Experimental Stratigraphy

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ABSTRACT

Stratigraphy has been a descriptive science for most of its history. Recently, thanks to the development of the mechanistic view of Earth embodied in plate tectonics and to improvements in our understanding of sediment dynamics, the stratigraphic community has developed a first generation of quantitative models for the filling of basins and the formation of stratigraphic patterns. How do we test such models? The field is the ultimate repository of information, but exposure is limited, and it is often difficult to constrain key governing variables independently. We have developed a novel experimental basin—nicknamed Jurassic Tank—that allows us to produce experimental stratigraphy under precisely controlled and monitored conditions of sediment supply, subsidence, base-level variation, and transport mechanics. The unique feature of the basin is a fully programmable subsiding floor. In the first application of the system, we looked for evidence of decoupling (out-of-phase behavior) between shoreline and base level, as has been predicted by some recent stratigraphic models. We found little support for this idea, but the results demonstrate the potential that experiments have for complementing field and theoretical studies of the filling of sedimentary basins.

Before you read this, try solving the problem posed in Figure 1.

INTRODUCTION

The central goal of sedimentary geology is to interpret the history of Earth's surface from sedimentary rocks. We develop competing hypotheses, debate, discuss, and compare, but unlike areas of science that deal in accessible time and space scales, in sedimentary geology it is often difficult to determine unambiguously who is right. The ultimate source of truth—the stratigraphic record itself—is like a fragmentary manuscript written in a long-forgotten language. Deposits are imperfectly exposed and hard to date, seismic images are highly filtered and expensive, and the precise sequence of events that produced real-world stratigraphy usually cannot be determined independently. Trying to understand the language of sediments using rocks alone would be like trying to understand Russian by opening *War and Peace* to the middle and staring at the pages.

Sedimentary geologists have long recognized this and sought Rosetta stones for the stratigraphic record through

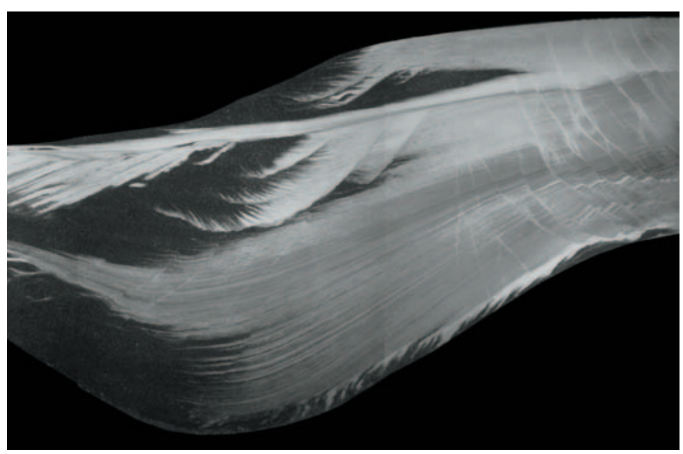

Figure 1. Can you interpret this panel? It shows a section of basin sediment taken parallel to transport (i.e., a dip section), with flow from right to left. Darker material is lighter and hence more mobile. Distal part of deposit was formed under water, and proximal part is fluvial. Break between light and dark material is a good indicator of shoreline position. The challenge: Deduce history of sediment supply, subsidence, and base level for this section using only information above and geometry of the preserved deposits. Answer is given in Figure 5.

studies of modern environments and processes. Most of our understanding of sedimentary lithofacies, for instance, comes from synthesis of the mainly horizontal information we have from modern depositional environments with the mainly vertical information provided by ancient deposits. A particularly fruitful line of research has clarified the origin of sedimentary structures (e.g., cross-stratification) in terms of bed forms and other relatively generic features of sediment-depositing flows (Allen, 1984; Middleton and Southard, 1984). This research, carried out in both field and laboratory, has taught us much about the alphabet of the language of sediments.

The paragraphs and chapters of the sedimentary narrative are written in the form of larger-scale sequences of sedimentary facies. A basic tenet in stratigraphy is that patterns in these sequences are controlled by three main independent variables: sea level, subsidence (rate and distribution), and sediment supply (e.g., Sloss, 1962). To this trinity we should add a fourth variable group that controls the efficacy of the transport system (e.g., water supply for rivers, wave climate or tidal range for the continental shelf). The first attempts to understand how changes in these independent variables are recorded stratigraphically were descriptive. However, the physical mechanisms that distribute sediment (not to mention biological and chemical processes) are complex enough that it is difficult to model stratigraphy using descriptive methods alone. Two major developments have allowed us to create a first generation of physically based, quantitative stratigraphic models (Cross, 1990; Harbaugh et al., 1999; Paola, 2000; Slingerland et al., 1994): (1) development of quantitative models of the mechanics of basin subsidence, an outgrowth of plate-tectonic theory; and (2) improvements in our understanding of how sediment-transport systems work. By coupling subsidence and transport, we produce theoretical models of stratigraphy. (Because of the complexity of the equation systems involved, quantitative stratigraphic models are nearly always numerical.) These models should allow us to read the sedimentary record with greater subtlety and precision. However, it is worth pausing before rushing off to apply our newly minted models to the stratigraphic record—after all, ancient basins are one setting where it is very hard to check our model results independently!

The Rationale for the eXperimental EarthScape Facility

In most sciences, carefully controlled experiments are the preferred means of testing theoretical models. For a variety of reasons, experimentation has not played much of a role in stratigraphic science, but the experimental approach is well developed in other areas of sediment dynamics, particularly in civil engineering and geomorphology. One of the main logistical hurdles to experimental stratigraphy is the necessity of including tectonic effects such as subsidence and uplift. We have addressed this by building a large experimental basin that incorporates a unique, flexible subsiding floor to simulate the development of sedimentary basins under a wide variety of subsidence conditions. This new experimental facility (the eXperimental EarthScape or XES basin) can be used to study the formation of stratigraphy under completely controlled conditions of base-level change, subsidence, sediment supply, and transport—the same influences that control natural basin stratigraphy. The experimental system includes the most fundamental physical processes associated with basin filling—river, wave, current, and mass-flow sediment transport—and it allows the boundaries between transport environments (e.g., the shoreline) to evolve on their own. The resulting data sets document spatial and temporal changes in sediment budgets, morphodynamics, and stratigraphic response.

The main advantages of experimental stratigraphy are that boundary conditions can be controlled, processes with natural analogs that occur over long time scales can be thoroughly documented, the resultant deposits can be dissected at high resolution and visualized in three dimensions, and transport processes can be directly related to depositional products. On the other hand, experimental systems leave some important things out (e.g., biogenic processes and Coriolis effects), and they distort others (e.g., topographic slopes tend to be exaggerated).

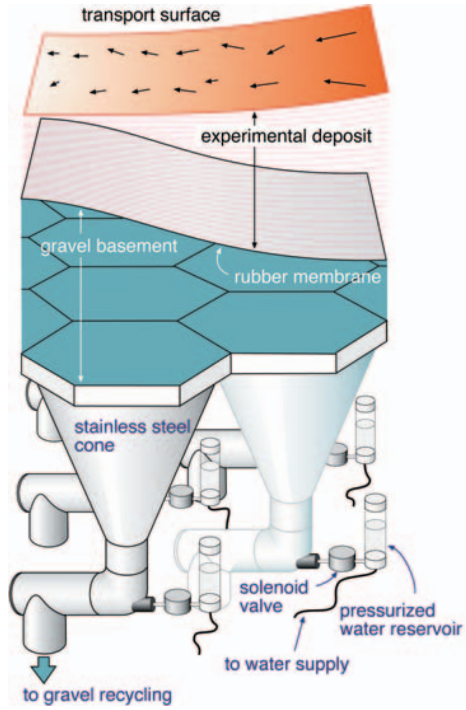

Figure 2. Schematic diagram of subsidence mechanism used in eXperimental EarthScape (XES) subsiding-floor experimental basin. Pulses of water shot through narrow tubes knock gravel out of pipe, causing subsidence of gravel surface.

Formally, we use theory to link experiments and field cases. Once a theory has had a good workout in a controlled system, we can be more confident about using it to scale the experimental results to the field, to evaluate effects that cannot be scaled down to experiments, and to model cases where we cannot check the answer independently. Stratigraphic experiments are especially well suited for testing formal "inversion" models for reconstructing variables like sea level and sediment supply directly from the stratigraphic record (Lessenger and Cross, 1996), and for evaluating how unique such reconstructions are (Heller et al., 1993).

At a more informal level, experiments help build intuition. There is nothing like watching a transport system evolve in front of you and then dissecting it to see how the depositional filter has rendered it in stratigraphy. We manipulate only boundary conditions. Within the basin, the transport systems organize themselves and do what they want rather than what we programmed them to do. Self-organization—the spontaneous emergence of patterns and structures—is a hallmark of sediment-transporting

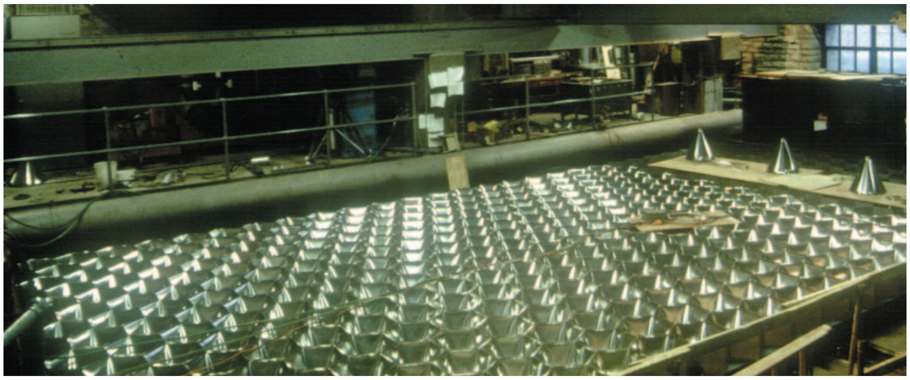

Figure 3. Honeycomb floor of full eXperimental EarthScape (XES) basin, with 432 subsidence cells. A 10-cell version was used for experiment described in this paper.

systems, and it gives even simple experiments the capacity to surprise us and trump our expectations. These surprises give us new ideas and things to look for in the field. As long as our intuition-building is tempered by a good understanding of the limitations and distortions of the experimental systems, it is one of the most valuable uses of stratigraphic experiments.

THE XES FACILITY

The XES facility is a large basin (13 m × 6.5 m) developed and built with funds from the National Science Foundation and the University of Minnesota that allows the accumulation of strata through the use of a flexible subsiding substrate (Fig. 2). The basin floor is a honeycomb of 432 independent subsidence cells (Fig. 3) through which a gravel basement is slowly extracted from below, providing space to accommodate deposition. An experiment starts with the basin filled with gravel. The top of the gravel is covered with a thin rubber membrane, which forms the base of the experimental deposit. Each subsidence cell is a hexagon forming the top of a cone that tapers down into a standard elbow pipe (Fig. 2), where the gravel sits at the angle of repose. Subsidence is induced by firing a pulse of high-pressure water into the gravel in the elbow, knocking a small volume into an exhaust line. Each subsidence cell has its own sealed pressure tube that drives the pulses via a computer-controlled solenoid valve. We have refined the pulsing so that each pulse produces ~0.12 mm of subsidence—the "earthquake slip" in the experiments. Hence, the subsidence is effectively smooth and continuous in time. The subsidence also is spatially continuous: The cells are separated only at floor level, so the gravel can flow laterally to accommodate differential subsidence with no imprinting of the hexagonal pattern onto the basement surface. The system provides ~1.3 m of usable accommodation space in the basin. Depending on loading of the gravel basement, lateral slopes of up to 60° can be produced between adjoining cells.

Premixed sediment and water can be fed from anywhere along the perimeter of the basin, and base level is independently set by a computer-controlled head tank mounted outside of the basin. More details of the design and mechanics of the basin are available on our Web site: www1.umn.edu/safl/research/research.html.

During an experiment, the surface-flow pattern is recorded using video and still cameras. In addition, a topographic scanning system, based on the design of Rice et al. (1988) and Wilson and Rice (1990), allows us to document the 3-dimensional evolution of the surface topography during the run for later comparison with the surface-flow images, the preserved deposits, and theoretical predictions.

Once an experiment is complete, the resultant deposits are cut in a series of precise parallel faces, beginning near one edge. Each face is photographed. About every 10 faces, a peel is taken of the cut face. This serial microtome process allows us to build a 3-dimensional image of the deposits by stacking the sequence of photographed slices. Additional equipment being added to the basin includes rainfall and wave generators, a high-resolution sonar system for recording underwater topography, and a system for rapid digital photography of sectioned deposits.

INITIAL EXPERIMENTAL RESULTS

The Experiment

Our first study (XES 96-1) involved a small prototype basin with 10 subsidence cells (Heller et al., 2001; Paola, 2000; Pratson and Gouveia, 2002). It was designed to study the effects of slow and rapid changes in base level on shoreline position and the resultant sequence stratigraphy. The experimental design was inspired by theoretical models proposed by Pitman (1978), Angevine (1989), and Jordan and Flemings (1991). This work suggested that for slow (long-period) base-level changes, shoreline would not track base

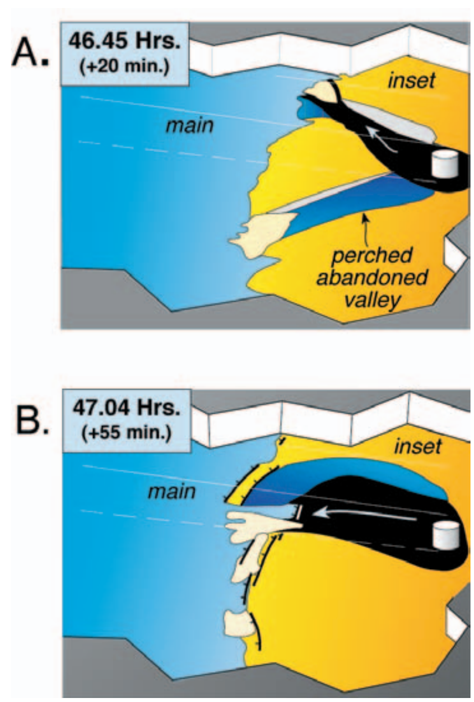

Figure 4. Drawings from photographs showing sediment surface at two times, 15 minutes apart, during the rapid base-level fall. Numbers in parentheses give time after start of the base-level cycle. Basin centerline is shown by dashed line; sediment-feed point is shown by small cylinder. Locations of two sections shown in Figure 5 are shown by white lines (main and inset panels). Zone of active flow is shown in black, and fault symbols show normal faults associated with exposure of delta front. Base-level history is given in Figure 5, with time for these images indicated by arrow.

level, as one would expect, but rather should track the *rate of change* of base level (i.e., shoreline would be 90° out of phase with base level). This idea is so strange—imagine that the high-water mark on your local beach occurred not at high tide but midway between low and high tide—that at first blush, it seems impossible. But over long time scales, the coastal plain is not a static surface on which sea-level rise and fall are passively imprinted. Rather, the surface morphology evolves along with changing sea level: Shelf transport produces different morphology from fluvial transport, and the boundary between the two regimes depends on where the shoreline is. If beaches could reshape themselves during a tidal cycle, our intuition about the relationship between shoreline and tidal height might be quite different.

Slow and rapid cycles are defined relative to a natural time constant for the basin (e.g., the "equilibrium time" defined in Paola et al. [1992]). Angevine's (1989) analysis of the Pitman model also suggested that the shoreline response to base-level change would be relatively weak for long-period base-level cycles. In contrast, rapid (short-period) base-level cycles were predicted to produce strong shoreline response directly in phase with base level, just as our intuition tells us. But it was the prediction that shoreline could get out of phase with base level that was most interesting, because it is so counterintuitive and because it has profound implications for inferring sea level stratigraphically. Unfortunately, Pitman's theory has proved difficult to test in the field (e.g., Miller et al., 1985, 1993). Could we find evidence for it experimentally?

We fed a mixture of water and sediment into one end of the basin (Fig. 4). The sediment was a 50:50 mixture (by volume) of quartz and coal sand, proxies for coarse and fine-grained clastics, respectively. Absolute base level was independently controlled from the opposite end of the basin. Subsidence was induced in a bowl-shaped pattern with a maximum in the center of the basin. Constant rates of water and sediment discharge and of subsidence were maintained throughout the run. The sediment discharge was set to balance the total rate of volumetric accommodation in the basin. We imposed two cycles of base-level change separated by periods of steady-state deposition (Fig. 5) to allow for relaxation of transient effects. The slow cycle had a total duration of 30 h, nearly 10 times the estimated equilibrium time of 3.4 h. The rapid cycle had a duration of 2 h.

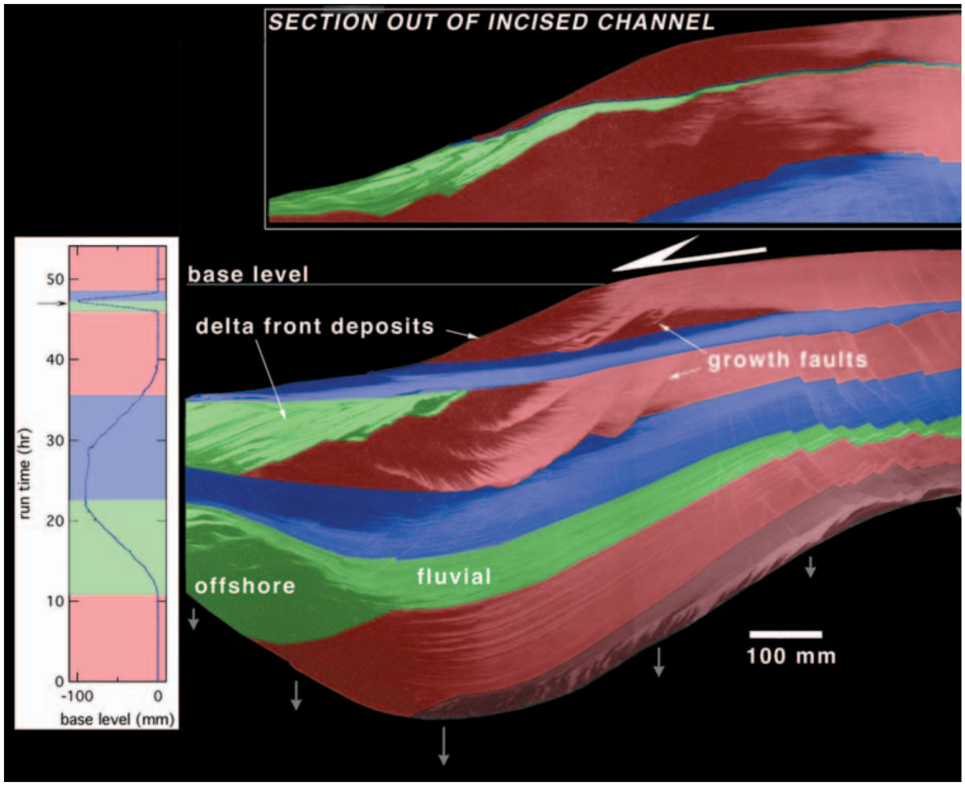

Figure 5. Flow-parallel (dip) panel of experimental deposit from base-level run. Color bands allow correlation of deposit with base-level curve to left. Arrow in base-level curve shows time of images in Figure 4. Spatial subsidence pattern is indicated by basement position at bottom of panel. Darker material is coal sand; lighter material is quartz sand. Inset shows upper part of stratigraphy from an area outside incised valley that formed during rapid base-level cycle. Locations of sections are shown in Figure 4.

What Happened?

Although some degree of incision occurred during both base-level falls, incision and valley formation were much

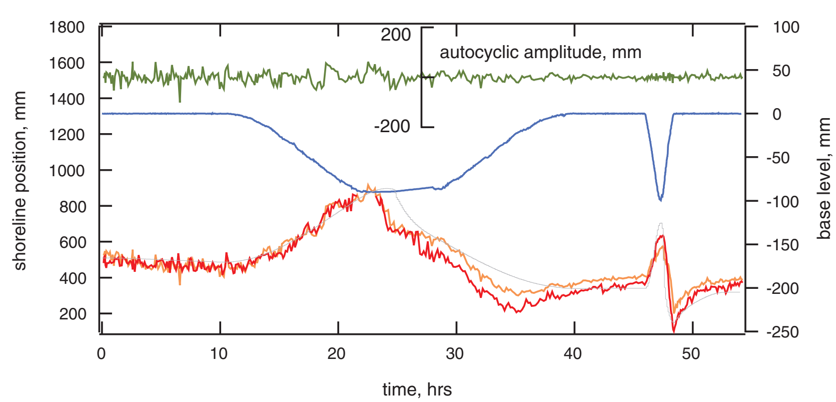

Figure 6. Shoreline position (red and orange) and base level (blue) during base-level run. Red shoreline curve was taken within incised valley, orange one just outside it. Gray curve is shoreline predicted with theoretical model of Swenson et al. (2000). Green curve at top shows high-frequency (autocyclic) variation in shoreline position. Classic "shazam" zigzag pattern that autocyclic variation produces in stratigraphy is clearly visible in Figures 1 and 5.

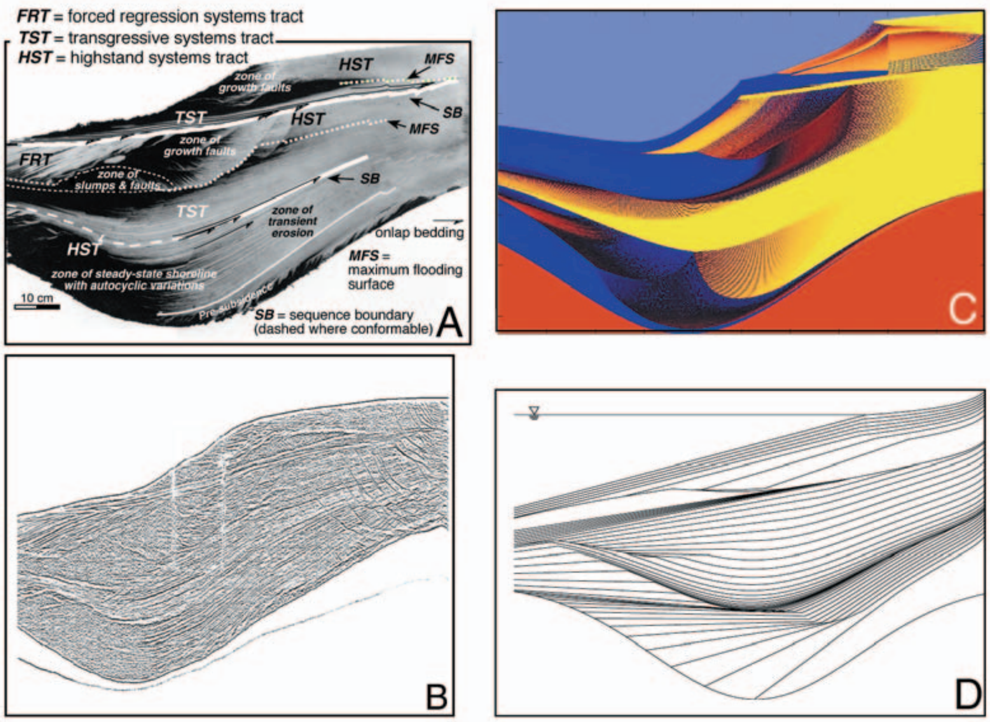

Figure 7. Various ways of using eXperimental EarthScape (XES) experimental deposits. **A.** Sequence-stratigraphic analysis (Heller et al., 2001). **B.** Synthetic seismic panel. **C.** Predicted stratigraphy (grain size, warmer colors are larger) using the SEDFLUX model (Syvitski and Hutton, 2001). **D.** Predicted stratigraphy (time lines) using model of Swenson et al. (2000).

stronger for the rapid base-level fall (Fig. 4). The rapid fall was characterized by initial exposure of the delta front and development of a narrow incised valley many times deeper than the pre-incision flow depth that extended headward along the length of the basin. The stratigraphic signature of the base-level cycle was quite different for sections inside and outside the incised valley (Fig. 5). Within the valley, the fall resulted in an unconformable sequence boundary that is easy to identify in stratigraphic cross sections. Significant valley filling, and resultant onlap, did not commence until the beginning of the subsequent base-level rise. During the rise, erosion of the valley walls significantly widened the incised valley. As a result, the cross-valley profile as recorded in the stratigraphy was substantially wider and more gently sloping than the actual valley at the end of the base-level fall. Although exaggerated because the sand in the experiment was relatively erodible, we believe this to be a general effect: Incised valley profiles will generally be composites that reflect both incision and widening by lateral erosion as the valley is filled. Areas outside the incised valley received no sediment and experienced the base-level cycle as a hiatus. In the field, these interfluve areas would show features such as soil development associated with a period of prolonged exposure and nondeposition.

In contrast, the slow base-level cycle produced a nearly symmetric regressive and transgressive stratigraphic record. Most of the base-level fall was accompanied by deposition and thus did not produce an unconformity that, in sequence stratigraphic parlance, would mark a sequence boundary. The basin fill developed during the slow cycle was also much more laterally continuous than for the rapid cycle. Overall, the rapid cycle had far greater impact on the distribution of sediment storage, the 3-dimensional geometry of fluvial and submarine transport systems, and the development of clearly segregated regressive and transgressive facies tracts.

Test of Theoretical Predictions

It had been predicted that shoreline response to the slow cycle would be attenuated and out of phase. First, it is clear from Figure 6 that in no sense was the slow-cycle response attenuated; the slow-cycle shoreline excursion was 417 mm, 2.1 times that for the rapid cycle. The shoreline remained closely locked to base level during the base-level fall, but deviated somewhat after that. Transgression began immediately upon stabilization of base level, and the point of maximum transgression occurred during the rise, as the rate of rise began to decrease (Fig. 6). There was also a noticeable overshoot in the transgression: the point of maximum transgression is landward by ~32% of the total shoreline excursion distance of the initial shoreline location. The same phenomenon occurred at the end of the rapid cycle, but the overshoot is proportionally much larger: 133% of the total excursion distance. Otherwise, the rapid-cycle–shoreline behavior closely tracked base level, as all existing theories would predict. On the whole, the experiment does not offer strong support for the idea that shoreline follows rate of change of base level rather than base level itself for long-period cycles. Theoretical analysis of the shoreline-response problem by Swenson et al. (2000) suggests that our failure to observe the predicted shoreline behavior cannot be explained by differences between the experimental geometry and the assumptions of Pitman (1978). Rather, it appears that Pitman's result is closely linked to his assumption of a constant sedimentation rate at the shoreline, a condition that is not satisfied in the experiments or, generally speaking, in nature.

Internally Generated Phenomena

These fell into two categories. Growth faults evolved before and during the rapid fall, trapping sediment at the fault breakaway zone (Fig. 5). The continuous increase of dip rotation with fault offset shows how steady the motion on the faults was. It is particularly striking that at no time prior to the rapid base-level cycle was there any surface manifestation of the presence of the faults. The only visible fault motion during the experiment was a collapse of the delta front during the rapid fall (Fig. 4B), with an offset of no more than 20 mm.

The second internally generated phenomenon was high-frequency fluctuation in shoreline position (Fig. 6) associated with shifting of the threads of maximum flow in the fluvial system. Such autocyclic variation in shoreline position will not surprise anyone familiar with the stratigraphic record, but it is interesting that it is prominent in such a small-scale experiment. The amplitude of the autocyclic variation does not change significantly during the slow base-level cycle, but it diminishes measurably after that. Persistent removal of sediment by subsidence on localized growth faults may account for this during the steady-state interval before the rapid base-level fall. During the rapid fall, autocyclic variation is suppressed as incision focuses and trains the flow. While the fluvial system was less constrained during the rise, it was still sufficiently confined to inhibit fully developed lateral shifting.

TESTING OF STRATIGRAPHIC MODELS

The main goal of these experiments is to provide data to test and refine stratigraphic models and other interpretive tools. We are approaching this from several directions. A sequence-stratigraphic analysis of the section is shown in Figure 7A. For comparison of the experimental results with seismic-stratigraphic interpretation techniques, we use the model stratigraphy to produce synthetic seismic cross sections. The methods for doing this are explained in Pratson and Gouveia (2002); the results are shown in Figure 7B. In addition, the experimental results can be compared directly with existing theory. Apart from specific hypotheses like out-of-phase shoreline behavior, we can also compare the experimental results directly with theoretical stratigraphy, as illustrated in Figures 6, 7C, and 7D. In this case, the two models shown do a reasonable job, although there are problem areas, such as the modest shoreline overshoot at the end of the first cycle, that are not predicted well.

Of course, one of the best and simplest things to do with experimental stratigraphy is to deduce cause from stratigraphic pattern (Fig. 1). It's a very hard problem, and in our experience, the great temptation is to make the causes more complicated than necessary. And this was a relatively simple experiment! If nothing else, the difficulty of analyzing sections such as Figure 1 should remind us to treat the more difficult and underconstrained natural cases with respect, along with a generous supply of Ockham's famous razors.

COMMUNITY INVOLVEMENT IN XES

One of our main motivations in writing this article is to get the word out that the XES basin, and associated facilities at St. Anthony Falls Laboratory, are by no means a closed shop. Insofar as it is possible, we would like St. Anthony Falls Laboratory to be a resource for the earth sciences community. We are continuing to work on making the experimental results available via the Internet and/or CD-ROM. We also invite you to provide input and suggestions for future experiments. We are, of course, especially interested in input based on field experience and in case studies we can use for comparison with experimental results. Experiments on small space and time scales can never replace careful field study of real examples. On the other hand, interpreting natural stratigraphy is difficult enough so that we must take advantage of every opportunity for insight. Experimental stratigraphy is one more Rosetta stone that will help us decipher the language of sediments.

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REFERENCES CITED

Allen, J.R.L., 1984, Sedimentary structures, their character and physical basis: Amsterdam, Netherlands, Elsevier, 1206 p.

Angevine, C.L., 1989, Relationship of eustatic oscillations to regressions and transgressions on passive continental margins, *in* Price, R.A., ed., Origin and evolution of sedimentary basins and their energy and mineral resources: Washington, D.C., American Geophysical Union, p. 29–35.

Cross, T.A., 1990, Quantitative dynamic stratigraphy: Englewood Cliffs, New Jersey, Prentice Hall, p. 615.

Harbaugh, J., Watney, L., Rankey, G., Slingerland, R., Goldstein, R., and Franseen, E., 1999, Numerical experiments in stratigraphy: SEPM (Society for Sedimentary Geology) Special Publication 62, 362 p.

Heller, P.L., Burns, B., and Marzo, M., 1993, Stratigraphic solution sets for determining the roles of sediment supply, subsidence, and sea level on transgressions and regressions: Geology, v. 21, p. 747–750.

Heller, P.L., Paola, C., Hwang, I.-G., John, B., and Steel, R., 2001, Geomorphology and sequence stratigraphy due to slow and rapid base-level changes in an experimental subsiding Basin (XES 96-1): American Association of Petroleum Geologists Bulletin, v.85, p. 817–838.

Jordan, T.E., and Flemings, P.B., 1991, Large-scale stratigraphic architecture, eustatic variation, and unsteady tectonism: A theoretical evaluation: Journal of Geophysical Research, v. 96, p. 6681–6699.

Lessenger, M.A., and Cross, T.A., 1996, An inverse stratigraphic simulation model—Is stratigraphic inversion possible?: Energy Exploration & Exploitation, v. 14, p. 627–637.

Middleton, G.V., and Southard, J.B., 1984, Mechanics of sediment movement, *in* Short Course 3: Providence, Rhode Island, Society of Economic Paleontologists and Mineralogists Eastern Section Meeting, p. 401.

Miller, K.G., Mountain, G.S., and Tucholke, B.E., 1985, Oligocene glacio-eustasy and erosion on the margins of the North Atlantic: Geology, v. 13, p. 10–13.

Miller, K.G., Thompson, P.R., and Kent, D.V., 1993, Integrated Late Eocene—Oligocene stratigraphy of the Alabama coastal plain: Correlation of hiatuses and stratal surfaces to glacioeustatic lowerings: Paleoceanography, v. 8, p. 313–331.

Paola, C., 2000, Quantitative models of sedimentary basin filling: Sedimentology, v. 47 (suppl. 1), p. 121–178.

Paola, C., Heller, P.L., and Angevine, C.L., 1992, The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory: Basin Research, v. 4, p. 73–90.

Pitman, W.C., 1978, Relationship between eustasy and stratigraphic sequences on passive margins: Geological Society of America Bulletin, v. 89, p. 1389–1403.

Pratson, L., and Gouveia, W., 2002, Seismic simulations of experimental strata: American Association of Petroleum Geologists Bulletin (in press).

Rice, C.T., Wilson, B.N., and Appleman, M., 1988, Soil topography measurements using image processing techniques: Computers and Electronics in Agriculture, v. 3, p. 97–107.

Slingerland, R., Harbaugh, J.W., and Furlong, K., 1994, Simulating clastic sedimentary basins: Englewood Cliffs, New Jersey, PTR Prentice Hall, 211 p.

Sloss, L.L., 1962, Stratigraphic models in exploration: Journal of Sedimentary Petrology, v. 32, p. 415–422.

Swenson, J.B., Voller, V.R., Paola, C., Parker, G., and Marr, J.G., 2000, Fluvio-deltaic sedimentation: A generalized Stefan problem: European Journal of Applied Mathematics, v. 11, p. 433–452.

Syvitski, J.P.M., and Hutton, E.H., 2001, 2D SEDFLUX 1.0C: An advanced process-response numerical model for the fill of marine sedimentary basins: Computers & Geosciences (in press).

Wilson, B.N., and Rice, C.R., 1990, An indoor soil erosion research facility: Journal of Soil and Water Conservation, v. 45, p. 645–648.

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