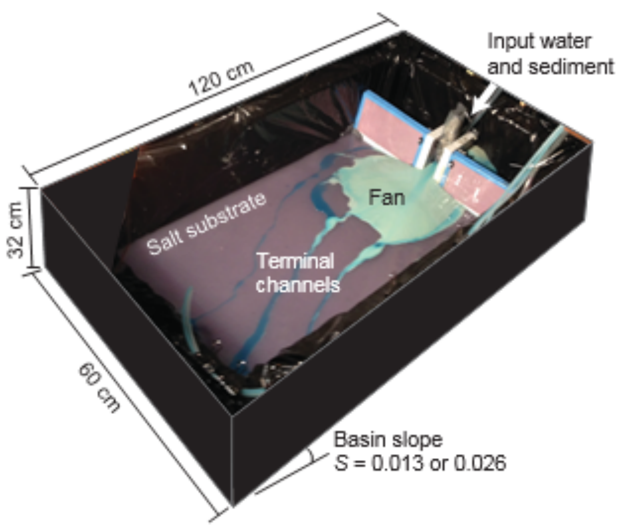


Figure 2. Diagram of 3-dimensional basin used for physical experiments. Constant rates of sediment supply and water flowed through the inlet and created a fan with terminal channels. A polymer covered the base of the basin and acted as a proxy for a mobile salt substrate over which the fan prograded.

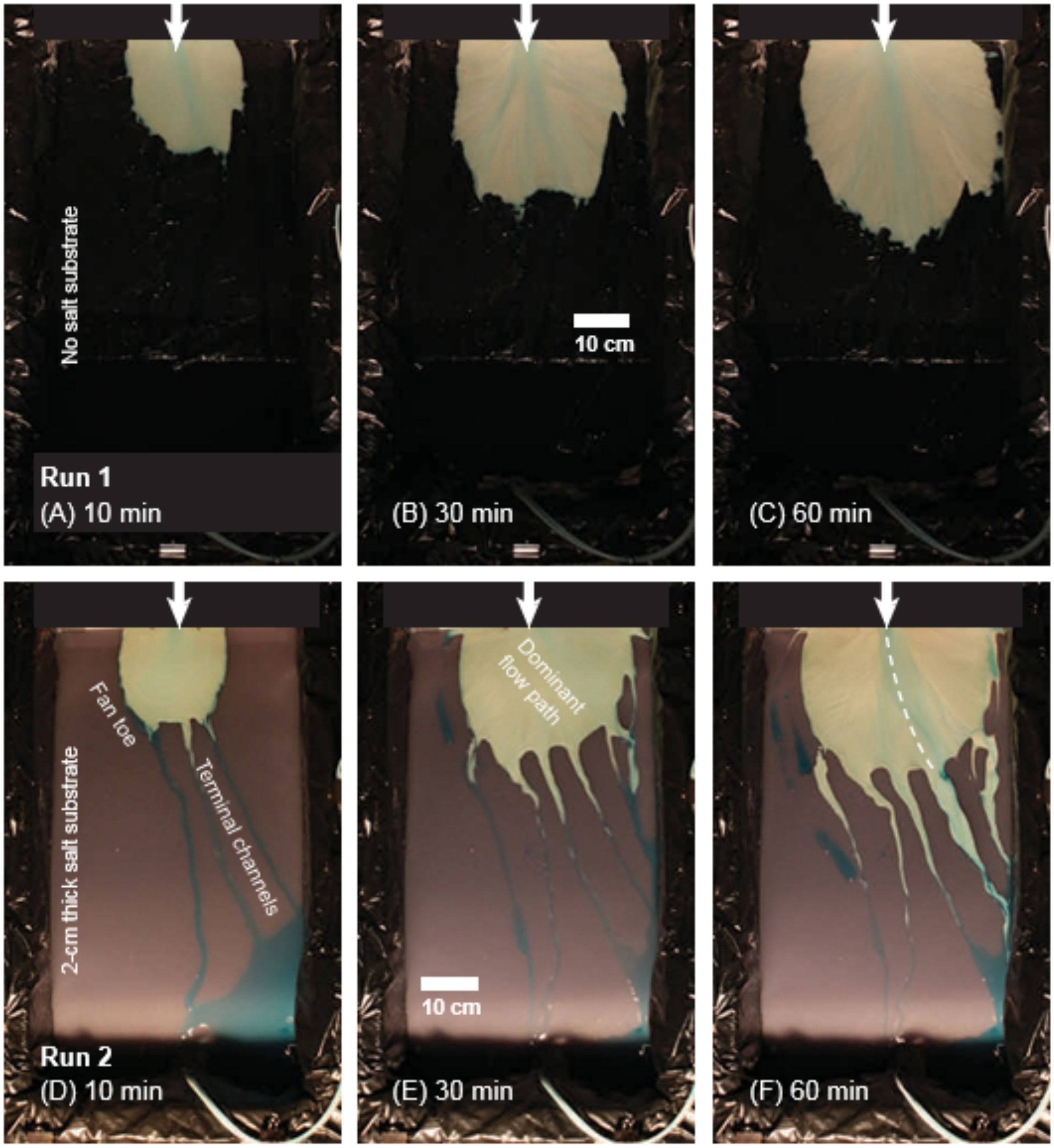

No salt substrate
10 cm
Run 1
(A) 10 min
(B) 30 min
(C) 60 min
Fan toe
Terminal channels
2-cm thick salt substrate
Dominant flow path
10 cm
Run 2
(D) 10 min
(E) 30 min
(F) 60 min

Figure 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. Direction of flow is indicated by the arrow at the top of the image.

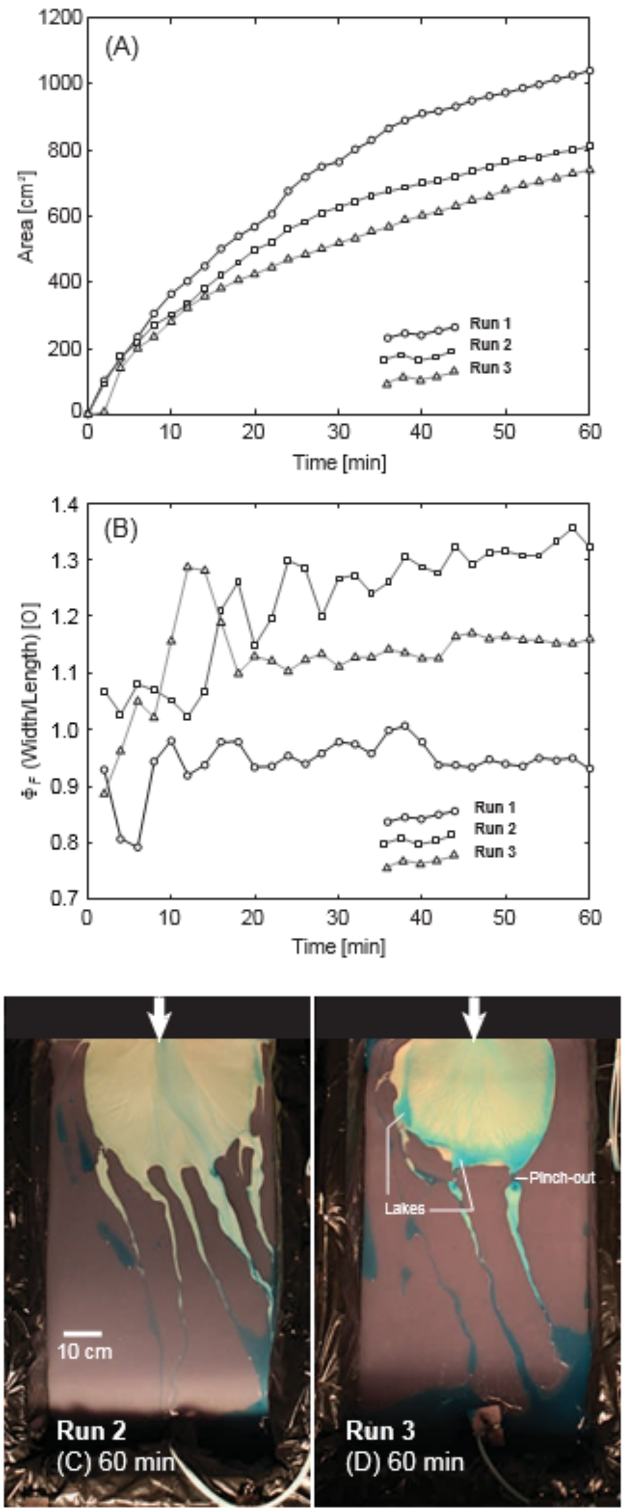
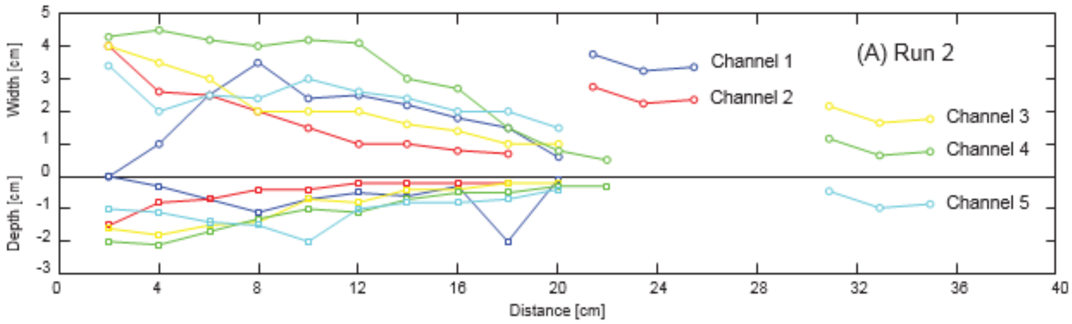
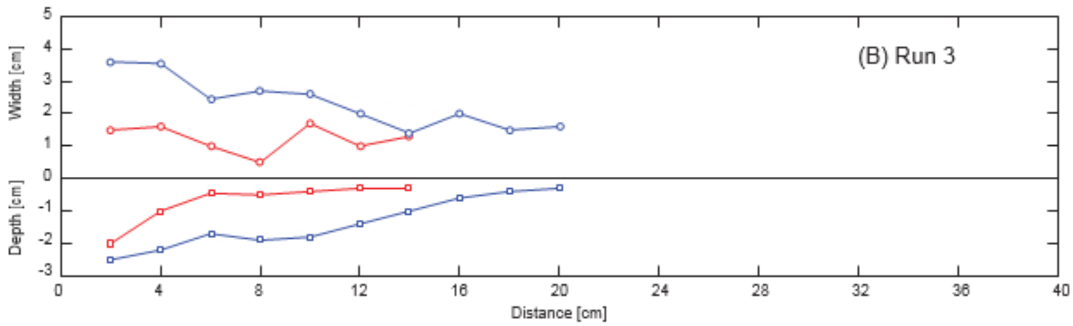

(A)
Area [cm²]
Time [min]
Run 1
Run 2
Run 3
(B)
Φ_F (Width/Length) [O]
Time [min]
Run 1
Run 2
Run 3
Lakes
Pinch-out
10 cm
Run 2
(C) 60 min
Run 3
(D) 60 min

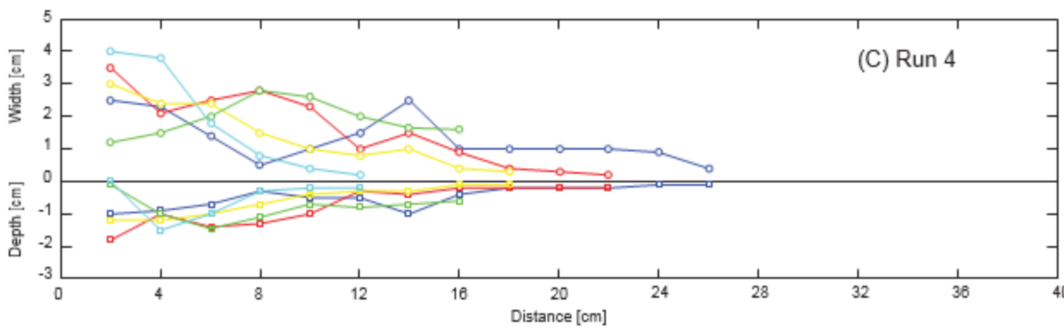
Figure 4. Variations in salt thickness. (A) Calculated fan surface area of Run 1, Run 2 and Run 3. Note that fan surface area decreased as thickness of the mobile polymer substrate increased. (B) Index for fan planform geometry (Φ_R) as a ratio of maximum width to length of the fan for Run 1, Run 2 and Run 3. The index for planform geometry indicates if the fan surface is more laterally dominated (higher Φ_R) or if the fan surface is more elongated (lower Φ_R) in the down-basin direction). Overall, Φ_R increases in experiments with a mobile substrate layer, and the ratio increases with a relatively 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 pinchouts of terminal channels at the salt forebulge, and the smaller number of terminal channels.



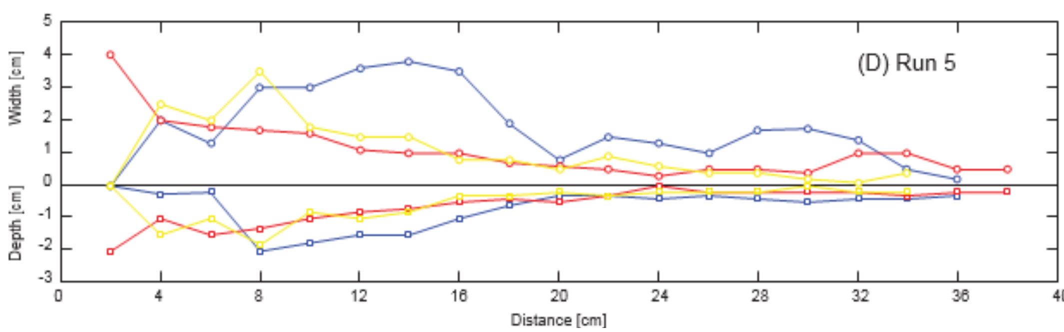
(A) Run 2
Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Width [cm]
Depth [cm]
Distance [cm]



(B) Run 3
Width [cm]
Depth [cm]
Distance [cm]



(C) Run 4
Width [cm]
Depth [cm]
Distance [cm]



(D) Run 5
Width [cm]
Depth [cm]
Distance [cm]

Figure 5. Width and depth measurements of terminal channels which have sediments present; this is measured in 2 cm increments following the course of the channel. Each channel is represented by a given color. (A) In Run 2, the maximum distance sediment travelled was 20 cm into the 5 established channels; the thinner substrate was able to establish more channels that could efficiently transport sediment downstream. (B) Run 3 developed two channels that deposited sediment into the 3-cm thick substrate layer. Due to upstream pinchouts as well as the salt forebulge, a very small amount of sediment was deposited in the channels and sediment supply was cut off early on. (C) Run 4 established 5 channels off of the fan body that transported sediments between 16 and 26 cm downstream. These channels were established throughout the toe and sides of the fan body. Deposition in the channels off the fan sides were influenced by the upwelling of salt. (D) Run 5 established 3 channels near the toe of the fan which transported sediment the most efficiently downstream of all the experiments. Sediment was deposited up to 38 cm down-basin.

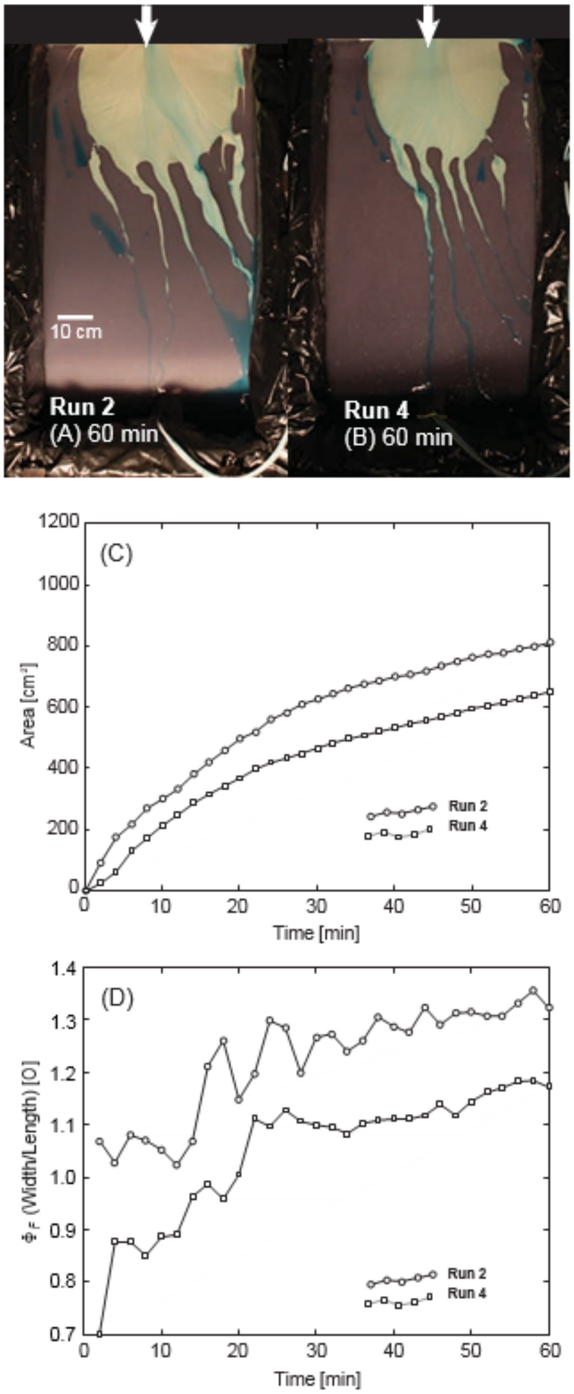

Run 2
(A) 60 min
10 cm
Run 4
(B) 60 min
(C)
Area [cm²]
Time [min]
Run 2
Run 4
(D)
(Width/Length) [O]
Time [min]
Run 2
Run 4

Figure 6. Variations in sediment supply rates. A) Final image of Run 2; this image emphasizes the surface area of the fan in comparison to Run 4 as well as the wideness of the established channels. B) Final image of Run 4; this run has the same number of established channels, however the width and depth values are smaller than Run 2, as a result of the smaller sediment discharge rate. This is visibly noticeable in comparing Fig. 6A to Fig. 6B. 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, and D) Index for fan planform geometry (Φ_R) for Run 2 and Run 4; Run 2 shows a higher ratio, indicating a stronger lateral progradation than Run 4. Run 4 has stronger down-basin progradation.

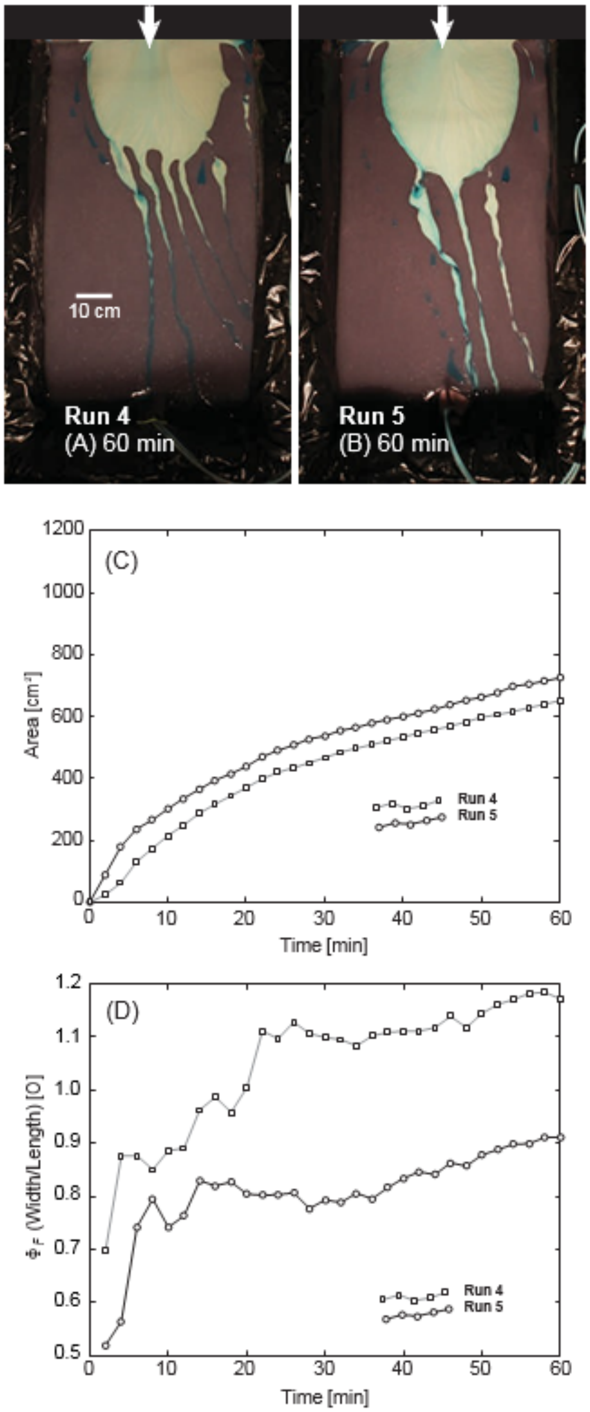

10 cm
Run 4
(A) 60 min
Run 5
(B) 60 min
(C)
Area [cm²]
Time [min]
Run 4
Run 5
(D)
Time [min]
Run 4
Run 5

Figure 7. Variations in basin slopes. (A) Final image of Run 4; the fan body is noticeably wider and 5 channels were established throughout the run. (B) Final image of Run 5 with a narrower, more elongated fan body and 3 channels located on the fan toe transporting sediment off of the fan body C) Calculated surface area over time for Run 4 and Run 5; the overall fan surface area for Run 4 is larger than Run 5; this is due to the lower slope allowing the fan body to laterally grow and increase its surface area. D) Index for fan planform geometry (Φ_R) as a ratio of maximum width to length of the fan for Run 4 and Run 5., The index for planform geometry indicates if the fan surface is more laterally dominated (higher Φ_R) or if the fan surface is more elongated (lower Φ_R) in the down-basin direction). Over the course of the run, Run 4 consistently maintained a higher Φ_R value than Run 5. The fan surface for Run 4 was more laterally dominated, while Run 5 produced a more elongated fan shape, resulting in a smaller Φ_R value.

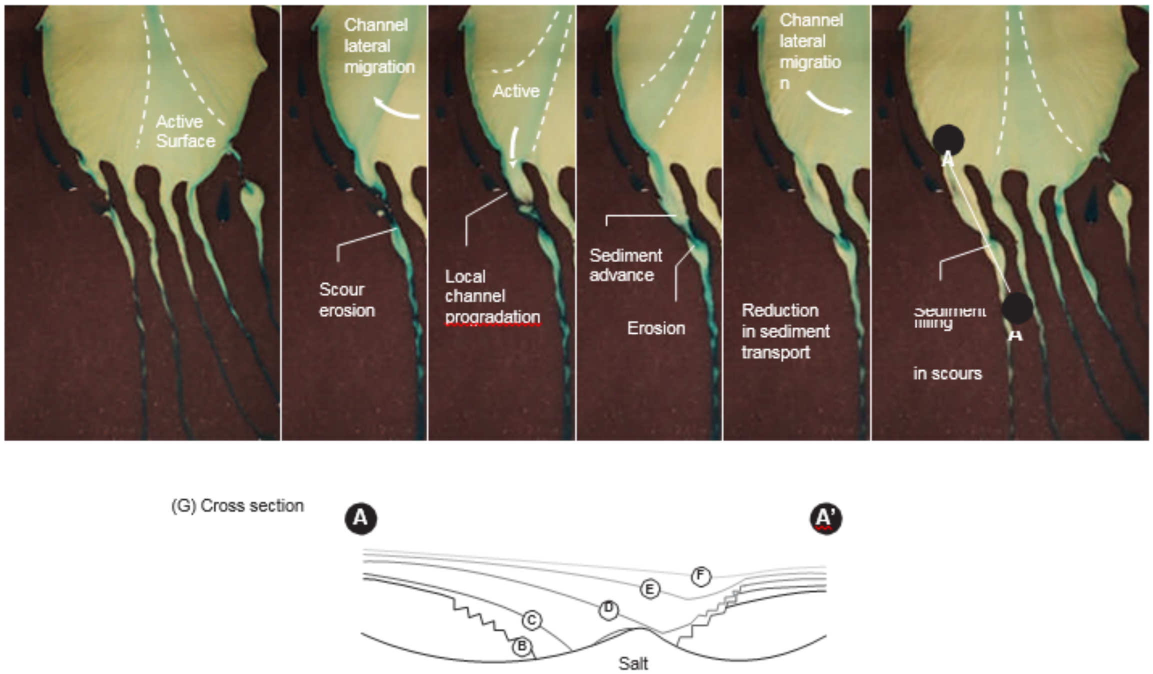

Active
Surface
Channel
lateral
migration
Scour
erosion
Active
Local
channel
progradation
Sediment
advance
Erosion
Channel
lateral
migratio
n
Reduction
in sediment
transport
A
Sediment
filling
in scours
A
(G) Cross section
A
A'
F
E
D
C
B
Salt

Figure 8. (A-F) An example of a sequence of terminal channel evolution is represented with an event associated with a channel lateral migration on a fan. (A) indicates the current active surface of flow. B) As the flow laterally migrated on the fan body, it began to flow into a specific channel; this flow generated scours at the tips of sand deposits (bars). C-D) shows the increase in sediment being transported into the channel and deposited, generating a local channel progradation as the terminal channel deposit grows. E) The channel then begins to shift towards another location and the flow begins to move away from the channel, followed by F) abandonment of this channel from flow and sediment filling in the scours after approximately 6-7 minutes. G) Stratigraphic section reconstructed based on observed surface processes between a given terminal channel and the salt substrate: a terminal channel deposit starts with an erosional surface around a salt high that gradually fills in the surface as a sediment wedge or bar. The terminal channel will then subside at differing rates until a new depositional event begins; as long as there is remaining salt underneath the channel, the depositional cycle will occur again.

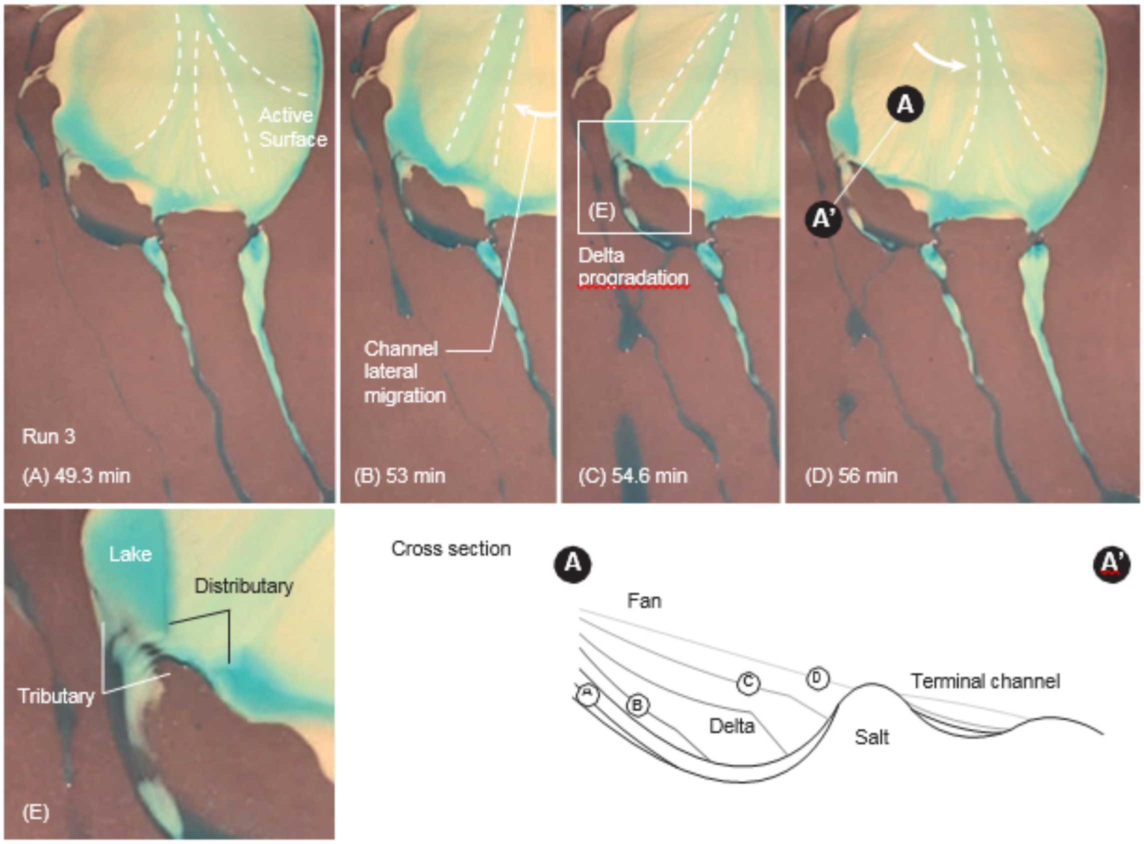

Active
Surface
Run 3
(A) 49.3 min
Channel
lateral
migration
(B) 53 min
(E)
Delta
progradation
(C) 54.6 min
A
A'
(D) 56 min
Lake
Distributary
Tributary
(E)
Cross section
A
A'
Fan
C
D
Terminal channel
A
B
Delta
Salt

Figure 9. Evolution and interactions of fan channels on a thicker salt substrate over time. Images illustrate channel migration and the formation of lakes, followed by a lake delta. (A) Shows the initial location of the active channels on the fan body. (B-C) illustrates the migration of the channels to the river right-hand side, the advanced shoreline and the filling of the local lake. The presence of the local lake minimized the amount of sediment that could be transported into the terminal channel, resulting in deposition in the local lake, forming a lake delta. (D) Once the delta prograded, a thick accumulation of sediment filled the lake; the transition from a distributary to a tributary system developed over the short distance of the lake. (E) The fan/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. (F) Stratigraphic reconstruction that shows the transition between fan and delta deposits as a result of lake development.

Appendix B: Tables

Table 1. Experimental parameters

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

Table 2. Sediment distributions between fan and channels

Run Name		Fan	C Total	C1	C2	C3	C4	C5	C6
Run 2	Mass (g)	7000	367	22.6	38.4	89.9	139.8	66.8	9.5
	Proportion	95.0	4.99	0.31	0.52	1.22	1.90	0.91	0.13
Run 3	Mass (g)	7134	76.9	13.2	63.7				
	Proportion	98.9	1.06	0.18	0.88				
Run 4	Mass (g)	6100	189.1	39.5	58.3	38.2	28.8	22.7	1.6
	Proportion	97.0	2.97	0.58	0.93	0.61	0.46	0.36	0.025
Run 5	Mass (g)	6200	172.4	87.7	53.3	31.4			
	Proportion	95.5	2.65	1.35	0.82	0.48			

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