EXPERIMENT ON TURBIDITY CURRENTS AND THEIR DEPOSITS IN A MODEL 3D SUBSIDING MINIBASIN

JACOB VIOLET¹, BEN SHEETS¹, LINCOLN PRATSON², CHRIS PAOLA¹ AND GARY PARKER¹
¹: St. Anthony Falls Laboratory, University of Minnesota, Mississippi River at 3rd Ave. SE, Minneapolis, MN 55414 USA
²: Division of Earth and Ocean Sciences, Old Chemistry Building, Box 90227, Duke University, Durham, North Carolina 27708 USA

e-mail: viol0004@tc.umn.edu, shee0076@tc.umn.edu, lincoln.pratson@duke.edu, cpaola@tc.umn.edu, and parke002@tc.umn.edu

ABSTRACT

Minibasins on the continental slope are formed by the movement of salt or mud layers in the subsurface. The north slope of the Gulf of Mexico (GOM), for example, is riddled with salt-withdrawal minibasins ranging in scale from a few to tens of kilometers. These minibasins are often connected to each other by channels, which have been carved through the ridges (sills) between basins by turbidity currents. The same turbidity currents may fill the minibasins with their sediment (the deposits aptly named turbidites). An experiment on deposition by turbidity currents in a subsiding minibasin is described here. Bowl-shaped subsidence prevailed for the first half of the experiment (Stage 1), and subsidence was turned off for the second half (Stage 2). Three types of turbidity currents were introduced into the basin; continuous events with a duration of 36 minutes each, large pulse events with a duration of 3.81 minutes each, and small pulse events with a duration of 1.85 minutes each. In total there were 4 continuous events, 4 large pulse events and 24 small pulse events, evenly split between Stage 1 and Stage 2. In the course of the experiment a short leveed channel formed toward the proximal end of the basin. The leveed channel was later infilled by deposition. Dip and strike views of the deposit bear remarkable resemblances to corresponding views from a high-resolution seismic survey of a GOM minibasin (Basin 4, Brazos-Trinity Turbidite System, GOM continental slope).
INTRODUCTION

The north slope of the Gulf of Mexico (GOM) is riddled with small basins produced by the withdrawal of a salt layer at depth (e.g. Pratson and Ryan, 1994; Winker, 1996). Views of these minibasins are provided in Figure 1 (Pratson and Haxby, 1997); Figure 2 is a seismic image of the stratigraphy within such a minibasin (courtesy of C. Winker and C. Pirmez). GOM minibasins lie on the continental slope, display relief on the order of hundreds of meters and have radii on the order of a few to tens of kilometers. The basins are typically surrounded by compensational ridges created by the rising of salt at depth. Minibasins are often connected by a network of channels carved through the intervening ridges by turbidity currents (Liu and Bryant, 2000). These turbidity currents deposit sediment in minibasins, and in doing so often create excellent reservoirs for hydrocarbons.

Recent field studies (e.g. Badalini et al., 2000; Beaubouef and Friedman, 2000) have revealed much information about the processes by which these minibasins fill with sediment. Further progress requires, however, a better knowledge of the flow dynamics of turbidity currents and how they deposit sediment in confined basins. Insofar as direct field observation of turbidity currents is problematic, experimentation offers an avenue for the study of minibasin morphodynamics.

Recently Lamb et al. (in press) and Toniolo (2002) have performed experiments on turbidity currents flowing into long, narrow (i.e. 2D) minibasins. These experiments have revealed different modes of deposition depending on whether or not the turbidity current events consist of a series of short surges or pulses, or are quasi-continuous and capable of creating a fully ponded turbidity current within the minibasin. In addition, the role and magnitude of the flow event and the presence or absence of overspill from the downstream lip of the minibasin has been studied. These 2D experiments have been useful in quantifying flow processes and modes of deposition in minibasins.

Two important variables are lacking in these 2D studies a) the basin floor cannot be allowed to subside and b) three-dimensional flows and deposits
cannot be reproduced. The latter restriction, in particular, renders the modeling of compensationally stacked depositional lobes and the self-formation of leveed channels impossible.

This paper describes an experiment in a 3D subsiding model minibasin designed to overcome the two dimensional restrictions of previous work.

EXPERIMENTAL SETUP

Subsidence mechanism  The experiment described in this paper was performed in the subsiding eXperimental EarthScape (XES) facility at St. Anthony Falls Laboratory, University of Minnesota. The key feature of the XES facility is a subsiding floor that allows for arbitrary patterns of spatial and temporal variation in subsidence rate.

The full XES facility is a rectangular basin with dimensions of 5.82 m by 11.97 m; the basin is 1.53 m deep. Water and sediment can be fed into the basin in order to create sedimentary deposits. The floor of the basin consists of 432 hexagonal cells arranged in a honeycomb fashion. Several of these cells are illustrated schematically in Figure 3. Each cell funnels downward into a cone hopper like that found in a grain elevator. Above and within these hoppers sits a well-rounded, well-sorted pea-gravel. In order to facilitate flow of the gravel, the sidewall angle of each hopper has been set to be higher than the angle of repose of the gravel.

The subsidence rate above each cell is controlled by the release of gravel from the hopper. As shown in Figure 3, the bottom of each hopper funnel is diverted horizontally so that the gravel cannot flow out by its own weight. Local subsidence is produced by the release of a small burst of water through a valve at the base of each hopper funnel. The control of this jet allows the subsidence at the cell center to an accuracy of within 0.1 millimeter per burst. This mechanism allows for a local subsidence rate varying from zero to 1 cm/hour.

In order to perform an experiment, the gravel basement is first made sufficiently thick to allow for the maximum subsidence planned during the experiment. The gravel basement and walls of the facility are then covered by a
continuous, flexible rubber membrane. A deposit is created by releasing a mixture of water and sediment into the basin. The flexible rubber membrane prevents the leakage of water and sediment into the gravel basement, even when spatially varying subsidence causes it to stretch.

The original design of the subsidence mechanism was tested in a prototype basin with ten cells; the results of those experiments are reported in Paola et al. (2001). It was verified in those experiments that up to 1.3 m of spatially uniform subsidence could be induced without any imprint of the hexagonal cell pattern being transferred to the deposit above.

At the time of writing of this paper only one-quarter of the area of the XES basin proper is in use, so that the usable dimensions of the basin are 5.82 m by 2.99 m, encompassing a total of 120 cells, as shown in Figure 4. The valve of each cell is controlled by a computer that can be set to provide the desired subsidence pattern. It is not possible, however, to program the desired subsidence pattern precisely in advance, because spatially differential subsidence causes internal deformation of the gravel. The position of this interface is continuously monitored by a number of pressure transducers placed at the interface between the gravel and the membrane. At any given time the readings from these transducers may indicate that the amount of subsidence realized is too large in some zones and too small in other zones. These readings are analyzed automatically in order to provide compensating adjustment so that the subsidence realized above any cell is within a specified tolerance of the target subsidence rate for that cell.

In Figure 4, the figure to the left shows the initial configuration of the rubber membrane (top of the gravel basement) at the beginning of the experiment. The bowl-shaped depression shown therein defines the initial bed of the model minibasin.

**Water and sediment delivery system** The setup of the basin for the experiment reported here was very similar to that of a previous experiment in the same basin, in which controls on fluvial architecture were studied (Sheets et al., 2002; Cazanacli et al., 2002; Strong et al., in press). In order to create both
continuous and pulse-like turbidity currents flowing into the basin, however, it was necessary to modify the water and sediment delivery system.

The water and sediment delivery system is schematized in Figure 5. Water and sediment are introduced into a large tank below the XES basin. Sediment is fed into the tank from three dry hopper sediment feeders; tap water is supplied to the tank so as to maintain a constant specified sediment concentration. The slurry is continuously pumped from the mixing tank below the downstream end of the XES basin to a constant-head tank above the upstream end of the basin.

The system is designed to recirculate all the slurry at a discharge of 6.5 liters/s during periods when a turbidity current is not being introduced into the XES basin. Part of the slurry overflows the inner cylinder of the constant-head tank and then flows by gravity back into the mixing tank at a rate of 2.0 liters/s. The rest of the slurry flows into a holding tank immediately adjacent to the upstream end of the XES basin, and then flows by gravity back to the holding tank at a rate of 4.5 liters/s. All recirculated slurry entered the mixing tank with velocities that proved sufficient to keep the sediment suspended.

The flow from the constant-head tank into the holding tank is carried by three pipes, each carrying a flow of 1.5 liters/s. In order to create a turbidity current flowing into the basin, one or more of these pipes is diverted into one of three tanks in the splitter box, from whence the slurry enters the basin through one of three pipes. Turbidity currents at two inlet discharges were created. A discharge of 1.5 liters/s was created by diverting the central pipe into the central tank of the splitter box. A discharge of 4.5 liters/s was created by diverting each of the three pipes into its respective tank in the splitter box. The inner diameter of each pipe extending from the splitter box into the basin was 7.62 cm.

This recirculating system accomplishes two goals. It allows the maintenance of the desired flow discharge and sediment concentration for the duration of the run. In addition, the constant-head tank damps flow transients when part of the flow is introduced into the basin.
**System for maintenance of water surface elevation**  A toroidal float at the downstream end of the basin houses a recharge line. The recharge line is connected to a special constant head tank the sole purpose of which is the maintenance of water surface elevation in the basin. Whenever the water surface elevation in the constant head tank connected to the float is different from the water surface elevation in the basin, water is fed into or drained from the basin until the elevation of the latter equals that of the former. Water surface elevation was maintained constant throughout the experiment. During the experiment water was constantly fed into the basin through the float at a rate that balanced the removal rate from the manifold described below.

**Manifold for the removal of turbid water**  A manifold pipe perpendicular to the incoming flow was placed under water at the downstream end of the basin. Turbid water was sucked out of the basin with this manifold in order to minimize the effect of reflection of the turbidity current from the downstream wall of the basin. Suction was maintained at a discharge at least as high as the inflowing turbidity current. The siphon system described above maintained constant water surface elevation. Although detailed measurements were not taken, the concentration of sediment in the water so removed was observed to be much smaller than that of the incoming slurry.

**Sediment and slurry concentration**  The sediment used to create the slurry consisted of a mixture of three grades of silica flour, each with a specific gravity of 2.65. The design slurry concentration was 5 percent by volume. The sediment mix consisted of 40 percent nominal 20 \( \mu \)m material, 45 percent nominal 45 \( \mu \)m material, and 15 percent nominal 120 \( \mu \)m material. Grain size distributions of each of the constituent grades of sediment, as well as that of the mix are given in Figure 6. Toward the end of the experiment the coarsest material (120 \( \mu \)m sand) was removed from the mix. The resulting grain size distribution consisting of only the 20 \( \mu \)m and 45 \( \mu \)m silicas is also given in Figure 6. The statistics of the grain size distributions of the three grades of sediment and the two mixes are given in Table 1.
The sediment mixture and concentration were chosen based on earlier experiments in the 2D minibasin described in Lamb et al. (in press). The wide range of grain sizes was chosen to promote sediment sorting, in order to create a clear depositional signal.

**Bed profiling system** Insofar as the deposit created during the experiment was completely subaqueous except near the very end of the run, an acoustic (sonar) system was used for profiling the bed. The sonar scanner was mounted on an automated translation system. The zone that could be effectively scanned was 4.70 m long and 2.22 m wide, i.e. less than the area of the total basin used in the experiment; it is indicated by the gray rectangles in Figure 4. A transect of transverse bed profile was measured every 0.1 m down the basin. Bathymetric measurements were taken with a streamwise resolution of 0.1 m and a transverse resolution of 0.01 m. Under ideal conditions the accuracy of elevation measurements determined with the sonar profiler was \( \pm 0.5 \) mm in the vertical. Conditions were not always ideal, however, especially near sudden elevation changes along e.g. a bedform.

**Initial bed configuration, drainage layer and coal delta** The experiment was commenced with an initial bowl-shaped depression (Figure 4). The lowest point of the initial minibasin was located just downstream of the center of the basin. The relief between the outer edges of the basin and the lowest point was 200 mm. The initial depth of water above the lowest point in the basin was approximately 0.80 m. The lowest point of the membrane was 0.90 m below the water surface; the difference of 0.10 m corresponds to the thickness of the drainage layer described below. The initial basin geometry was chosen to be a generic scale model of a typical salt-withdrawal minibasin on the north slope of the Gulf of Mexico, as determined from NOAA multibeam bathymetry (http://www.noaa.gov; Pratson and Ryan, 1994).

In order to allow for minimum disturbance of the deposit during post-experiment draining, a drainage layer was placed above the rubber membrane. The drainage layer consisted of two sub-layers, a pea-gravel sub-layer approximately 0.08 m thick, and an upper sand sub-layer approximately 0.02 m
thick that acted as a filter layer, helping to prevent the sediment of the deposit from being sucked out with the water during draining. A network of tubing was buried within the gravel sub-layer to allow water to be pumped out slowly after the end of the run. The elevation profiles given in Figure 4 represent the top of the rubber membrane.

A channel leading into the minibasin was simulated by building out two subaqueous deltas of crushed coal at the upstream end of the basin, one to the left of center and one to the right of center. This created an initial depression at the center of the upstream end of the basin into which turbidity currents were introduced. The size distribution of the crushed coal in this delta is characterized in Figure 6; and statistics of the grain size distribution are given in Table 1. A photograph of the initial bed in the basin with the drainage layer and coal deltas in place is shown in Figure 7.

EXPERIMENTAL PROCEDURE

The experiment was performed in two stages. During Stage 1, the bed was allowed to subside in such a way as to accentuate the bowl-shaped pattern of the initial basin. That is, the deepest part of the basin basement (top of drainage layer) was subsided another 250 mm, from an initial depth below the water surface of approximately 0.80 m (membrane at 0.90 m) to a final depth of approximately 1.05 m (membrane at 1.15 m). This point of subsidence maximum dropped at a rate of 9 mm/hour during Stage 1. The edges of the basin were not subsided; the temporal basement subsidence rate varied smoothly in space from the edges to the deepest part. This resulted in a maximum basement relief of 550 mm at the end of Stage 1 (Figure 4). The degree of subsidence was chosen so as to create accommodation volume equivalent to that of the total volume of sediment fed into the basin during Stage 1. During Stage 2 the experiment was continued without further subsidence. The rationale for the two stages is as follows: Stage 1 allowed the possibility of filling of the created accommodation space by deposition from the turbidity currents, and Stage 2 allowed the possibility of overspill from the basin.
Three types of turbidity current flow events were employed: small pulse flows, with an inlet discharge of 1.5 liters/s, lasting 1 minute 51 seconds; large pulse flows, with an inlet discharge of 4.5 liters/s, lasting 3 minutes 49 seconds; and continuous flows, with an inlet discharge of 1.5 liters/s, lasting 36 minutes. These flows were chosen to cover a fairly wide span of turbidity current magnitudes and durations. After each event the sediment was allowed to settle for 100 minutes. During Stage 1, subsidence continued during settling periods at the same rate as during events. The sequencing of flows is described in Table 2. The same pattern of flows was used for both stages. The discharges and durations were chosen such that the sediment volume sent to the basin by 6 small pulse events was approximately equal to the volume of sediment sent to basin by 1 large pulse event, this sediment volume being, in turn, approximately equal to one-third of the sediment volume sent to the basin by one continuous event. The time scales insured that the durations of the smaller events were approximately the necessary time for the events to traverse the basin length (Lamb et al., in press).

After the 100 minutes of settling time was completed, the bed was scanned with the sonar profiler. During Stage 1, subsidence was paused during the scanning process. No pause was necessary in Stage 2 because the bed was not subsiding. The scanning process typically required 30 minutes.

In order to help define the stratigraphy of the deposit, a thin layer of painted sand was sprinkled on the deposit surface after the completion of scanning (but before recommencing subsidence in the case of Stage 1). Six different colors were used in sequence as stratigraphic markers. Colored sand was not used for the first continuous event and the middle four small pulse events of the first set of six small pulses of Stage 1, in order to test whether the contact between the different deposits could be detected by current sorting alone. Furthermore, during the third and fourth continuous events coal was periodically injected into the inflowing turbidity current. This was done in order to record any variations in the deposition pattern in time and space during each of these continuous events.
One unintended aspect of the run was the creation of a flow impact crater structure just downstream of the inlet, due to the impingement of the turbid inlet flow against an erodible bed, as seen in Figure 8. Near the end of the experiment this crater structure started to breach the water surface. To alleviate further aggradation upon this flow impact structure the coarsest caliber of silica (nominal size of 120 µm) was removed from the sediment mix immediately after the third large pulse event but before the fourth package of six small pulse events (Table 2). This reduced the slurry sediment concentration from 5 percent to 4.25 percent, and rendered the sediment mix finer, as shown in Figure 6. This had a noticeable effect on the deposit, as discussed below.

The experiment lasted for 56.7 hours. This time included 2.40 hours of continuous events, 0.25 hours of large pulse events, 0.75 hours of small pulse events and 53.3 hours of settling time. In addition, about 16 hours of time was devoted to scanning. A total of 33 sonar scans of the surface elevation of the deposit were taken. The first of these corresponds to the initial substrate and delta surface; the rest were taken after each of the 32 flow events.

Once the experiment was finished, the basin was slowly drained by siphoning the standing water from above. After this the deposit was drained through the buried tubing in the drainage layer. Approximately three weeks were required to drain the deposit; the long time insured minimal disturbance (e.g. slumping) during draining. The drained deposit is shown in Figure 8.

After draining the deposit was sliced, and its stratigraphy was recorded by digital and analog photography at 74 strike locations. The streamwise distance between strike slices varied between 5 and 10 cm depending on internal detail. During slicing 363 sediment samples were also taken at various locations in the deposit to allow for a characterization of grain size variation with deposit position.

FEATURES OF THE DEPOSIT

The deposit is divided into four regions for the purpose of discussion: deltaic, proximal, medial and distal, as defined in Figure 8. The boundaries are specified in terms of the streamwise distance (x) from the upstream end of the
basin. The deltaic region extended from the upstream end of the basin \((x = 0 \text{ m})\) to \(x = 0.70 \text{ m}\). The proximal region extended from \(x = 0.70 \text{ m}\), where the turbidity currents were fed into the basin, to \(x = 1.50 \text{ m}\), a point not far downstream of the distal lip of the crater as was discussed above (Figure 8). The medial region extended from \(x = 1.50 \text{ m}\) to \(x = 3.10 \text{ m}\), the latter point corresponding to the \(x\)-coordinate of the point of maximum subsidence. The distal region extended from \(x = 3.10 \text{ m}\) to the end of the tank at \(x = 5.82 \text{ m}\). The deltaic region is neglected in the discussion here, as it was composed mostly of coal.

Several data sets are used to describe the deposit: topographic scan surfaces, isopach maps, deposit strike and dip sections created from the scan surfaces, and digital photos of the dried deposit. Isopach maps were obtained by subtracting the bed elevation at an earlier time from that at a later time (with a correction for subsidence). The resulting map shows positive values where net deposition occurred in the intervening period, and negative values where net erosion occurred. Strike-oriented slices as mentioned above were made after the experiment was completed; each of them records the entire history of the experiment at the cross-section in question. Views of slices covering the proximal, medial and distal regions are given in Figure 14. In all strike slice images an orange line divides Stage 1 deposits below from Stage 2 deposits above. A preliminary analysis of the deposit grain size patterns has been performed, although it is not presented here.

**Development and obliteration of a leveed channel** Four scans are shown in Figure 9. This scanned topography at different times during the first half of Stage 1 shows the same proximal flow impact crater structure visible on the dried deposit (Figure 8), confirming the accuracy of these scans. The flow impact crater dominates the surface expression of the proximal region of the deposit.

Of interest in the deposit of the first continuous event (Figure 9b) is the appearance of a short leveed channel in the center of the basin downstream of the flow impact crater, in the proximal portion of the medial region. This channelized region is highlighted by a white boundary (Figure 9b). These levees were first apparent after the end of the first event. The levees are well expressed
from \( x = 1.5 \text{ m} \) to just beyond \( x = 1.9 \text{ m} \), though some expression is apparent as far downstream as \( x = 2.5 \text{ m} \).

Figure 9c shows that the first package of six small pulse events tended to infill the channel. The levees in the medial region are still apparent after the six small pulse events have been run (Figure 9c), but levee relief is more subtle than just after inception (Figure 9b). The first large pulse event completed the process of infilling (Figure 9d).

A more detailed channel levee construction and infilling history is given in Figure 10, which shows nine expanded views of the topography from the region bounded by the white box in Figure 9b. Again, the leveed channel was constructed by the first continuous event. Each of the small pulse events contributed to channel obliteration. The channel was still recognizable, but with a much reduced width, after the sixth small pulse event. A bathymetric signature of the channel was no longer visible after the first large pulse event.

The process of inception and infilling of the leveed channel is most evident in the isopach maps. Figures 12a and 12b are isopach maps from the region bounded by the white box in Figure 9b. The isopach of the first continuous event (Figure 12a) shows a zone of low deposition in the center, bounded by zones of high deposition on either side marking the construction of the short leveed channel. Note that proximally this channel has an erosional base (e.g. at \( x = 1.2 \text{ m} \)); it becomes depositionally based farther downstream (e.g. at 1.8 m). These represent two of the basic leveed channel types schematized by Imran et al. 1998. The isopach map of the sum of the package of the first six small pulse events and the first large pulse event (Figure 12b) indicates that deposition was highest in the center of the channel and lower on the levees to either side. These flows thus contributed to burial of the leveed channel.

The stratigraphic record of the channel is displayed in Figures 14a, 14b, and 14c. Figure 14a shows a slice at \( x = 1.40 \text{ m} \) (0.70 m from the source) corresponding to a point at a breach in the flow impact crater from which the short leveed channel of Stage 1 emanated. While the large concave-upward structure in the deposit may also be partly indicative of the flow impact structure,
the photograph provides a view of the erosional channel base apparent in the isopach map (Figure 12a). The stratigraphy at $x=1.70$ m (1.00 m from the source, shown in Figure 14b) demonstrates that the leveed channel was the most interesting feature of the deposit. Figure 14b shows, near its base, the full expression of the channel and levees downstream of the flow impact crater. The expanded inset about the deposit centerline (Figure 14b) shows that the channel narrowed as it filled, as also observed in the close-up surface scans (Figure 10), and that these small pulse flow deposits have a draped geometry in strike view.

Figure 14c shows a very slight expression of the leveed channel near the bottom of the section. This section, at $x=2.25$ m, is near the distal reach of the levees created by the first continuous event. Comparison of the deposit at $x=2.25$ m to the signal in the surface scan of the first event (Figure 14b) confirms the lateral and distal extent of this leveed structure.

**Deposit Structure by Reach: Proximal, Medial and Distal** While Figure 14a lies on the transition from proximal to medial deposits, its general structure is characteristic of all other views taken from the proximal region. (Additional images are available upon request.) These proximal deposits consist mostly of material from Stage 1; recall that the orange line separates Stage 1 and 2 deposits. The deposits reflect the concave-upward geometry of the flow impact crater. An expanded view of this structure is given as an inset near the center of Figure 14a. Most of the material fed in during Stage 2 bypassed the proximal region.

Other proximal deposit features are worth noting. Large amounts of (black) coal mixed in with the (white) silica sediments evidence entrainment of deltaic coal in the central region of the deposit (Figure 14a). Also the Stage 2 deposits in Figure 14a consisted predominantly of compensationally stacked lobe bodies offset from the center of the section.

While the deposits in the medial region are dominated by the more proximal leveed channel discussed above, other interesting feature can be found in the strike sections. The insets to the left and right in Figure 14b detail the same lobe stacking found in the peripheries of the proximal reach, and seen in Figure
14a. The two sections of Figures 14a and 14b also exhibit an isolated but prominent layer of red sand about the deposit centerline. This red sand was first sprinkled on the water surface of the basin after the first small pulse event of the first package of six pulses (which was immediately after the first flow event of the experiment). After technical problems with placement, this red marker sand was also added to the feed sediment during the first 30 seconds of the second small pulse of the first package of six pulses. In all future additions of colored sand the problem of surface tension was overcome with a water sprinkler, and so the subsequent marker layers are thin where not reworked by the flow. Roughly speaking, however, the thick layer of red sand in Figures 14a and 14b demarcates the border between channel creation (below) and destruction (above).

Stage 1 deposition in the medial region includes a phase of sedimentation near the center of the basin (distal channel expression near the base of the section), and a subsequent phase in which sedimentation is spread broadly across the entire basin (Figure 14c). The Stage 2 deposit shows the deposition of lobes concentrated toward both sides of the deposit, followed by the deposition of a lobe at the center-top of the deposit placed by the last continuous event.

The left inset of Figure 14c shows a green and red area that is the result of post-depositional soft sediment deformation of material containing the marker sands added in between small pulse events of the fourth package. The reworked marker sands provide an analogy of ripup clasts. Climbing current ripples are apparent in the right side of the deposit (right inset in Figure 14c). These ripples can also be seen on the surface of the final dried deposit (Figure 8). The ripples’ oblique geometry records the lateral expansion of the flow downstream of the flow impact crater structure.

Figure 14d shows a cross-section at $x = 3.1$ m, at the border between the medial and distal regions. In nearly all cases the deposits of individual events are simply stacked one atop the other, although a localized region of soft sediment deformation, this time associated with green marker sediment placed after the third continuous event, can be seen in the inset. The deposits are
thickest at the center of the image, which corresponds to the point of maximum subsidence, and thinner to either side. This result seems to imply that immediate accommodation space localized deposition whereas the presence or absence of subsidence had little impact on deposition from the currents. Figure 14e shows a distal cross-section at $x = 4.4$ m. The deposits are very thin and sheet-like, and are of relatively uniform thickness in the lateral. This stratigraphy is the result of passive deposition with no reworking.

The insets in Figures 14d and 14e show the degree to which the stratigraphy of the deposit is highlighted by the colored sediment. The depositional layer associated with each event can be identified. It was noted earlier that no colored tracers were used after the first continuous event and each of the middle four events of the first package of six small pulse events, in order to see if the individual layers could be discerned without the use of tracers. Although difficult to see in Figures 14d and 14e, every tracer-free deposit produced by these six flows was discernible in the original high-resolution photographs in terms of a white cap of fine-grained sediment at the top of each deposit.

High-resolution images corresponding to Figures 14a ~ 14e have been placed on the web site http://www.ce.umn.edu/~parker to allow the reader to peruse them in detail.

The sonar scans were used to make synthetic cross-sections of stratigraphy which complement the photographic views of Figures 14a~e. Figure 15 shows that the stratigraphy of the section pictured in Figure 14b can be accurately reproduced from the sonar scans. The sonar elevation data were also used in Figure 16 to produce a dip section of the deposit down the center of the basin. This synthetic view is of interest because the deposit was not physically sliced in the dip direction.

The reader should note that in Figures 15 and 16 the vertical scale has been exaggerated by a factor of 2:1, whereas none of the photographs of Figure 14a~e is distorted. Figure 15a shows the initial basement and the deposit of the first continuous event, and Figure 15b shows the entire depositional history of the
run. Comparison of Figures 15b and 14b reveals good correspondence; the events recorded in photographs were evidently faithfully recorded in the sonar bed profiles.

Figure 16a shows a dip section of the initial basement and the deposit of the first continuous event. This section runs down the centerline of the basin, and thus runs through the center of the short leveed channel that was constructed in the upper medial region by this flow. The plot records the excavation of the flow impact crater and deposition along the channel centerline. Because the channel and levees are expressed well in Figure 14b, it can be concluded that the rate of deposition along the levees must have been higher than that recorded in Figure 16a along the channel thalweg (as already noted in Figure 12a).

Figure 16b shows a dip section recording the entire history of the experiment. The image records the gradual progradation of the deposit into the basin, as well as upstream migration of the flow impact crater. Toward the end of the run the physical diameter of this structure had shrunk. This is associated with incipient breaching of the water surface, as was discussed above.

Erosion and deposition by event type The data in Figure 11 illustrate consistent differences in patterns of deposition and erosion of the scanned bed. All four continuous events (Figures 11a, 11d, 11e, and 11i) show deposition that is concentrated in the proximal and medial zones, with little tendency for erosion. The only exception to this pattern is the first continuous event (Figure 11a), which shows substantial erosion upstream of the concentrated depositional zone. This erosion is associated with the entrainment of coal early in the flow event. The first, third and fourth packages of small pulse events (Figures 11b, 11f and 11h) all show much broader, thinner deposits than the continuous events, again with little tendency for net erosion. The depocenters of these events tend to be farther downstream than those of the continuous events. The third packet of small pulse events (Figure 11f) shows some tendency for the deposition of lateral lobes to either side of the center of the basin, suggesting compensational stacking of sediment in the proximal/medial zones (as also seen in Figures 14a,
14b and 14c). The first, third and fourth large pulse events (Figures 11b, 11f and 11h) all show notable proximal erosion. In addition, their depocenters lie farther downstream in comparison to the continuous events or the small pulse event packages. The implication of Figures 11a~j is that different types of flows can create very different patterns of deposition and erosion. The tendency for the pulse events to move sediment farther out in the basin than the continuous events is in agreement with the findings of Lamb et al. (in press). The data for the second package of six small pulse events and the second large pulse event proved to be corrupted.

It is of value to compare the deposit of the last continuous event (Figure 11j) to the deposits of the other continuous events (Figures 11a, 11d and 11e). The depocenter of the last continuous event is located well downstream of those of the other three. This pattern can be explained as a result of three aspects of the experiment. First there existed an overall tendency for sediment to prograde into the basin throughout the run (as illustrated in Figure 16b). Second, the depocenter was influenced by the incipient breaching of the water surface by the flow impact crater structure observed toward the end of the run. This relative absence of proximal accommodation space tended to push the depocenter downstream. Third, after incipient breaching was observed, the coarsest (sand) component of the sediment feed mix (120 um material) was removed for the remainder of the experiment. The finer material tended to travel farther before depositing. However, it can be seen from all isopachs (Figures 11a ~ j) that the sediment depocenter was universally upstream of the point of maximum subsidence at x = 3.1 m.

The effect of removing the coarsest (sand) component of the sediment mix from the feed is captured in Figure 13. Figure 13a shows the isopach associated with all 8 events of the first half of Stage 2, during which sand had not yet been removed from the sediment feed mix. Figure 13b shows the same isopach for all 8 events of the second half of Stage 2, during which sand had been removed from the sediment feed mix. The deposit of the first half of Stage 2 (Figure 13a) shows a primary depocenter in the proximal zone, with a secondary ring-shaped
depocenter in the medial zone surrounding an area of relatively low deposition. This reflects the deposition of lobes to either side of the downstream slope of the flow impact crater; the lobes merge close to the center of the basin farther downstream. For the second half of Stage 2 (Figure 13b), erosion is prominent in the proximal zone, and the depocenter is near the center of the basin, farther downstream than during the first half of Stage 2 (Figure 13a). The lack of proximal accommodation space in the second half of Stage 2 likely acted to cause this shift of the depocenter downdip. The Stage 2 depositional lobe patterns in both Figures 13a and 13b correspond to those seen in the stratigraphy (Figure 14c).

DISCUSSION

Recently Beaubouef et al. (2003) have reported on ultra-high (2m) resolution seismic data from Basin 4 of a well-known chain of four Pleistocene intra-slope salt-withdrawal minibasins on the north slope of the Gulf of Mexico. This chain is often referred to as the Brazos-Trinity Intra-Slope System (East Breaks, e.g. Beaubouef and Friedman, 2000). The images reported therein reveal a heretofore unrecognized feature of deep-sea sedimentation: an internal delta. The deposits in Basin 4 show a channelized topset and low foreset prograding into a zone that has the hallmarks of a bottomset emplaced by the passive rain of fine-grained sediment. That is, the bottomset appears to have been emplaced by a turbidity current ponded within the basin in a manner described experimentally by Lamb et al. (in press) and Toniolo (2003).

The results of the present experiment bear comparison with the field data of Beaubouef et al. (2003). Figure 17a shows a strike view of a seismic image of the proximal deposit in Basin 4; the corresponding strike views of the medial and distal deposits are given in Figures 17b and 17c, respectively.

The general structure of Figure 17a is remarkably similar to the structure visible in Figure 14b from the present experiment. The main difference between them is that Figure 17a shows a multiplicity of channels, whereas Figure 14b shows only one channel. Figure 17b likewise may be compared to Figure 14c,
and Figure 17c to Figure 14e. The experimental distal deposits show precisely the same sheetlike structure in the present experiment as in Basin 4. The experiments of Lamb et al. (in press) and Toniolo (2002) show that these deposits can be formed by turbidity currents that have become ponded within a confined basin.

The same similarity in morphology can be seen in terms of a comparison of the dip section of Basin 4 given in Figure 18 and the dip section of Figure 16b from the experiment. Both show similar wedges of sediment prograding into the basin.

An interesting aspect of the experiment is the relative insensitivity of the depositional pattern to subsidence. There is little in the Stage 1 deposits (with subsidence) to discriminate them from the Stage 2 deposits (no subsidence) based on tectonics. The depocenter of all flow events was upstream, and in most cases well upstream of the point of maximum subsidence. The work of Kostic and Parker (2003a,b), Lamb et al. (in press) and Toniolo (2002) indicate that a deposit created by passive settling without reentrainment from a turbidity current creates a sheet-like drape that covers bed irregularities indiscriminately. That is, strongly depositional turbidity currents do not appear to interact strongly with bed topography. Although erosion was clearly present in the experiment, it can be surmised that a more strongly erosional flow might have interacted more strongly with basin tectonics.

The short leveed channel was formed by the first continuous event, and infilled by the following seven pulse events. This result suggests that a continuous flow is necessary for the setup of conditions conducive to self-channelization, as previously indicated by Imran et al. (1998). Continuous flow is not in itself sufficient, however, as subsequent continuous flows did not reform the channel.

CONCLUSIONS

The experiment described here represents the first experimental attempt to study deposition from turbidity currents in a fully three-dimensional, subsiding
basin. Three kinds of turbidity currents were studied: continuous events, small pulse events and large pulse events. During Stage 1 of the experiment the bed of the basin subsided in a bowl shape. During Stage 2 subsidence was turned off. The major conclusions of the experiment can be summarized as follows.

A continuous turbidity current event constructed a short submarine channel bounded by levees in the upper medial zone of the basin. The leveed channel was later infilled by deposition from small and large pulse events.

The continuous turbidity current events tended to form depocenters that were more proximal than the pulse turbidity current events. The large pulse events tended to create depocenters farthest out in the basin.

In no case did the depocenter of an event correspond to the zone of maximum subsidence in the basin; in all cases but one the depocenter was well updip. The pattern of deposition during Stage 2, when the basin floor was not subsiding, was not markedly different to that of Stage 1, when the basin floor was subsiding. That is, the pattern of deposition was relatively insensitive to tectonics. This in turn suggests that the flows were for the most part purely depositional, with the flow responding only weakly to changing bed topography.

While the morphology and stratigraphy created during the experiment was predominantly depositional, significant erosion did occur in the proximal zone, and some erosion occurred in the medial zone as well. The effect of channel formation and filling and lobe switching of sheet-like deposits was particularly evident in the medial zone, where current ripples and post-depositional sediment deformation were also observed. The distal zone was dominated by uniform sheet-like deposits reminiscent of those deposited from a ponded turbidity current.

The pattern of deposition observed in the experiment was in many ways similar to that observed in Basin 4 of the Brazos-Trinity Intra-Slope System, Gulf of Mexico (Beaubouef et al., 2003). That is, the pattern resembled a prograding deep-sea internal delta with a channelized topset, low foreset and sheet-like bottomset.
ACKNOWLEDGEMENTS

The performance of the experiment reported in this paper was funded by St. Anthony Falls Laboratory Industrial Oil Consortium (leader: Chris Paola; participants: Anadarko, ChevronTexaco, ConocoPhillips, ExxonMobil, and Japan National Oil Company). This paper constitutes the M.S. thesis of the first author. The first author was funded by Minnesota Sea Grant (3458004) and a National Science Foundation GAANN fellowship (5208006). The comments and assistance of R. Beaubouef, C. Pirmez and C. Winker are greatly appreciated.

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PRATSON, L.F., AND W.F. HAXBY, 1997, Panoramas of the Seafloor: Scientific American, v. 4, p. 82-8


Table 1: Characteristics of the Sediments Used in the Experiment

<table>
<thead>
<tr>
<th>Sediment Type</th>
<th>$D_g$ ($\mu m$)</th>
<th>$D_{50}$ ($\mu m$)</th>
<th>$\sigma_g$</th>
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<tr>
<td>20 micron nominal silica</td>
<td>19.8</td>
<td>26.4</td>
<td>3.93</td>
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<tr>
<td>45 micron nominal silica</td>
<td>30.4</td>
<td>41.9</td>
<td>4.13</td>
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<tr>
<td>120 micron nominal silica</td>
<td>131</td>
<td>128</td>
<td>1.42</td>
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<tr>
<td>Mix of all three</td>
<td>31.9</td>
<td>44.5</td>
<td>4.21</td>
</tr>
<tr>
<td>Mix of finest two</td>
<td>24.9</td>
<td>33.0</td>
<td>4.10</td>
</tr>
<tr>
<td>Coal</td>
<td>221</td>
<td>228</td>
<td>1.75</td>
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</table>

Table 2: Characterization and Sequencing of Turbidity Current Flow Events

<table>
<thead>
<tr>
<th>Events in order of occurrence</th>
<th>No. of events</th>
<th>Length of event (min)</th>
<th>Relative Runtime</th>
<th>Event Discharging (m$^3$/s)</th>
<th>Water Discharging (m$^3$/s)</th>
<th>Sed. Discharging (m$^3$/s)</th>
<th>Settling time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>1</td>
<td>36</td>
<td>0</td>
<td>0.0015</td>
<td>0.001425</td>
<td>0.000075</td>
<td>1.00</td>
</tr>
<tr>
<td>Small Pulses</td>
<td>6</td>
<td>1.85</td>
<td>136</td>
<td>0.0015</td>
<td>0.001425</td>
<td>0.000075</td>
<td>100 (a.e.)</td>
</tr>
<tr>
<td>Large Pulse</td>
<td>1</td>
<td>2.81</td>
<td>747</td>
<td>0.0045</td>
<td>0.004275</td>
<td>0.00023</td>
<td>1.00</td>
</tr>
<tr>
<td>Small Pulses</td>
<td>6</td>
<td>1.85</td>
<td>851</td>
<td>0.0015</td>
<td>0.001425</td>
<td>0.000075</td>
<td>100 (a.e.)</td>
</tr>
<tr>
<td>Large Pulse</td>
<td>1</td>
<td>3.81</td>
<td>1462</td>
<td>0.0045</td>
<td>0.004275</td>
<td>0.00023</td>
<td>1.00</td>
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<tr>
<td>Continuous</td>
<td>1</td>
<td>36</td>
<td>1506</td>
<td>0.0015</td>
<td>0.001425</td>
<td>0.000075</td>
<td>100 to Stage 2 or end</td>
</tr>
</tbody>
</table>

[Diagram showing stages and run-time with various discharge events marked.]
FIGURE CAPTIONS

Figure 1. a) Acoustic image of salt-withdrawal minibasins on the north slope of the Gulf of Mexico; b) expanded view from Figure 1a. Images courtesy Lincoln Pratson.

Figure 2. Dip view of a seismic image (above) and interpretation (below) for a salt-withdrawal minibasin on the north slope of the Gulf of Mexico. Figure and interpretation from Winker and Booth (2000) and personal communications from C. Winker and C. Pirmez, Shell International Exploration and Production Inc. Flow was from left to right.

Figure 3. Cutaway diagram showing the hexagonal cells and basement and schematized transport surface and stratigraphy to illustrate the function of the eXperimental EarthScape (XES) used for the experiments described herein.

Figure 4. a) The configuration of the rubber membrane (top of the gravel basement) at the beginning of the experiment; the bowl-shaped depression defines the initial configuration of the model minibasin: b) the configuration of the rubber membrane (top of the gravel basement) at the end of Stage 1 of the experiment. In each diagram, the gray rectangle denotes the zone that was scanned for elevation profiles.

Figure 5. Schematic diagram showing the recirculating system for the water and sediment, the coal delta and the drainage layer and the downstream siphon manifold for removing turbid water.

Figure 6. Grain size distributions of the three grades of silica flour used to create the sediment mix, the sediment mix itself, the mix resulting from the exclusion of the coarsest grade of silica flour and the coal utilized in the creation of the delta. This latter silica mix was used only toward the end of the experiment.

Figure 7. Photograph of the basin just before commencing the run, showing the two deltas of crushed coal at the upstream end of the basin, the depression in between, and the three pipes used to introduce turbidity currents. Turbidity currents were introduced into this basin at the top and flowed toward the bottom.
Figure 8. Photograph of the final deposit after draining of the water. The turbidity currents flowed from top to bottom. The darkened navel-like structure near the center of the deposit marks its lowest point; the darkening was caused by standing water which required a long time to remove.

Figure 9. Bed topography a) just before commencing the run, and after b) the first continuous flow event of Stage 1, c) the package of the first six small pulse events of Stage 1, and d) the first large pulse event of Stage 1.

Figure 10. Detailed view of the bed topography within the white box in Figure 9b: a) just before commencing the experiment, and after b) the first continuous event, c) the first small pulse event, d) the second small pulse event, e) the third small pulse event, f) the fourth small pulse event, g) the fifth small pulse event, h) the sixth small pulse event and i) the first large pulse event.

Figure 11. Isopach maps for a) the first continuous event, b) the first package of six small pulse events, c) the first large pulse event, d) the second continuous event, e) the third continuous event, f) the third package of six small pulse events, g) the third large pulse event, h) the fourth package of small pulse events, i) the fourth small pulse event and j) the fourth large pulse event. In all cases a positive value of elevation corresponds to net deposition and a negative value corresponds to net erosion. (The data for the second package of six small pulse events and the second large pulse event proved to be corrupted.)

Figure 12. Isopach maps for a) the first continuous event of Stage 1, and b) the sum of the first package of six small pulse events and the first large pulse event of Stage 1. The field of view corresponds to the white box of Figure 9b, i.e. where the short leveed channel was observed.

Figure 13. Isopach maps for a) the first half of Stage 2, for which sand (F 110) was included in the sediment feed mix, and b) the second half of Stage 2, for which sand (F 110) was excluded from the sediment feed mix.

Figure 14. Images of cross-sectional slices of the deposit after the end of the run at: a) x = 1.40 m (proximal); b) x = 1.70 m (medial); c) x = 2.25 m (medial); d) x = 3.10 m (medial-distal boundary); and e) x = 4.40 m (distal). All primary images are to the same scale; the insets in each image have been expanded.
to the extent necessary to allow visibility of the features in question. The flow ran out of the page with respect to all images.

Figure 15. Synthetic stratigraphy of a strike section at \( x = 1.7 \) m constructed from the sonar bed profiles: a) plot of the initial substrate surface and the deposit of the first continuous event; b) plot of the depositional architecture of the entire experiment. The flow ran out of the page.

Figure 16. Synthetic stratigraphy of a dip section down the centerline of the basin: a) plot of the initial substrate surface and the deposit of the first continuous event; b) plot of the depositional architecture of the entire experiment. The flow was from left to right.

Figure 17. Strike-oriented seismic profiles through the Upper Fan of Basin 4 of the Brazos-Trinity Intra-Slope System, Gulf of Mexico: a) proximal, b) medial and c) distal. Figure and interpretation provided by R.T. Beaubouef, ExxonMobil Exploration Company, after Beaubouef et al. (2003). Figure 18. Dip-oriented seismic profile through the Upper Fan of Basin 4 of the Brazos-Trinity Intra-Slope System, Gulf of Mexico. The flow was from right to left. Figure and interpretation provided through by R.T. Beaubouef, ExxonMobil Exploration Company, reversed in perspective relative to that given in Beaubouef et al. (2003).
Figure 1.

Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 7.
Figure 8.
Figure 9.
Figure 10.
Figure 11.
Figure 12.

Figure 13.
a) $x = 1.40 \text{ m (0.70 m from source)}$

- lobe deposits of Stage 2

- demarcation of boundary between Stages 1 and 2

b) $x = 1.70 \text{ m (1.00 m from source)}$

- red marker sand placed before and during small pulse 2 of packet 1

- lobe deposits of Stage 2

Figure 14.
c) $x = 2.25 \text{ m (1.55 m from source)}$

d) $x = 3.10 \text{ m (2.40 m from source)}$

e) $x = 4.40 \text{ m (3.70 m from source)}$

Figure 14 (contd.).
Figure 15.

Figure 16.
Figure 17.

Figure 18.