COEVOLUTION OF MINIBASIN SUBSIDENCE AND SEDIMENTATION: EXPERIMENTS

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ABSTRACT: Subsidence patterns resulting from differential sediment loading on a mobile substrate (e.g., salt) are an important process for the development of accommodation and stratigraphic architectures in intraslope minibasins. Numerous studies of minibasin systems have focused on either the tectonic processes involved in salt deformation or the stratigraphic interpretation of the sedimentary fill of minibasins. This study focuses on the coevolution of depositional and tectonic processes to investigate the response of substrate movement to minibasin sedimentation. Using a silicone polymer to model a viscous mobile substrate, a series of 2D experiments were conducted to explore the effects of variation in 1) sediment supply rate, 2) depositional style (intermittent sediment supply), and 3) the thickness of the deformable substrate on subsidence patterns and minibasin stratigraphic development. Experimental results indicate that larger initial thickness of salt substrate as well as lower sedimentation rates result in greater amounts of subsidence for a given amount of deposit. Furthermore, in the experiments with intermittent sediment supply, increasing subsidence rate was observed as sedimentation continued, while decreasing subsidence rate occurred once sedimentation ceased. These accelerations and decelerations in subsidence were attenuated as the total thickness of the minibasin deposit increased and the thickness of the remaining salt decreased. Lower sediment supply rate led to a narrower but deeper minibasin formation. The increase in overall time allowed the salt substrate to have a greater response to the overburden. In contrast, the linked depositional and tectonic processes caused higher sediment supply rate to increase the planform size of the minibasin. Based on the experimental results, a new model of autostratigraphic minibasin evolution is suggested: 1) differential loading causes initial subsidence, 2) ponded (basin infilling) architecture occurs during a period of acceleration in subsidence, and 3) perched (spilling) architecture occurs over the duration of final subsidence deceleration.

INTRODUCTION

Intraslope minibasins, such as those found in the Gulf of Mexico, are “synkinematic basins subsiding into relatively thick, allochthonous or autochthonous salt” (Jackson and Talbot 1991). These small (< 10 km wide) basins are locations of rapid (up to 1 km/My) subsidence where overburdened sediment is deposited onto a ductile salt substrate (Hudec et al. 2009). Salt-withdrawal basins often contain significant hydrocarbon accumulations (Weijermars et al. 1993; Prather et al. 1998). Successful hydrocarbon exploration in these systems is dependent on accurate interpretation of depositional processes in the basins.

Two common approaches have been taken when studying minibasin systems. The first is a salt-tectonic approach, which traditionally focuses on the structural deformation of a mobile salt body driving stratal development. Studies by Jackson and Vendeville (1994), Vendeville and Jackson (1992a and 1992b), and others have explored the behavior of mobile salt under extensional or compressional tectonic regimes to understand large-scale changes in basin accommodation. Contrastingly, a basin-fill-history approach focuses on the sediment transport processes in minibasins and the strata that develop in response to changes in the processes (Prather et al. 1998; Winker and Booth 2000; Lamb et al. 2006; Toniolo et al. 2006a, 2006b). The fundamental understanding of evolution of minibasin stratigraphic architecture requires understanding these two end members, but in order to get the full picture an evaluation of the interactions between tectonics and sedimentary processes is indispensable. For the first time, this study attempts to quantify coevolution of minibasin sedimentation and salt subsidence using a series of analogue experiments performed under controlled boundary conditions. Previously cyclic strata reflecting minibasin fill-and-spill processes and associated with episodic rates of sediment influx were reported from the Auger Basin, Gulf of Mexico (Booth et al. 2003). In the current experiments, intermittent sediment input was used to gain better understanding of cyclic sedimentation. We also briefly discuss the application of our experimental results to the minibasin stratigraphic development at natural scale.

A variety of different processes contribute to the subsidence mechanisms in salt-withdrawn minibasins (Hudec et al. 2009). Subsidence may be driven by 1) buoyancy forces (i.e., sediments overlying salt deposits become denser by compaction than salt, creating an unstable density gradient on a less dense mobile salt; Hudec et al. 2009), 2) tectonic forces, such as diapir shortening (Humphris 1979), extension-related diapir fall (Vendeville and Jackson 1992a), subsalt deformation and faulting (Vendeville et al. 1995; Schultz-Ela and Jackson 1996), and downhill flow of salt sheets causing decay of salt topography (Talbot 1998), or 3) differential sediment loading on the mobile salt (Jackson and Talbot 1986; Weijermars et al. 1993; Cohen and Hardy 1996), which causes lateral pressure differences on the substrate and induces flow in the mobile substrate. The tectonic environment, slope gradient, sedimentation rate, and salt geometry determine the prevalence of any one of these mechanisms. These factors can vary from region to region, creating a wide range of possible minibasin styles (Hudec et al. 2009). Hudec et al. (2009) showed that buoyancy forces alone are insufficient to initiate
A mobile substrate (salt) was modeled with a viscous silicone polymer, polydimethylsiloxane, often referenced by the Dow Corning, USA code SGM-36. SGM-36 has been extensively used to simulate salt in laboratory experiments due to its similar rheological behavior to salt (e.g., Vendeville and Jackson 1992a, 1992b). Weijermars et al. (1993) have explained the accountability of the material for modeling natural salt in detail. We focus on basin evolution created solely by the interaction between an increasing sediment load and the deformation of salt.

**EXPERIMENTAL SETUP**

**Salt Analogue**

A mobile substrate (salt) was modeled with a viscous silicone polymer, polydimethylsiloxane, often referenced by the Dow Corning, USA code SGM-36. SGM-36 has been extensively used to simulate salt in laboratory experiments due to its similar rheological behavior to salt (e.g., Vendeville and Jackson 1992a, 1992b). Weijermars et al. (1993) have explained the accountability of the material for modeling natural salt in detail. We provide only a brief summary here. Under experimental sediment loading conditions this polymer behaves as a linear viscous fluid (Newtonian fluid) and allows the experimenter to simulate the dynamics of wet salt that deforms by diffusion creep, the deformation of solids by diffusion of vacancies through the crystal lattice (Weijermars et al. 1993). Wet salt effectively has no yield strength over short geologic time scales, even at shallow burial depths, and can also be described as a viscous Newtonian material (Weijermars et al. 1993). A scaling analysis between experimental and natural systems is presented in the discussion section of Scaling Experimental to Field-Scale Minibasins.

**Experimental Design**

A series of 12 experiments of deforming salt (henceforth DS) were conducted in a clear polycarbonate flume (100 cm wide, 50 cm tall, and 10 cm deep). Experimental parameters are listed in Table 1. Prior to starting the experiments, a specified volume of silicone polymer was added to the flume and then allowed to flatten under the influence of gravity. Using a computer-controlled sediment feeder, quartz sand (\(D = 200 \mu m\)) was fed into the center of the flume. This created a self-formed, triangular sediment pile with angle-of-repose side slopes, which induced a differential load on the polymer. The sediment deposit rested on and slowly subsided into the polymer. The polymer flowed outwards from below the sediment pile as it was displaced by the subsiding sediments and upwelled close to the sides of the flume (Fig. 1).

We note here that the morphology of the sediment surface in the experiment is different from the morphologies of natural minibasins that are created dominantly by turbidity currents and debris flows. In comparison to a natural minibasin deposit, this sand-pile geometry exaggerates differential sediment loading, which leads subsidence at the center of the basin relatively higher than the sides. However, a key improvement over other previous salt analogue experiments is that deposition in our experiments is self-organized by grain avalanches. Common practice in previous salt analogue experiments (e.g., Vendeville and Jackson 1992a, 1992b) was to add sediment layers manually in a pattern decided by the experimenter. In such experiments the distribution of sediment is not freely formed; therefore feedback interactions between sedimentation and tectonics can be obscured.

Six experimental runs were conducted utilizing a thin initial polymer substrate depth (\(h_{pp} = 8 \text{ cm}\)). Another equivalent six experiments were tested with a thick initial substrate depth (\(h_{pp} = 16 \text{ cm}\)) to examine the effect of salt-body thickness. These sets of experiments will be indicated by the experiment names “08” and “16”, e.g., DS-08 and DS-16. The two thicknesses serve as an analogue model for “salt limited” and “salt unconfined” natural basins. A thin polymer substrate represents a salt-limited minibasin system, while thicker substrate represents a salt-unconfined minibasin arrangement. In this study, a salt-limited system is defined as a sediment-filled minibasin that is able to subside nearly to the point at which sediments contact the rigid basement and form a salt weld over the time period that the system is observed. A salt-unconfined system is defined as a minibasin in which the sediments are not able to subside close enough to make contact with the rigid basement over the total experimental run time.

Sediment supply rates were held constant throughout each run but varied across the experimental suite. To explore the subsidence patterns under different loading conditions, three different sediment feed rates (i.e., low, medium, and high; these sediment feed rates are indicated in the experiment names with “L”, “M”, and “H”, such as DS-08-L) were used. The changes in feed rate were coupled with total experimental run time to keep the total volume of sediment added to the basin equal in all experiments. For example, experiments for constant sediment feed with the low rate (1 cm³/s) ran for 2 hours while experiments with the constant medium rate (2 cm³/s) ran for 1 hour to match the total volume of sediment (Table 1).

Turbidity currents are important mechanisms for the transport of sediment from shallow-water sources to deep-water depositional sinks (Lamb et al. 2010). Turbidity currents can be generated by mass failures (Normark et al. 1993) and by other infrequent events such as hyperepical plumes (Lamb et al. 2010). Pirmez et al. (2012) have shown that in general, periods of high sedimentation correspond to sea-level lowstands and times of low sedimentation correspond to subsequent highstands. In order to capture the natural minibasin systems that receive sediment through infrequent turbidity-current events, as well as cycles of sediment supply that correspond to 10⁴ to 10⁵ yr eustatic cycles, the experiments...
Intermitency was either zero, i.e., constant supply, 5-min cycles (5 minutes of sedimentation followed by 5 minutes of nondeposition), or 30-min cycles (30 minutes of sedimentation followed by 30 minutes of nondeposition). The experiments are denoted by labels “00”, “05”, and “30”, respectively. These two frequencies of sediment supply (e.g., DS-08-L-05 and DS-08-L-30 experiments) were designed to facilitate the observation of subsidence patterns that result from substrate response to different periods of nondeposition, as well as different substrate response time for an equivalent sediment load.

**Data Collection and Processing**

For each run the evolution of the minibasin system was observed through time-lapse images. Images were automatically taken in 20-second intervals throughout the experiment. The images were first corrected for lens distortion and perspective utilizing image-processing software (Tal...
et al. 2012). Once the images had been corrected and properly scaled, image-processing scripts developed specifically for these experiments automatically mapped the top and bottom surfaces of the sediment pile for each image. The mapped elevations, i.e., the sediment surface ($\eta_T$) and the base of sediment deposit ($\eta_b$), provide values of subsidence ($\Sigma = -\eta_b$ measured positively downward), overburden thickness ($\eta_T + \Sigma$), basin width ($L$), as well as area of created accommodation ($A_B$) (Fig. 1C).

**EXPERIMENTAL RESULTS: VERTICAL SUBSIDENCE**

**Role of Substrate Thickness**

Salt thickness was one of the dominant controls on the total subsidence of the deposit. The unconfined basin setting, which had a thicker initial substrate (i.e., $\eta_{PT} = 16$ cm), resulted in greater subsidence per time when compared to the experiments with thinner initial substrate, e.g., DS-08-M-00 and DS-16-M-00 (note the different ranges of the vertical axis in Fig. 2A and B and in Fig. 3A and B). In the experiments with $\eta_{PT} = 16$ cm, overburden sediments did not get very close to the rigid basement by the end of experimental runs (Fig. 3A, B). However, equivalent experiments with $\eta_{PT} = 8$ cm (Fig. 2A, B) show that the sediment subsided near the rigid basement at the end of the run and nearly fully expelled the polymer from beneath the overburden sediments, which limited the total depth of the subsidence.

**Role of Sediment Supply Rate**

The relationship between the total amount of subsidence and the total depositional thickness ($\eta_T + \Sigma$) was influenced by both the thickness of the salt body and the sediment accumulation rate (Fig. 4). The highest amount of total subsidence was achieved when sediment was supplied with the lowest rates (e.g., DS-08-L-00 and DS-16-L-00 in Fig. 4). The high sediment supply rate in DS-08-H-30 and DS-16-H-30 (Fig. 4) resulted in considerably lower subsidence at the center of the deposit for the same overburden thickness (data shown in Fig. 4 for DS-08-H-30 and DS-16-H-30 is only taken from the first 30 min of subsidence during continuous sediment influx). This inverse relationship between the sediment accumulation rate and total subsidence was more pronounced for the thicker-initial-substrate experiments (Fig. 4B). As presented in the previous section, greater substrate thickness resulted in greater overall subsidence rate (compare Fig. 2A and B with Fig. 3A and B). Therefore, the effect of change in sediment supply rate was even greater with the thicker salt substrate (Fig. 4B).

**Role of Intermittent Sediment Supply**

Strong acceleration of subsidence was observed in the first period of sedimentation in the intermittency experiments. Strong acceleration is most clear during the initial period of sedimentation in the 30-min intermittency experiments, i.e., DS-08-H-30, DS-08-M-30, DS-16-H-30, and DS-16-M-30 (Fig. 5). During all periods of sedimentation, an increase in the rate of subsidence was observed during times of sedimentation and was followed by a deceleration in subsidence when sedimentation stopped. Note that subsidence did not cease during the pause in sediment supply. The rate of subsidence decreased even when there was no change in the thickness of the sediment deposit. For example, DS-16-M-30 (Fig. 5D) displayed a clear acceleration of subsidence over the first 30 min of the experimental run. However, at 60 min the total subsidence of DS-16-M-30 and DS-16-L-00 were approximately equal to each other (Fig. 3B) because subsidence in DS-16-M-30 had decelerated significantly during paused sedimentation between 30 and 60 min. Also, after resuming the second cycle of sedimentation, DS-16-M-30 displayed a second period of accelerating subsidence that was less pronounced than that observed during the first hour of run time (Fig. 5D). The acceleration and decelerations of subsidence during pulsed sedimentation were also observed in 5-min intermittency experiments. In these runs, rates of subsidence acceleration and deceleration were subtler than those observed during the 30-min intermittency experiments (Fig. 5). The 5-min intermittency experiments also show a similar damping of the magnitude of acceleration and deceleration as the sedimentation cycle repeats.

Interestingly, the data show fluctuations in the subsidence rate even for the runs with the consistent sediment influxes, e.g., DS-08-L-00 in Figure 5B. Grain avalanches occurred repeatedly and caused the sediment surface to fluctuate over time. This internal sediment transport process thickens and thins the deposit in cycles and induces changes in subsidence rate. This is in line with recent studies on the process of autogenic fluvial sediment storage and release (e.g., Kim et al. 2006; Kim and Jerolmack 2008; Reitz et al. 2010; Powell et al. 2012). A detailed analysis of the autogenic dynamics of sedimentation and salt subsidence would be an interesting topic but is beyond the scope of this study.

**Role of the Deposit Geometry**

In addition to initial substrate thickness and sedimentation rate, subsidence patterns were influenced by the geometry of the minibasin deposit (here, a triangular sand pile) and the changes in the remaining salt thickness underneath the minibasin deposits as sediment continued to enter the basin. Even with constant sediment supply rate in the experimental runs, subsidence rate measured at the center of the deposit did not always increase linearly. Overburden thickness at the center of the deposit initially increased quickly, but the rate of thickness change gradually decreased due to the elongation of the two slopes on the sediment pile. Subsidence rate also initially increased rapidly but then decreased with time (Fig. 5), which in part reflects the role of the deposit geometry.

**EXPERIMENTAL RESULTS: LATERAL WIDENING**

**Role of Substrate Thickness**

After comparing the time series of width in the thin-substrate runs (Fig. 2C, D) to equivalent runs with thick substrates (Fig. 3C, D), a greater final width in thin-initial-substrate runs was observed. The change in initial salt thickness provided a range of 80–100 mm differences in the final widths between experiments with equivalent sediment supply conditions.

All experiments displayed two phases of basin width evolution, as shown in the bottom two graphs of Figures 2 and 3. Phase 1 was characterized by rapid basin widening once sedimentation started. Phase 2 was the subsequent period of a significant reduction in basin widening rate. This phase occurred approximately 5–40 min in run time when basin width became restricted to a certain width. Phase 2 in the experiments with the 8 cm initial salt thickness showed widening rate slightly and continuously decreasing over time (Fig. 2C, D). In the 16 cm salt-thickness runs, widening was almost halted in phase 2 (Fig. 3C, D). If the substantial reduction in the widening rate (see Fig. 2D, 3D) is considered as timing for the transition between phases 1 and 2, the initial salt thickness is most likely the main control of the transition timing. When comparing DS-16-L-00 (Fig. 3D) and DS-08-L-00 (Fig. 2D), phase 1 in DS-16-L-00 lasted about 10 min while phase 1 in DS-08-L-00 did not end until 30–40 min into the experiment.

**Role of Sediment Supply Rate and Intermittency**

The time that the system takes to transition from initial rapid widening to subsequent slow widening of the basin was also controlled by the rate at which sediments were supplied to the basin. When comparing DS-16-
FIG. 2.—Subsidence ($\eta_B$) and sediment surface elevation ($\eta_T$) measured in experiments with 8 cm initial salt substrate in A) DS-08-M-00, DS-08-H-30, and DS-08-H-05 and B) DS-08-L-00, DS-08-M-30, and DS-08-M-05. Time series of basin width ($L$) captured in C) DS-08-M-00, DS-08-H-30, and DS-08-H-05 and D) DS-08-L-00, DS-08-M-30, and DS-08-M-05. Phase 1 and Phase 2 indicate initial fast widening of the basin and converging of the width to an equilibrium value, respectively.
FIG. 3.—Subsidence ($\eta_B$) and sediment surface elevation ($\eta_T$) measured in experiments with 16 cm initial salt substrate in A) DS-16-M-00, DS-16-H-30, and DS-16-H-05 and B) DS-16-L-00, DS-16-M-30, and DS-16-M-05. Time series of basin width ($L$) captured in C) DS-16-M-00, DS-16-H-30, and DS-16-H-05 and D) DS-16-L-00, DS-16-M-30, and DS-16-M-05. Phase 1 and Phase 2 indicate initial fast widening of the basin and converging of the width to an equilibrium value, respectively.

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M-00, which had the medium sediment feed rate (2 cm$^3$/s) among the experiments, and DS-16-L-00, which had half the sediment feed rate (1 cm$^3$/s) (Fig. 3C, D), phase 1 of rapid basin widening in DS-16-L-00 was about 10 min but DS-16-M-00 showed continuous phase 1 widening over the 60-min run. In general, experiments conducted with high sediment inputs and 5-min intermittency had smaller width profiles than experiments with 30-min intermittency of the same sedimentation rate. Except in the initial rapid widening stage, basin width evolution in experiments with rapidly pulsed sedimentation input (5-min intermittency) was similar to width evolution of constant sediment input of half the sedimentation rate.

As previously noted, the thin-substrate experiments were designed to simulate confined minibasins in which sediments were able to fully subside through the polymer substrate to the point of contact with the underlying rigid basement. In natural minibasin systems, the point of contact between overburden sediments and the rigid basement is defined as a salt weld (Jackson and Cramez 1989). In the thick-salt runs, no contact between overburden sediments and the rigid basement is defined under the underlying rigid basement. In natural minibasin systems, the point of contact generally is delayed until the accommodation in the basin becomes infilled. In this case, the basin cannot keep pace with the rate at which sediments accumulate and significant accommodation to develop. The subsidence was enough to accommodate the supplied sediment within the existing minibasin without additional basin widening. In this way, nearly vertical walls of the minibasin developed as a result of increased vertical subsidence of overburden sediments. In contrast, the experiments with the thin substrate continued to have a widening minibasin throughout the entire experimental run.

Effect of Sediment Supply Rates on Subsidence Pattern

For minibasins of equivalent overburden thickness and sediment load, the basin receiving sediment at a lower rate underwent a greater amount of subsidence (Fig. 4). For lower-sediment-supply rates, a slower increase in the sediment load allowed a relatively longer period for the substrate to respond to the increasing loads, resulting in greater subsidence.

In the experiments, a decrease in basin width is observed to result from lower sediment supply rates (Figs. 2, 3). Since subsidence is able to keep pace with the growing thickness of the overburden sediments, the minibasin is able to actively create accommodation, which therefore effectively confines the lateral spreading of the sediment load and results in the development of basin infilling, i.e., ponded stratigraphic architectures. On the contrary, for high sedimentation rates the subsidence of the basin cannot keep pace with the rate at which sediments accumulate and the accommodation in the basin becomes infilled. In this case, the basin develops sedimentary layers covering an area that extends beyond the size of the minibasin, mimicking the evolution of perched aprons (Prather et al. 2012).

In order for significant accommodation to develop, either low sedimentation or low frequency of sedimentation must occur for a period long enough for the basin to subside in response to the sediment load. If a period of minor to no sedimentation is short in between major sedimentation events, subsidence will only briefly outpace sediment accumulation and significant accommodation in the basin will not develop.

DISCUSSION

Control of Substrate Thickness on Subsidence and Basin-Growth Patterns

Total vertical subsidence and basin width in experimental minibasins is controlled predominantly by the initial thickness of the polymer substrate (salt analogue). Experiments with thick (16 cm) substrates exhibited total subsidence approximately 40–50% greater than equivalent experiments with thin (8 cm) substrates. Experiments with thicker substrates had more salt free from friction acting at the boundaries, e.g., rigid basement, and produced high-flux expulsion of the polymer from beneath the subsiding sediments.

As previously noted, the thin-substrate experiments were designed to simulate confined minibasins in which sediments were able to fully subside through the polymer substrate to the point of contact with the underlying rigid basement. In natural minibasin systems, the point of contact between overburden sediments and the rigid basement is defined as a salt weld (Jackson and Cramez 1989). In the thick-salt runs, no sediment welding was observed.

Due to the restricted vertical subsidence capacity, experiments with a thin mobile substrate exhibited greater basin width than equivalent experiments with thicker polymer substrate. The sediment pile in the experiment maintained the sediment surface slope at the angle of repose. Therefore, while thin salt thickness diminished vertical subsidence, sediments spread laterally over the surface of the thin salt over the same time period as in those experiments with the thick substrate. In thick-substrate experiments, the width of the basin converged to equilibrium width relatively quickly and remained at a constant width once it was established.

In order for significant accommodation to develop, either low sedimentation or low frequency of sedimentation must occur for a period long enough for the basin to subside in response to the sediment load. If a period of minor to no sedimentation is short in between major sedimentation events, subsidence will only briefly outpace sediment accumulation and significant accommodation in the basin will not develop.
Autogenic Basin Evolution

The experiments had constant sediment discharge during the periods of sediment influx to the basin (the 5-min and 30-min intermittent runs also used constant sediment discharge during the influx durations). Constant sediment supply caused acceleration of subsidence; deceleration of subsidence was observed during periods of nonsedimentation; and acceleration and deceleration gradually decreased over the multiple sediment-flux cycles despite sediment pulses of the same magnitude. Even though the magnitude of sediment supply events stayed the same through time, subsidence acceleration was greatest in the initial stage of minibasin development when vertical aggradation of the sediment pile was most active, and diminished over sedimentation events. There are two main reasons for this reduction. 1) During the continued growth of the basin, acceleration became muted due to areal expansion of sediment loading as the sediment pile kept widening. Eventually, the autogenic decrease of surface aggradation rate of the sediment pile resulted in a diminished subsidence rate. This effect is most significant in basins with an upstream point sediment source, e.g., a fan, which produces a significant sediment lateral expansion as it grows. However, the effect of the deposit geometry becomes obsolete if the minibasin subsides vertically enough to fix the deposit width. 2) The decrease in the average salt withdrawal velocity decreases as the underlying salt thins. The frictional effects acting on the interface between the substrate and the basement retarded the flow of polymer from beneath the sediments. The average flow rate of the salt decreases as the substrate thickness gradually decreases (Piliouras et al. 2014). This decrease in the subsidence rate would be most effective in a salt-limited basin setting.

Scaling Experimental to Field-Scale Minibasins

Applying the experimental results to field scales necessitates comparison of the time scales of each system. We take the scaling approach of deforming salt experiments outlined in Weijermars et al. (1993). Nondimensional time $t^*$ can be accomplished by

$$t^* = \frac{(\rho_s - \rho_w)gh}{\mu} t$$

(1)
where $\mu$ represents viscosity, $g$ denotes gravity, $\rho_s$ denotes density of overburden, $\rho_a$ denotes density of ambient fluid, and $h_s$ denotes overburden sediment thickness, with subscript $s$ indicating properties of the overburden sediment deposit. If both natural and experimental systems are under uniform gravity, the previous equation can be used to scale experimental time for comparison with natural minibasin time scale as

$$t_{\text{pro}} = \frac{(\rho_{\text{pro}} - \rho_a)gh_{\text{pro}}}{\rho_{\text{pro}}} t_{\text{mod}} = \frac{(\rho_{\text{mod}} - \rho_a)gh_{\text{mod}}}{\rho_{\text{mod}}} t_{\text{mod}}$$

where the subscript “mod” (model) represents experimental systems and the subscript “pro” (prototype) represents the natural (field scale) system. Using Equation 2, comparison of the time scales of experimental and natural systems can be accomplished. For a first-order approximation, we assume sediment density of 2.65 kg/m$^3$ as well as equal porosity in the experimental and natural deposits. The time scale for the current experiment under dry conditions (i.e., $\rho_a = \rho_{\text{air}} = 0$ on the right-hand side of Equation 2) takes the following form:

$$t_{\text{pro}} = \frac{\mu_{\text{pro}}}{(\rho_{\text{pro}} - \rho_a)h_{\text{pro}}} = \frac{\mu_{\text{mod}}}{(\rho_{\text{mod}} - \rho_a)h_{\text{mod}}}$$

Experiments were conducted over time periods of 1–2 hours with average overburden thicknesses of 0.3 m and polymer viscosity of $2.5 \times 10^7$ Pa·s. When comparing to a Pleistocene Gulf of Mexico minibasin with an overburden thickness of 75–400 m (Beaubouef and Friedmann 2000) and average underlying salt viscosity of $10^{17}$ Pa·s (Weijermars et al. 1993), the 1-hour experimental run is approximately equivalent to 550 ky–3 My of evolution of the field scale system. These experiments may capture evolution over millions of years, and a significant portion of basin stratigraphy can be compared with the experimental results. The 30-min and 5-min intermittent sediment supplies in the experiments are roughly consistent with $10^3$ to $10^5$ ky Pleistocene sea-level oscillations. Therefore, these intermittent depositional events are analogous to those in which deltas prograde across the shelf during sea-level fall and provide terrestrial sediment directly to the intraslope minibasins.

We note that the sediment pile in the experiment builds a thicker overburden deposit due to its triangular geometry and induces a higher aggradation rate compared to subsidence rate. Turbidity currents and debris flows construct a shallowly sloping sediment surface and allow more detailed stratigraphic interpretation with more realistic geometry. The overburden thickness can potentially be two to three times smaller in the field than what we use here, which linearly decreases the equivalent time scale for a field case to two to three times smaller. However, the main conclusions about the controls of salt substrate thickness and sediment supply to the system on minibasin subsidence and width evolution remain the same.

**Development of Minibasin Stratigraphy**

The Brazos–Trinity Intraslope System is composed of a series of linked intraslope minibasins that have been well imaged and studied with modern 2D and 3D seismic imaging techniques and several borehole core studies (Winker 1996; Beaubouef and Friedmann 2000; Prather et al. 2012; Pirmez et al. 2012). This system shows high sedimentation rates as well as evidence for significant subsidence over the past 100 ky (Pirmez et al. 2012) that can be compared with experimental minibasins. In addition to being an experimental analogue, the Brazos–Trinity System serves as an analogue for ancient deep-water depositional systems that are frequently the target of hydrocarbon exploration (Pirmez et al. 2012). Early studies of these basins have interpreted the sedimentary deposits as having evolved under static accommodation (Beaubouef and Friedmann 2000). Their depositional model describes basin evolution as a three-stage process: 1) a ponded fill phase in an underfilled basin ($T = 2$ in Fig. 6A), 2) a perched filling stage as basin accommodation becomes limited ($T = 3$ in Fig. 6A), and 3) a bypassing phase once the basin has become overfilled. This fill-and-spill depositional sequence composed of filling of accommodation and subsequent bypass of sediments is often used as a guide of interpreting minibasin strata (e.g., Prather et al. 1998; Sinclair and Tomasso 2002). The fill-and-spill model often assumes that the accommodation is tectonically set prior to sedimentation and thus does not consider the implication of a syndepositionally subsiding basin (Fig. 6A). Experimental results from this study have illustrated a strong
influence of change in sediment load on basin subsidence profile and consequent changes in rates of accommodation creation.

Using these findings, we propose a minibasin depositional model similar to the three-stages model but instead driven by the subsidence-sedimentation coevolution mechanism: 1) Minibasin initiation: deposition initiates slow substrate deformation with lateral minibasin expansion ($T_{51}$ in Fig. 6B). Subsidence gradually accelerates and catches up the sedimentation rate. 2) The minibasin starts to fully accommodate supplied sediment. The width of the basin then reaches an equilibrium value when the salt subsidence rate approximately equals the sediment supply rate ($T_{52}$ in Fig. 6B). 3) As the remaining salt underneath the minibasin deposit decreases in thickness, sedimentation rate autogenically outpaces subsidence rate even without changes in sediment supply to the basin. Perched aprons and sediment-bypassing stages follow this decrease in subsidence rate ($T_{53}$ in Fig. 6B).

Figure 7 shows rates of increasing deposit thickness compared with subsidence rates over time in A, B) 8-cm initial salt thickness experiments and C, D) 16-cm initial salt thickness experiments.

CONCLUSIONS

1. A series of experiments were conducted to explore the effect of differential sediment loading on minibasin subsidence patterns. Experimental results have shown that subsidence patterns are dependent on 1) initial salt substrate thickness, 2) rate of sediment decayed quickly with time. All experiments maintained positive aggradation rates until the end of each experiment (Fig. 7), except increases in the ratio in DS-16-L-00 toward the end of the run. In the current experiments, in the final bypass stage ($T_{53}$ in Fig. 6B) the decrease in sedimentation rates was not clearly observed due to limited flume size and no upstream-to-downstream sediment transport in the flume. The final stages ($T_{3}$ in Figure 6) were estimated based on the limited observation. However, a large tank experiment with sediment transport to the downbasin direction will potentially produce a gradual switch from the ponded stage to the bypass stage.
supply to the basin, and 3) intermittent depositional events. Higher subsidence is achieved by thicker initial salt thickness and low sediment supply rate, and vice versa. Accelerations and decelerations in subsidence caused by intermittent sediment deposition are attenuated over sediment supply cycles as the depositional body increases and the remaining salt decreases.

2. Sedimentation rate and initial salt thickness also control the width evolution of minibasins. Low sedimentation rates and thicker salt substrate develop narrower basins with steeper basin walls than basins that evolve under equivalent conditions but higher sedimentation rates and thinner substrate.

3. A new conceptual model of minibasin development is proposed here, which incorporates the dynamic evolution of minibasins as they respond to sediment loading. An initial load of sediment acts to initiate subsidence, and the subsidence is slow. In the early stages of the developing basin, a thicker salt substrate quickly responds to the initial sediment loading and induces subsidence rates that are greater than the depositional rates, resulting in increasing basin accommodation and ponding of sediments in the basin. However, as the salt substrate gradually thins, increase in accommodation does not proceed at a faster pace than sediment accumulation. This results in sediment bypass and development of perched stratigraphic architectures. This new model of minibasin evolution will aid in reconstructing the coevolution of basin subsidence history linked to minibasin sedimentation.

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