

PS Physical Modeling of a Prograding Delta on a Mobile Substrate; Dynamic Interactions between Progradation and Deformation*

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Search and Discovery Article #51356 (2017)**

Posted February 6, 2017

*Adapted from poster presentation given at AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

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Abstract

Subsurface architecture of a delta that progrades on a mobile substrate (e.g., salt) is a product of complex interplay between depositional process and subsidence. Previous studies mostly focused on structural deformation of a salt layer in response to tectonic forcing, and left the dynamic feedback between sedimentation and subsidence unexplored. We present results from physical experiments of delta progradation on a mobile substrate. Five carefully designed experiments were performed to understand the effects of delta progradation rate on the shape and dimension of salt deformation and associated stratal architecture. All of the runs had constant sediment and water discharge, but the mobile substrate thickness and water depth varied from 2 cm to 4 cm and from 1 cm to 3 cm, respectively. The results showed that the deeper the water depth, the slower the shoreline progradation rate, while the thinner the salt thickness, the faster the delta progradation. The experimental results also provided data over a wide range of shoreline advance and subsidence rates enough to indicate changes in shape and dimension of salt deformation structure. Runs with fast shoreline progradation showed isolated salt domes developed internally into the delta plain and a rough planform pattern in the shoreline due to lobes built by channels flow between upwelled salt structures. However, runs with slow shoreline progradation developed connected long salt ridges around the toe of the delta, limiting sediment to transport beyond the ridges. This overall pattern in salt structures is time dependent. As a delta surface grows larger and the shoreline progradational rate autogenically decreases with time, chances to develop isolated salt domes decrease but more connected long salt ridges occur. The insight from the physical modeling of a delta on a mobile substrate is important to predict the mechanism for large-scale salt basin stratigraphy under a high sediment supply that interact with the substrate actively.

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ABSTRACT

The subsurface architecture of a prograding delta on a mobile substrate (e.g., salt) is a product of the complex interplay between deposition and subsidence. Previous studies focused mainly on structural deformation of a salt layer in response to tectonic forcing, leaving the dynamic feedback between sedimentation and subsidence unexplored. We present results from physical experiments of delta progradation on a mobile substrate. Five carefully designed experiments were performed to understand the effects of delta progradation rate on the shape and dimension of salt deformation and associated delta deposition. All of the runs had constant sediment and water discharges, but the water depth and mobile substrate thickness varied from 1 cm to 3 cm and from 2 cm to 4 cm, respectively. The results showed that increasingly deeper water depths slowed the shoreline progradation rate, while increasingly thinner salt thickness accelerated delta progradation. The experimental results also provided a wide range of shoreline advance and subsidence rates that show changes in the shape and dimension of the salt deformation structure. Runs with fast shoreline progradation showed isolated salt domes developed internally on the delta plain and a rough platform pattern along the shoreline due to lobes built by channel flow between upwelled salt structures. However, runs with slow shoreline progradation developed long connected salt ridges around the toe of the delta, limiting sediment transport beyond the ridges. This overall pattern in salt structures is time dependent. As a delta surface grows larger and the shoreline progradational rate autogenically decreases with time, chances to develop isolated salt domes decrease but more connected long salt ridges occur. Physical modeling of a delta on a mobile substrate is important in predicting the mechanism for large-scale salt basin stratigraphy under a high sediment supply that interacts with the substrate.

INTRODUCTION AND MOTIVATION

Deposition on a mobile substrate (e.g., salt) shows different subsurface architectures compared to a rigid basement due to its dynamic response to sediment loading. The dynamic feedback between deforming substrate and differential loading caused by a prograding delta has not been thoroughly studied yet.

Early Permian Kungurian Salt found in the Precaspian Basin, which is located north of the present-day Caspian Sea, divides the basin into several zones characterized by size, shape, and maturity. The different salt structures in each zone reflect the areal differences in salt development history. On the southeastern margin of the basin, Kungurian salt contains mainly down-built diapirs and stocks, while longer, more symmetrical salt walls along the northern and western flanks of the basin. In previous research, these differences in salt development are attributed to sediment transport from the Ural Mountains to the east of the basin.

A recent study using a 3-D numerical model predicted dome or finger-like diapirs and larger spacing between exposed diapirs associated with a given sedimentation rate. The modeling results also show that different initial salt layer thicknesses differ salt diapir geometry. The larger salt thicknesses create elongated-shaped diapirs and larger spacing between them because larger salt thicknesses cause relatively faster upwelling of the salt layer which then reaches the surface at earlier stages compared to the counter-part with thinner salt substrate. At the initial stages of diapir formation, the topographic highs in the salt surface can potentially localize the diapirs better.

The basic parameters controlling stratal architecture in depositional sequences are sediment supply (S) and rate of change in accommodation (A) and the change in accommodation is a key to stratigraphic development. In the areas with underlying salt layers, the salt is deforming over time while overlying deposition occurs. This causes the differential sediment loading and the subsidence of underlying mobile substrate which affects the change in accommodation. The dynamic feedback between deposition and change in accommodation is our main research focus here.

Previous studies focused on structural deformation of a salt layer in response to tectonic forcing. What still remains to be explored further are dynamic feedback between salt tectonics and sedimentation, especially associated with a differential loading caused by a prograding delta and/or clinoform.

An understanding of the physical processes of modeled sedimentation aids in the analysis of sedimentation in the natural system. We used physical modeling to examine the effect of delta progradation rate on deformation of a mobile substrate with ranges of initial basin depth and salt thickness were designed to understand the interactions between a delta prograding over a deforming salt substrate. In addition to basin sediment supply, factors such as basin depth and salt thickness can affect the delta progradation rate because differences in salt thickness change the subsidence rate, and changes in basin water depth due to the subsidence are strongly correlated to the shoreline progradation rate. Understanding the mechanism that develops different types of salt deformation in different environments can help improve the understanding of salt-related basin depositional histories.

EXPERIMENTAL SETTING

Discharges

Sediment discharge $Q_s = 0.94$ mL/sec
Water discharge $Q_w = 19$ mL/sec
($Q_s/Q_w = 0.049$)

Polymer (polydimethylsiloxane, PDMS)

Density 965kg/m³, Viscosity 2.5e4 Pa·s

Experiment variables

< Control of basin water depth >

	P3W1	P3W2	P3W3
Polymer thickness	3 cm	3 cm	3 cm
Water depth	1 cm	2 cm	3 cm
Run time	50 min	1 h 40 min	1 h 30 min

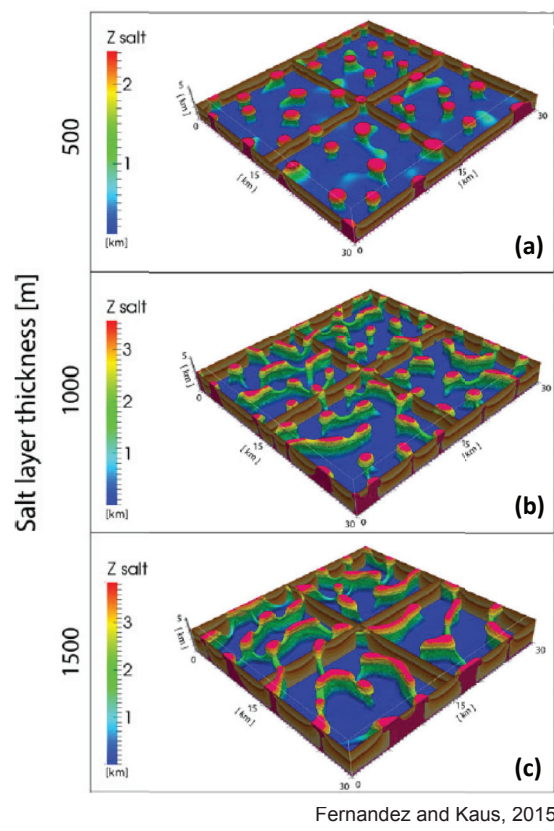
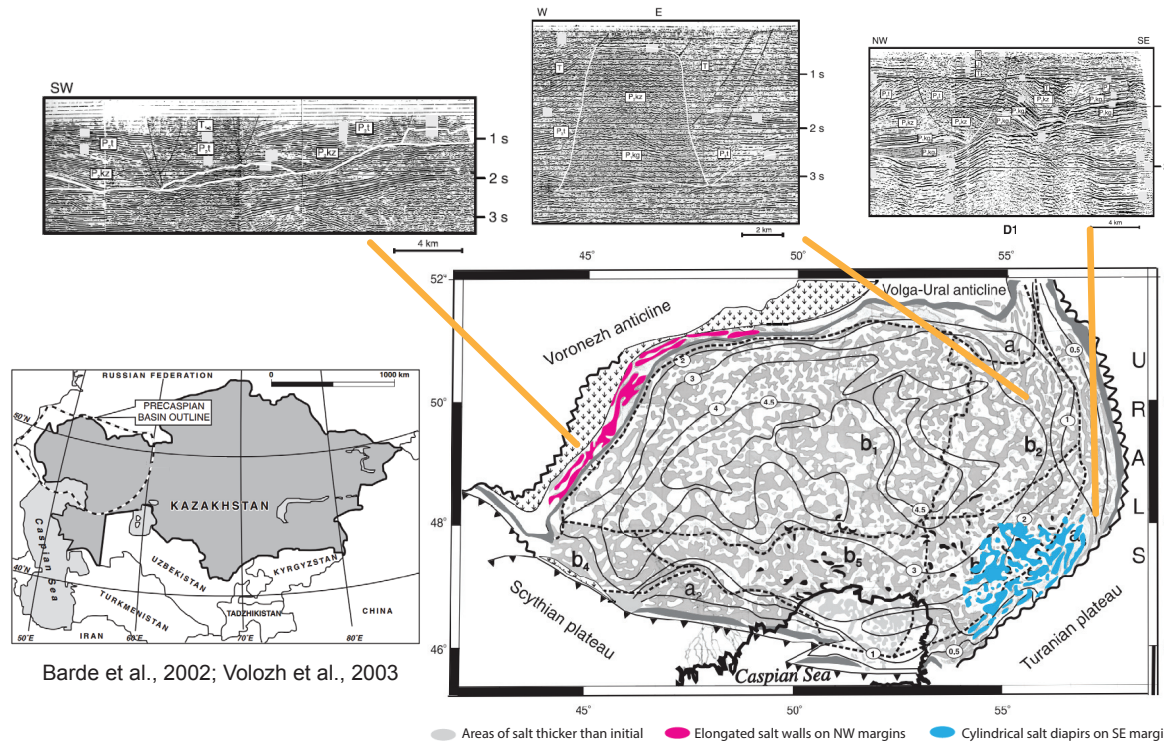
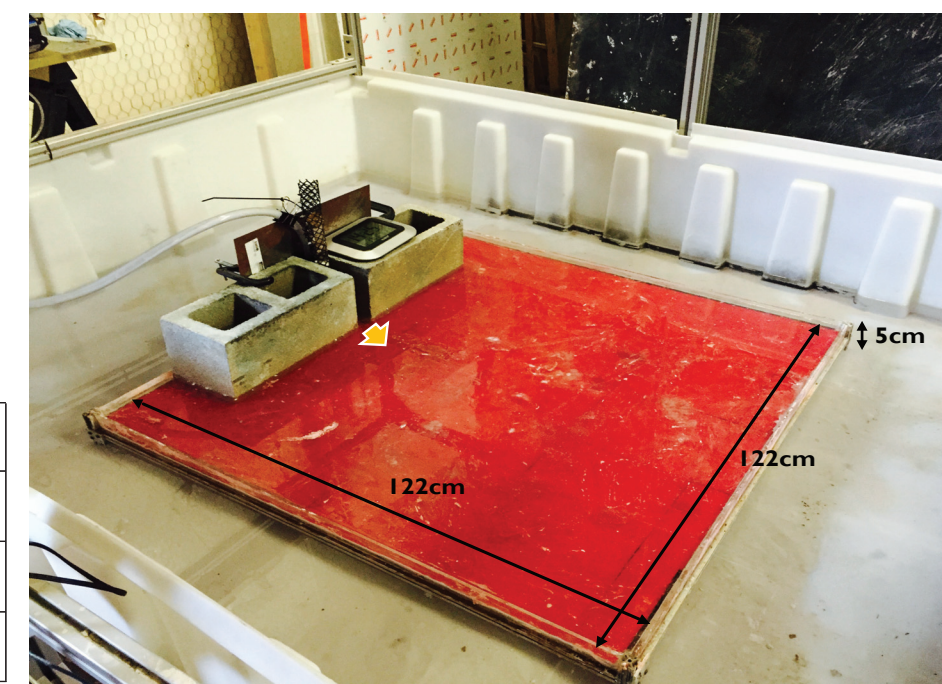
Sediment mixture

	White sand	Walnut shell
Size	170 μ m	
Density	2.650 g/ml	1.300 g/ml
Mixing ratio	7	3

< Control of polymer thickness >

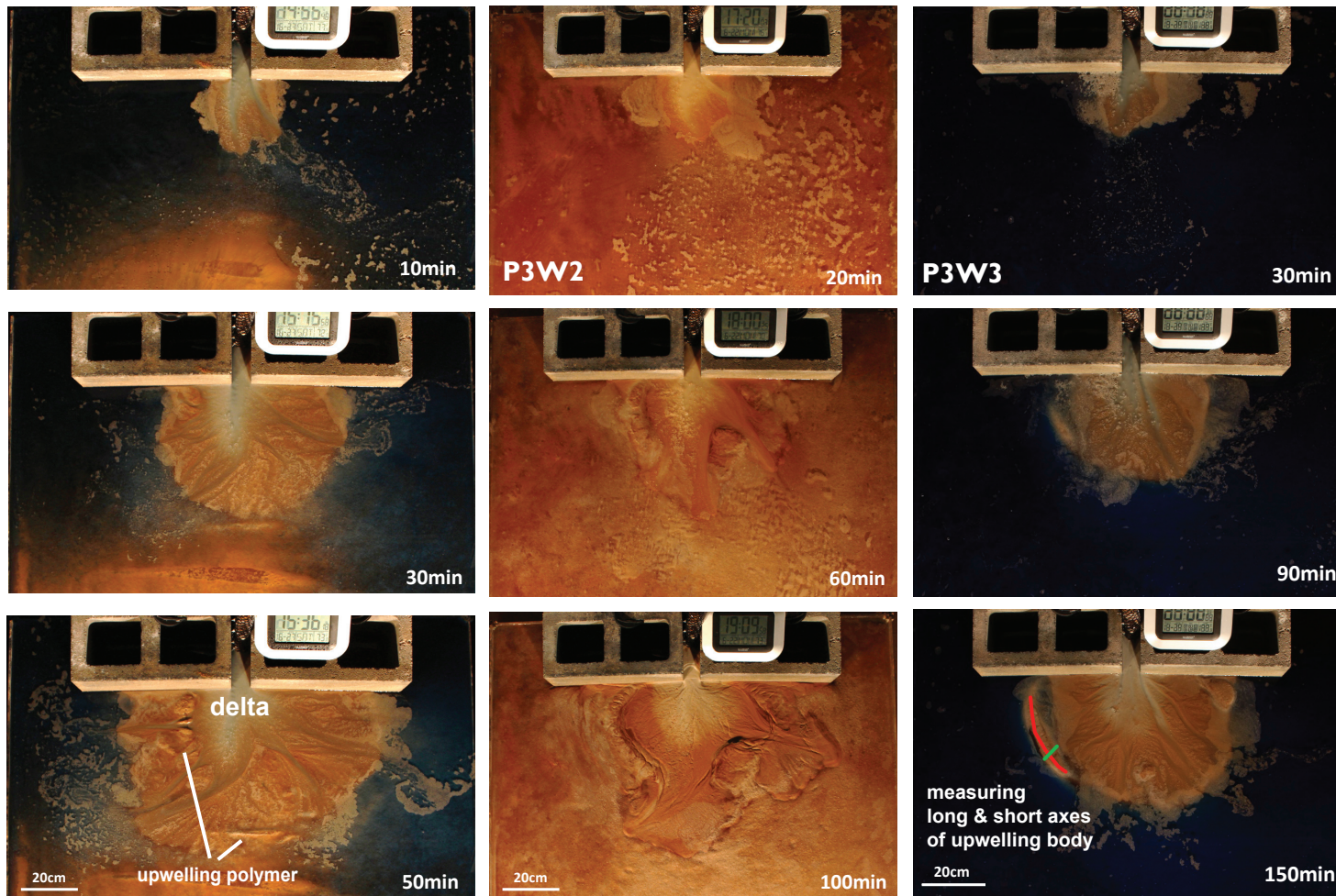
	P2W2	P3W2	P4W2
Polymer thickness	2 cm	3 cm	4 cm
Water depth	2 cm	2 cm	2 cm
Run time	5 h	1 h 40 min	7 h

EDDy (Experimental Delta Dynamics) basin



EXPERIMENTAL RESULTS

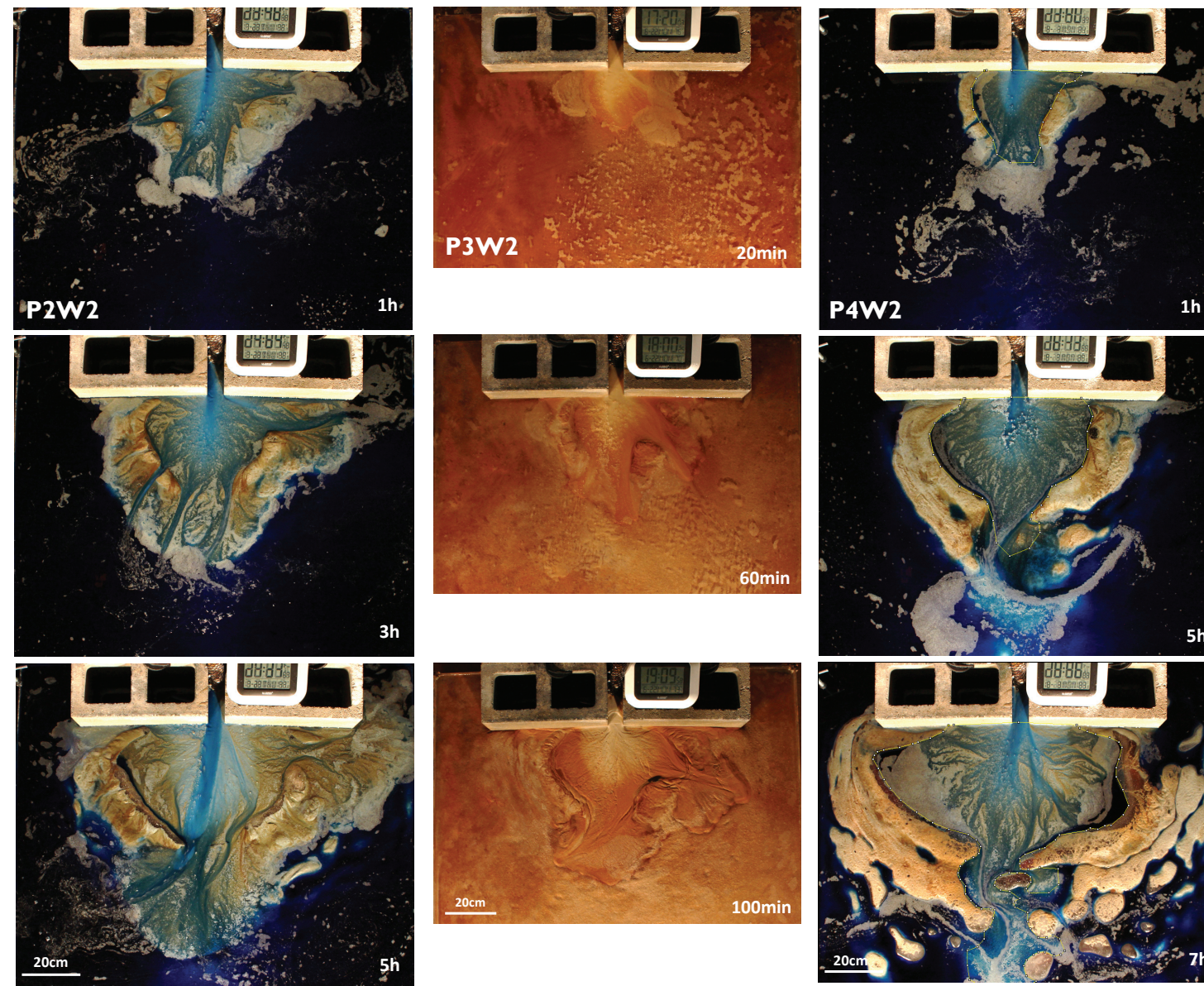
1. CONTROL OF BASIN WATER DEPTH



< DELTA EVOLUTION >

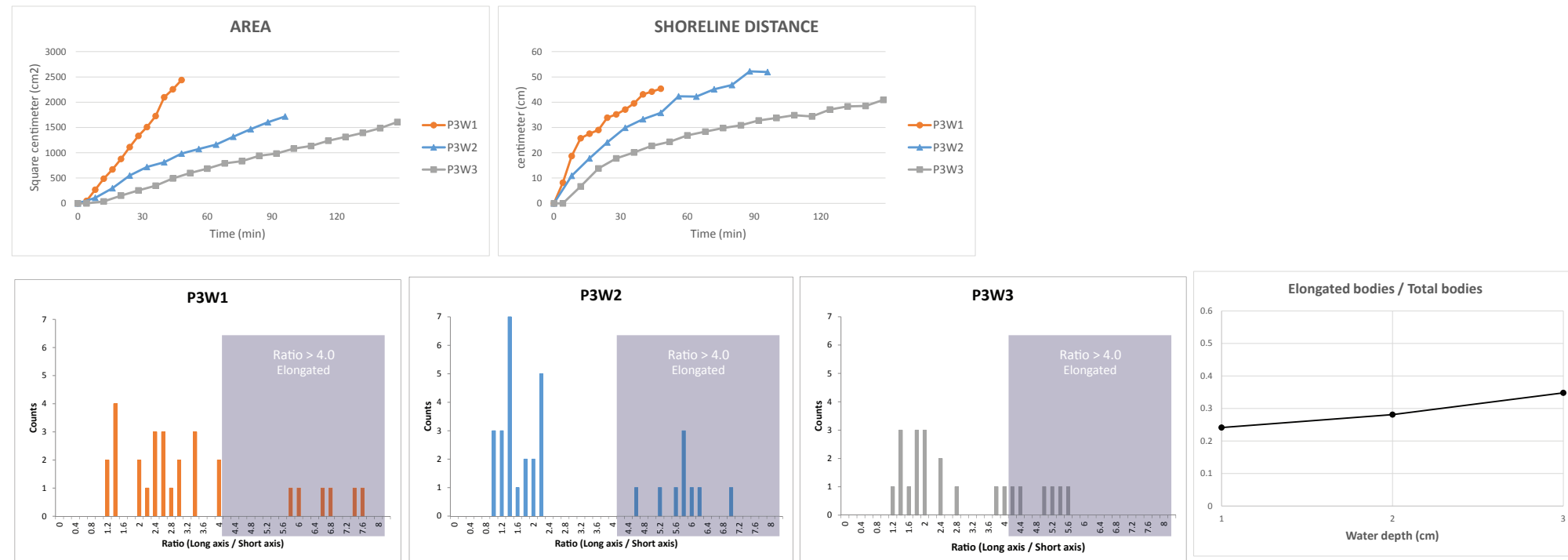
At the early stage of delta progradation, all three deltas prograded in all directions in radial pattern. P3W1 - showed the fastest progradation of the delta and maintained the overall radial symmetry with the least interruption by polymer diapirs. P3W2 - developed branching lobes caused by polymer diapirs. Toward the end of the run, the delta ended up having two dominant lobes that actively grew and caused basinward progradation at the localized locations. P3W3 - had an elongated polymer diapir develop at the river right-hand side of the delta surrounding around the delta toe and two isolated diapirs.

2. CONTROL OF POLYMER THICKNESS



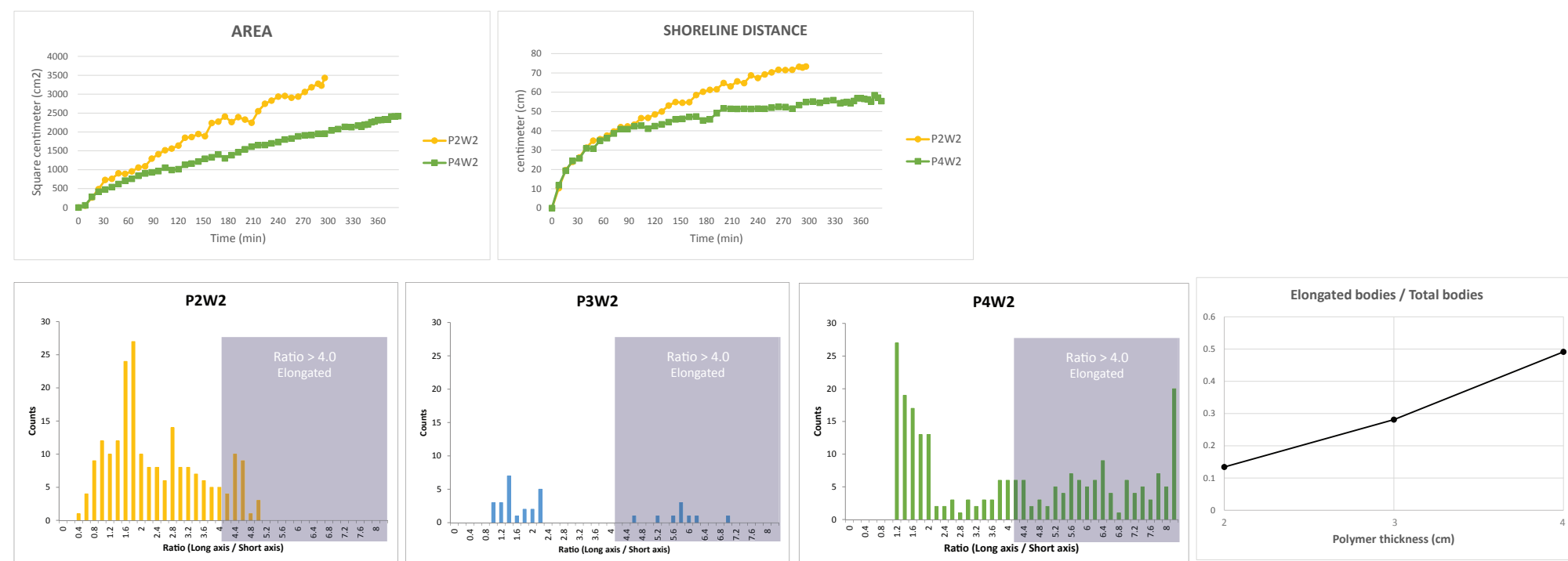
< DELTA EVOLUTION >

P2W2 - characterized by upwelling polymer bodies with several channels between and over the bodies. The polymer bodies started to develop radially across the delta shoreline in the early stage. Upwelling salt was split by channels before they gradually closed up channel paths and merged together to develop longer bodies around the delta. Three to five channels developed over the run; the two main channels continued to build two delta lobes: one at the center of the basin and the other to the river left-hand side of the delta. P4W2 - the polymer bodies upwelled and merged to make ridge-shaped bodies surrounding the delta rapidly at the beginning. These worked as barriers around the delta that confined the main delta body upstream of the salt ridges but allowed only one main channel connecting to the open basin. The surface area was still gradually expanding over time as the delta received more sediment and pushed the salt ridges to the radial directions.



< POLYMER MOVEMENT AND PROGRADATION RATE >

The deeper the water, the slower progradation due to more available space needed to be filled by sediment in order to advance the shoreline. The time series of the shoreline locations in the three experiments clearly show slower progradation with deeper basin water depths. Shoreline migration rates decrease over time in all three runs. As a delta surface grows larger, the shoreline progradational rate autogenically decreases with time because delta top uses more sediment increasing proportionally with the surface area increase. As the shoreline migration rate decreases, chances to develop isolated salt domes decrease but more connected long salt ridges occur. Accumulative counts of subaerially exposed salt structures mapped over every 4 min images. Overall, the number of individual polymer bodies counted above the base level increased with time. We also measured the ratio between the long and short axes of the polymer diapirs and referred to ones with an aspect ratio higher than 4 as elongated bodies and less than 4.0 as isolated bodies. The value increases with water depth, indicating more elongated bodies organized in a delta prograding slowly. The salt ridge developed where the shoreline progradation rate was smallest but the salt domes occurred the parts that the delta advanced faster.



< POLYMER MOVEMENT AND PROGRADATION RATE >

P4W2 had slower shoreline progradation rates compared to those in P2W2. Shoreline migration rates decrease over time in all experiments. Especially, the time series of the shoreline locations from P4W2 shows more drastic decreases in the shoreline migration rates due to the strong ridges that restricted the delta within the salt ridges. Polymer bodies of P4W2 merged in the early stage of the run and surrounded the delta which kept pushing the polymer walls outward. Polymer bodies of P2W2 eventually merged at the later stage. The channels flew between the exposed polymer bodies over a longer period, which let the polymer bodies remain separated longer. Accumulative counts of subaerially exposed salt structures mapped over every 8 min images. The mapped data indicates that P4W2 had significantly high ratio values compared to the data from P2W2. The numbers of normalized elongated salt diapirs increases with polymer thickness, indicating more elongated bodies organized in a delta prograding slowly.

DISCUSSION

1. CONTROL OF BASIN WATER DEPTH

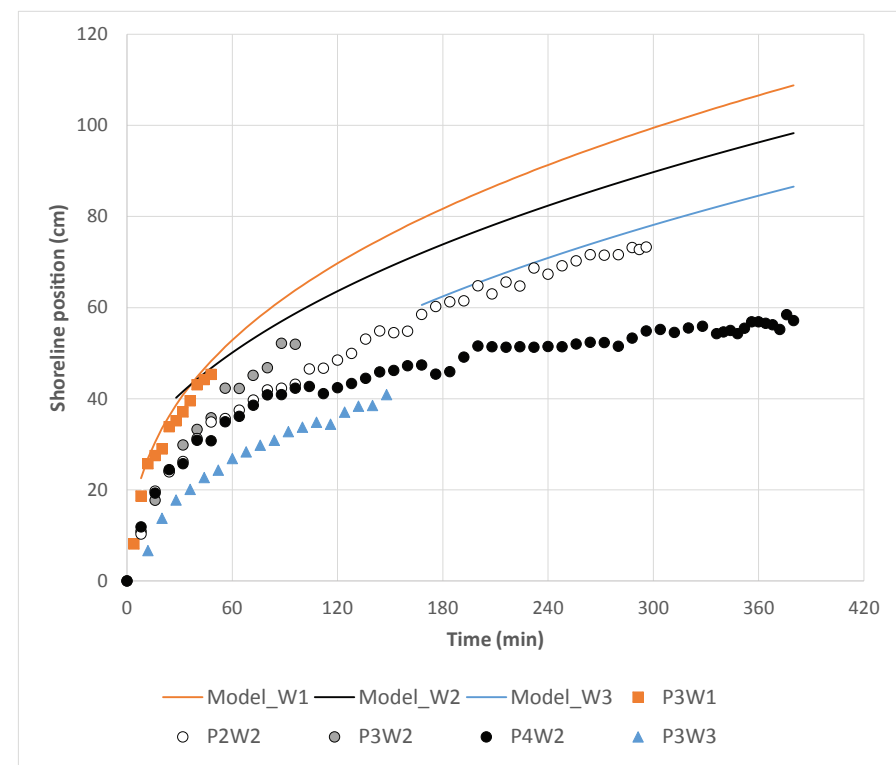
During the deposition and progradation of deltas on a mobile substrate, the mobile substrate starts to deform by differential loading of the delta deposits. This mobile substrate deformation and formation of diapirs creates more vertical space available for sediment to deposit and thus diminishes delta progradation. The shallowest water depth resulted in the fastest progradation. This rapid distribution of sediment mass over a larger area reduced differential loading on the salt beneath the delta, which decreased the salt flow rate underneath of the delta toward the basin side. This in turn diminished subsidence rate and aided in shoreline progradation. In this setting, the delta could maintain a more radial platform shape due to less local blockage by salt upwelling structures. Once the polymer upwells to the surface through the deposit, individual diapirs merge and create elongated and ridge-shaped polymer bodies. The experimental results show a higher proportion of all upwelled polymer bodies in deeper water runs are elongated and connected polymer bodies. Locally differential sedimentation rates caused isolated salt domes organized inside the delta plain. Areas between channels where deposits mostly thickened were dominated by the salt domes in the early stage of the experiment. As the delta progradation slowed with time autogenically, the polymer organized better to develop long ridges rather than isolated salt domes. In contrast, the slow prograding delta built a thick deposit that expanded slowly in area due to the deeper water condition, which allowed the salt layer to flow outward over a longer period and organize more connected radial ridges. The polymer ridge exposed above the water surface gradually became bigger and longer as the delta pushed more polymer outward and the delta deposit subsided into the polymer layer. The shoreline progradation was too slow to overcome the ridge height and cover this structure with sediment until the end of the run. In summary, there is a trend in the upwelling salt geometry associated with delta progradation rate. The faster progradation rate causes the isolated structure.

2. CONTROL OF POLYMER THICKNESS

Thicker initial mobile substrate resulted in larger amounts of subsidence for a given amount of sediment deposit. P4W2, the thicker polymer run, showed faster and larger polymer deformation, so diapirs become emergent and influenced delta progradation even in the early stage of the run. The initial small diapirs of P4W2 connected to form ridges that confined and surrounded the delta, which in turn caused more sediment loading in the area close to the sediment source and produced a positive feedback for a faster subsidence. This further reduced the shoreline progradation and thus again gave enough time for the mobile substrate merging to create a larger and longer ridge-shaped polymer wall around delta. The aspect ratios between long and short axes in P4W2 vs P2W2 reflect the trend of developing different salt upwelling structures under different initial salt thickness: the ratios in P4W2 are higher compared to P2W2.

< GEOMETRIC SHORELINE MODEL >

Simple geometric model of shoreline position comparing the experimental data. Geometric modeling results without mobile substrate with three model runs with 1 cm, 2 cm, and 3 cm water depth which marked with solid lines showed faster progradation rate compare to the experimental runs with mobile substrate and the equivalent water depths which marked with dots. Therefore, the progradation of the delta on a mobile substrate should have slower progradation rates than the one with a rigid basement. The set of modeling and experimental runs with 2 cm water depth produces a somewhat unexpected and interesting trend, when comparing the shoreline migration patterns in 0 cm salt layer (from model, hereafter POW2, solid black line), 2 cm salt layer (white dot), 3 cm salt layer (gray dot), and 4 cm salt layer (black dot). Based on the behavior of salt substrate discussed above, it was expected that progradation rate should be slower in the runs with thicker substrate and vice versa. However, there was an exception that the progradation rate of P3W2 was higher than the one of P2W2. The reason behind this unexpected result is likely that the polymer behavior occurs in the third dimension.



CONCLUSIONS

Basin water depth with a constant polymer thickness showed an inverse correlation between delta shoreline progradation rate and water depth, because as the basin water depth is higher, the accommodation space for sediment to fill was increased. Moreover, the basin water depth created various geometries of upwelled mobile substrate bodies that reached to the water surface. A delta with slow shoreline progradation caused by deeper basin water depth finally led more connected and elongated polymer ridges. A delta with fast shoreline progradation caused by shallower basin water depth produced upwelled mobile substrate diapirs trapped under the delta because the prograding delta covered diapirs and exerted sediment loading on them. Different initial polymer substrate thicknesses also affected salt subsidence and shoreline progradation rate. Mobile substrate undergoes subsidence by differential loading caused by delta progradation, and is followed by dynamic deformation interacting with overlying deltas deposits. This subsidence and deformation was greater as the thickness of the mobile substrate increased. Thicker mobile substrate caused faster subsidence and slower shoreline progradation, whereas thinner substrates caused slower subsidence and faster shoreline progradation. In terms of the geometry of substrate deformation, relatively slower subsidence, which relates to faster shoreline progradation, created more isolated salt domes under and around the delta. In this case, multiple channels and lobes were formed across the shoreline on the delta plain. In the other hand, faster subsidence, which relates to slower shoreline progradation, created connected diapirs and ridge-shaped bodies which blocked channels and let only a few channels and lobes developed across the shoreline. Basin water depth and thickness of mobile substrate differences affected the progradation rate of deltas. High progradation rate caused isolated salt domes to develop internally on the delta plain and around the delta. In the other hand, low progradation rate caused connected long salt ridges around the toe of the delta, limiting sediment to transport beyond the ridges. We found that the progradation rate of deltas can interact to its substrate to affect not only characteristics of the delta itself, such as channelization, stratigraphy, and geometry, but also deformation of substrate, mainly the diapirs geometry. The mechanism that develops different types of salt deformation beneath sediment deposition in different environments for large-scale salt basin stratigraphy under a high sediment supply that actively interacts with the substrate can be predicted. Moreover, understanding the substrate deformation mechanism can help improve the understanding of salt-related basin initial depositional environment and its histories in a nature system.