Storage thresholds for relative sea-level signals in the stratigraphic record

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ABSTRACT

The tug of relative sea level (RSL), set by climate and tectonics, is widely viewed as the most important boundary condition for the evolution of deltas. However, the range of amplitudes and periodicities of RSL cycles stored in deltaic stratigraphy remains unknown. Experimental results presented here suggest that extraction of RSL cycles from the physical stratigraphic record requires their magnitudes and periodicities to be greater than the spatial and temporal scales of the internal (autogenic) dynamics of deltas. These results predict stratigraphic storage of information pertaining to RSL cycles during icehouse Earth conditions. However, these thresholds commonly overlap with the magnitudes and periodicities of RSL cycles for major river deltas during greenhouse Earth conditions, suggesting stratigraphic signal shredding. This theory suggests quantitative limits on the range of paleo-RSL information that can be extracted from stratigraphy, which could aid the prediction of deltaic response to climate change.

INTRODUCTION

Since the work of Gilbert (1890), a plethora of studies have examined how relative sea level (RSL) change influences the production of stratigraphic surfaces (e.g., sequence stratigraphy) and stratigraphic patterns (e.g., alluvial architecture) (Vail et al., 1977; Van Wagoner et al., 1990; Blum and Tornqvist, 2000; Martin et al., 2009; Karamitopoulos et al., 2014). This has led many to argue that RSL change represents the most important boundary condition (allogenic forcing) affecting deltas and is the primary control on stratigraphic architecture. RSL change, defined as the sum of local absolute sea-level rise and subsidence rates, is driven by a range of processes. These span small-magnitude and short-period cycles (millimeters of change over days) driven by atmospheric dynamics to the large-magnitude and long-period cycles (hundreds of meters of change over hundreds of millions of years) resulting from plate tectonics (Miller et al., 2005). Are all of these RSL cycles stored in stratigraphy, and if not, what attributes must a cycle have for storage to occur? Answering this question requires development of quantitative theory and rigorous methods to test proposed thresholds, which is the focus of this work.

While much work highlights the response of deltas to allogenic forcings, we have less theory for prediction of autogenic dynamics and their stratigraphic products (Hoyal and Sheets, 2009). A suite of recent numerical experiments do examine the deposits of autogenic processes (Dalman et al., 2015) and how they interact with Quaternary-scale RSL cycles (Karamitopoulos et al., 2014), but at present we lack a quantitative framework to define how other cycle periods and magnitudes interact with autogenic processes. Results from a recent study by Jerolmack and Paola (2010) suggest that autogenic processes can alter, or in some cases shred, sediment flux signals during their propagation from source to sink. By shredding, Jerolmack and Paola mean a smearing of an input signal over a range of time scales such that the signal is not detectable at the outlet of a system. The Jerolmack and Paola theory suggests that when the scale of an input signal is less than the scale of a system's autogenic processes, these signals are prone to shredding. While the Jerolmack and Paola theory makes important quantitative predictions, it does not define conditions necessary for stratigraphic storage, as those researchers were primarily interested in sediment flux time series. Motivated by Jerolmack and Paola (2010), we aim to define stratigraphic storage thresholds for RSL change, in contrast to the transport thresholds of Jerolmack and Paola.

HYPOTHESIZED STORAGE THRESHOLDS

We hypothesize that the upper spatial and temporal limits of autogenic processes influence the storage of RSL cycle information in stratigraphy. We define the upper spatial limit of autogenic processes as the depth of the largest channels, H_c, because post-avulsion incision results in the greatest elevation changes. Next, we define the upper temporal limit of autogenic processes using the compensation time scale, T_c, which scales with the time for the shape of a deposit to solely be influenced by boundary conditions (i.e., subsidence patterns) (Wang et al., 2011). This time scale can be estimated as $H_c/\overline{r}$, where $\overline{r}$ equals the long-term aggradation rate. Thought of in another way, T_c represents the time necessary for a particle deposited at Earth's surface to be buried to a depth that is no longer susceptible to remobilization from autogenic incision events.

We define two non-dimensional numbers that compare the upper spatial and temporal scales of deltaic autogenic processes to the magnitude and periodicity of RSL cycles:

$$H^* = \frac{R_{\mathrm{RSL}}}{H_{\mathrm{C}}}, \tag{1A}$$

$$T^* = \frac{T_{\mathrm{RSL}}}{T_{\mathrm{C}}}, \tag{1B}$$

where R_{RSL} is the range of a RSL cycle (i.e., difference in elevation from cycle peak to trough) and T_{RSL} is the period of a RSL cycle. We hypothesize that deltas experiencing RSL cycles characterized by H^* and/or T^* >>1 will store RSL cycle information in stratigraphy. However, information associated with RSL in settings with both H^* and T^* <<1 will be shredded.

EXPERIMENTAL METHODS

We investigate storage of RSL cycles in stratigraphy using reduced-scale physical experiments that allow stratigraphic products to be directly linked to surface dynamics (Hoyal and Sheets, 2009; Martin et al., 2009). Experiments were conducted in the Tulane University (New Orleans, USA) Delta Basin, which is 4.2 m long, 2.8 m wide, and 0.65 m deep. First, we performed a control experiment to characterize the range of deltaic autogenic time and space scales (Fig. 1A). This experiment had constant water supply ($Q_{\mathrm{w,input}} = 1.7 \times 10^{-4}$ m^3/s), sediment supply ($Q_{\mathrm{s,input}} = 3.9 \times 10^{-4}$ kg/s), and a constant sea-level rise rate ($\overline{r}_{\mathrm{SL}} = 0.25$ mm/hr) which promoted the deposition of ~18 channel depths of stratigraphy. The constant $\overline{r}_{\mathrm{SL}}$ mimics a spatially uniform relative subsidence pattern. Long-term sea-level rise rate was set to balance accommodation creation and input sediment supply. The input sediment mixture was designed to mimic earlier experimental work (Hoyal and Sheets, 2009) and had a broad grain-size distribution, ranging from 1 to 1000 μm with a mean of 67 μm, and included a small amount of a polymer to enhance sediment cohesion. While the majority of the sediment was white in color, a fraction of the coarse tail of the distribution was replaced with dyed sediment of near equivalent size to aid visualization of stratigraphic architecture. The input water was dyed with a food coloring to aid characterization of morphodynamics.

Topography was monitored once an hour with a laser scanner, resulting in digital elevation models with a 5 mm grid in the down-basin and cross-basin directions, respectively. The high temporal and spatial data resolutions allow us to generate synthetic stratigraphic panels through the stack-

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ing of sequential scans, clipped for erosion (Martin et al., 2009). Finally, we collected digital images of the active delta top every 15 min.

We test the validity of our RSL cycle stratigraphic storage thresholds using experiments that share the same boundary conditions as the control experiment, with the exception of RSL cycles that vary in magnitude and periodicity between experiments. Here we focus on three experiments with cycles characterized by either (1) $T^* > 1$, but $H^* < 1$; (2) $H^* > 1$, but $T^* < 1$; or (3) H^* and $T^* < 1$.

RESULTS

Starting with the surface dynamics, we search for the signature of RSL cycles in time series characterizing channel mobility. Most theory suggests a reduction of channel mobility during falling RSL associated with topset incision (Van Wagoner et al., 1990). We use changes in the intensity of deltaic surface color as a proxy for the magnitude of channel mobility in the experiments. Intervals with high channel mobility occur when significant areas of the delta switch from being covered by dyed flow to being covered by dry white sediment or vice versa. We use the three color bands (RGB; red, green, blue) captured in digital photographs of the active deltaic surface captured once an hour to characterize channel mobility along a proximal transect (Figs. 1A and 1B). For intervals when the flow was dyed blue, dye intensity is calculated as the magnitude of B-R-G, while dye intensity is calculated as R-B-G when the flow was dyed red (Fig. 1C). In addition to allowing quantification of surface dynamics, channel mobility influences field-scale stratigraphy as it is inversely correlated to paleosol development. We then generate time series of the mean value of the absolute change in dye intensity along the transect for each measurement hour (Fig. 1D), which are used to generate power spectra. Next, we produce confidence bands for the identification of statistically significant periodicities by performing a χ^2 test on the power spectra of our control experiment. We find statistically significant peaks at the periodicity of imposed RSL cycles in experiments with H^* or $T^* > 1$. No peak is observed in the experiment where H^* and T^* were both <1 (Figs. 1E–1H).

Next we search for the signature of imposed RSL cycles in the experimental stratigraphy. We generate time series of mean deposition rates, $\overline{\partial\eta/\partial t}$, where η is a topographic elevation and t represents time, from synthetic stratigraphic panels oriented perpendicular to the mean flow direction (Figs. 2A–2H). Similar to our analysis of channel mobility, we find statistically significant peaks at the periodicity of imposed RSL cycles in the stratigraphy of experiments with H^* and/or T^* values ≥1. However, no statistically significant peak is observed in the stratigraphy of the experiment where H^* and T^* <1 (Figs. 2I–2L), a result consistent with our primary hypothesis.

As the signature of RSL cycles has been linked to many stratigraphic attributes, we perform additional analysis. These include time series analysis of the second moment of deposition rates, similar in spirit to the regional stratigraphic variability defined by Karamitopoulos et al. (2014). Results of this test are consistent with our analysis of channel mobility and mean deposition rates. Analysis of the facies architecture also suggest no significant differences between our control and low-H^* low-T^* experiments, while significant differences in the width-to-depth ratio of channel bodies and deposit sand fraction exists between the control and non-shredded experiments. Additional experiments were performed which further explore the T^* versus H^* phase space and support the above findings (for further information on these tests, see the GSA Data Repository[1]).

To explore the significance of the experimental results, we compile a database of H_c and T_c for field-scale deltaic depocenters (Fig. 3). Calculation of T_c is done with $\bar{r}$ values measured over time scales in excess of 100 k.y. Jerolmack and Sadler (2007) showed that for deltas, this time scale is necessary for persistence in deposition rates as a function of measurement interval to be achieved. These values are compared to Milankovitch-scale RSL cycles in the middle Pleistocene to the present when eccentricity cycles (~100 k.y.) resulted in RSL changes of ~100 m. We also compare our database to late Miocene conditions when obliquity cycles (~40 k.y.) resulted in RSL changes with ranges of 10–35 m. Our results show that R_{RSL} of middle Pleistocene to present cycles exceeds H_c of almost all compiled systems, while the T_{RSL} of eccentricity cycles is not consistently less than or greater

[1]GSA Data Repository item 2016054, additional signal preservation/shredding tests, expanded experimental methods, details on major river delta compilation, and movies of experiments, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

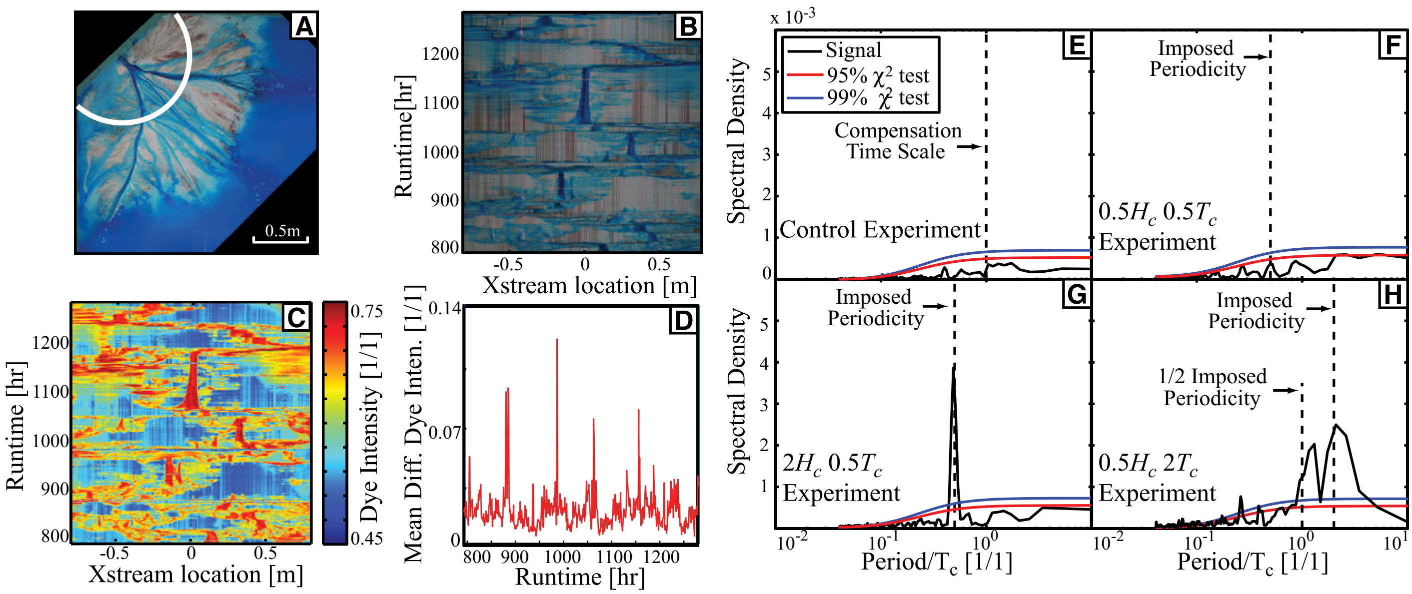

Figure 1. Analysis of surface morphodynamics along a proximal transect, and the process involved in generating morphodynamic time series. A: Photograph of active delta top at run-hour 627. Solid white line represents transect defined by 0.6 m radius from source. B: RGB (red, green, blue) color values are extracted from images and compiled to generate time series of visible color along transect. C: Matrix of visible color is converted to dye intensity normalized by the maximum possible dye intensity. D: Time series of mean difference in dye intensity between successive measurements generated and used as morphodynamic time series. E–H: Morphodynamic time-series power spectra and χ^2 confidence limits, where H_c and T_c are the depth of the largest channels and the compensation time scale, respectively.

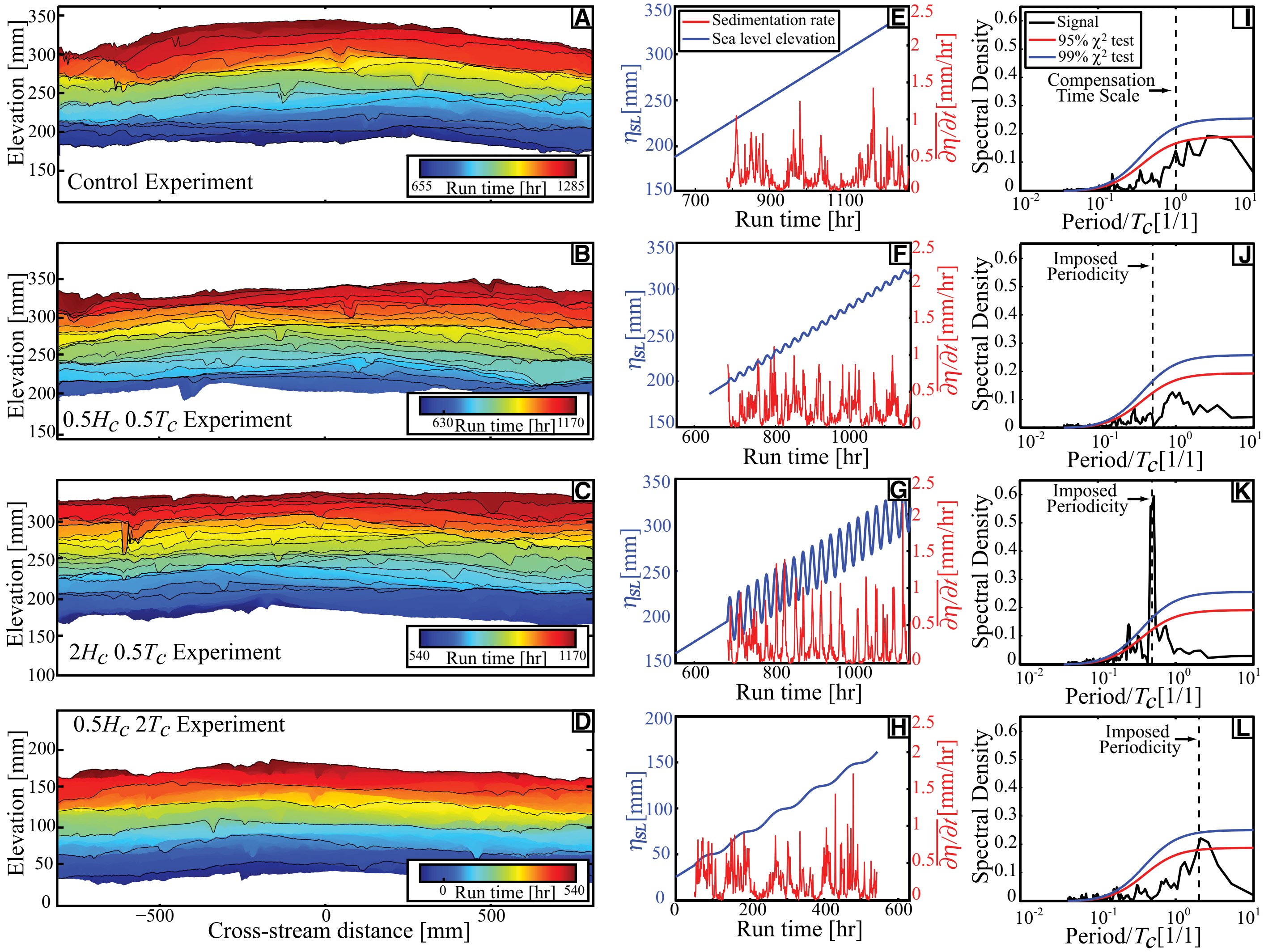

Figure 2. Analysis of mean deposition rate calculated from preserved experimental stratigraphy. A–D: Synthetic stratigraphy along a proximal transect with location illustrated by solid line in Figure 1A. Solid black lines represent time horizons separated by one T_c (A) or demarcating the start of each relative sea level (RSL) cycle (B–D), where H_c and T_c are the depth of the largest channels and the compensation time scale, respectively. E–H: Sea level (η_{SL}) and mean deposition rate time series. I–L: Power spectra of mean deposition rate time series and χ^2 confidence limits. Complimentary analysis performed at 1.1 m from source is provided in Data Repository (see footnote 1).

than our estimates of T_c. Exploring late Miocene conditions, we make the following observations: (1) the R_{RSL} and T_{RSL} of RSL cycles during this period are in excess to the autogenic scales of smaller systems like the Rhine Delta (Netherlands) or Rio Grande Delta (southwestern USA), (2) large systems, such as the Ganges-Brahmaputra Delta (India) and the Mississippi Delta (southern USA), have autogenic spatial and temporal scales greater than late Miocene RSL cycles, and (3) the autogenic scales of the majority of systems in our compilation lie close to scales of late Miocene RSL cycles.

DISCUSSION

To illustrate the importance of our proposed thresholds, we use our database of channel depths and compensation time scales to make predictions of RSL signal storage in icehouse and greenhouse Earth conditions (Miller et al., 2005). We use icehouse Earth to refer to periods with waxing and waning of continental-scale ice sheets, while greenhouse Earth refers to periods with no continental-scale glaciers and thus small-magnitude Milankovitch-forced RSL cycles. We use attributes of RSL cycles in the middle Pleistocene to the present to examine icehouse Earth conditions and attributes of late Miocene RSL cycles to represent greenhouse Earth conditions. While the late Miocene did have ice sheets, we use it due to our high-precision knowledge of small-magnitude sea-level fluctuations during this period, similar to greenhouse Earth RSL cycles.

Starting with icehouse Earth conditions, we note that the range of these RSL cycles far exceed the depth of almost all channels explored, suggesting signal storage. This finding is supported by the vast number of geomorphic and stratigraphic observations (Blum and Tornqvist, 2000) linked to recent RSL change. Exploring greenhouse Earth conditions, we predict signal storage in small systems, such as the Rhine or Rio Grande Deltas. However, we predict that these same cycles are not preserved in the stratigraphy of larger deltas, like the Ganges-Brahmaputra and Mississippi Deltas, due to their large autogenic space and time scales. Interestingly, the majority of systems explored lie close to the predicted storage thresholds, suggesting difficult-to-extract but present stratigraphic signatures. We acknowledge that some change in channel depths has occurred since the late Miocene due to changing boundary conditions. These changes, though, are unlikely to influence our general result: autogenic processes likely make it difficult, if not impossible, to extract the stratigraphic signature of Milankovitch-scale RSL fluctuations from medium to large deltaic deposits of greenhouse Earth conditions. This

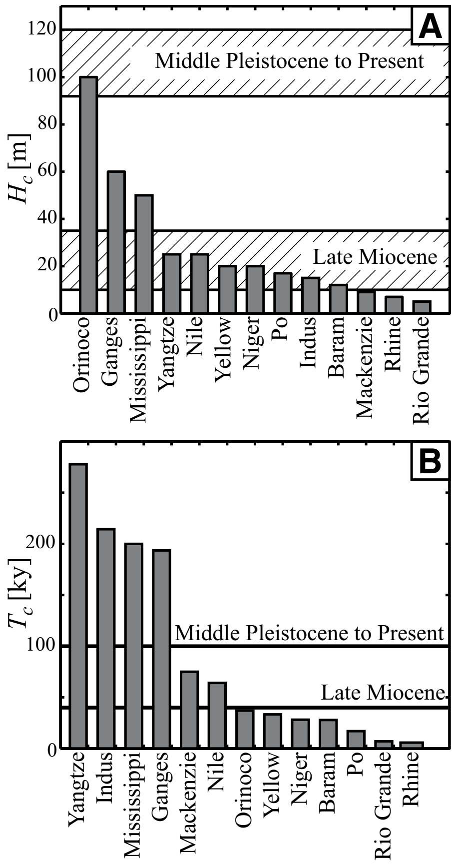

Figure 3. Comparison of autogenic spatial (A) and temporal (B) scales for major river systems to paleo-relative sea level (RSL) cycle magnitudes and periodicities, respectively. Hashed regions in compilation of the maximum depth of river channels, H_c, (A) define the range of middle Pleistocene to present and late Miocene RSL cycles. Solid horizontal lines in compensation time scale, T_c, compilation (B) define dominant middle Pleistocene to present eccentricity-driven and dominant late Miocene obliquity-driven periodicity in sea level. Geographic locations of river deltas are provided in the Data Repository (see footnote 1).

examination suggests a fundamental property of the stratigraphic record and its generation: that below critical thresholds, autogenic and allogenic products cannot be separated due to a smearing of forcing conditions by the stratigraphic filter. This result is similar in spirit to thresholds proposed in the routing of forcing conditions via fluid turbulence (von der Heydt et al., 2003) and sediment transport (Jerolmack and Paola, 2010).

While we performed several tests on the experimental physical stratigraphy, additional attributes of the stratigraphy can still be examined. However, to provide a rigorous test of RSL storage in stratigraphy, a test must include a comparison to a comparable system evolving in the absence of changing boundary conditions. As discussed previously (Van Wagoner et al., 1990; Dalman et al., 2015), autogenics—for example, a cycle of channel extension, avulsion, abandonment, and later reoccupation—produce architecture with inherent scales which must be differentiated from allogenic product scales. This should also hold for analysis of trends in biostratigraphy, chemostratigraphy, and/or magnetostratigraphy.

Further, our results emphasize the need to consider system dynamics in addition to geometry when developing stratigraphic theory. For example, while steep delta foresets are exposed during RSL fall in our shredded experiment, they do not result in incisional confinement greater than observed in our control experiment. Similar to theory proposed by Nijhuis et al. (2015), we suggest that this occurs due to a slow morphodynamic response rate relative to the RSL fall rate.

While autogenic processes might limit the range of paleo-environmental information stored in stratigraphy, these thresholds can also be viewed in a positive light. Our results suggest strong statistical similarities between stratigraphy constructed solely by autogenic processes and stratigraphy constructed in the presence of shredded RSL cycles. Thus it might not be necessary for individuals performing stratigraphic prediction to include these changing boundary conditions in forward deltaic-evolution models. Simply modeling the internal dynamics should produce statistically reasonable predictions.

SUMMARY

This study suggests quantitative limits to the fidelity of the stratigraphic record set by the space and time scales of autogenic processes. The thresholds proposed here likely limit our ability to invert this record for critical paleo-environmental information. While we focus on resolving paleo-RSL change in deltaic stratigraphy, similar stratigraphic thresholds, set by autogenic process scales, likely exist in other depositional environments and for other classes of signals (i.e., tectonics and upstream climatic forcings).

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REFERENCES CITED

Blum, M.D., and Tornqvist, T.E., 2000, Fluvial responses to climate and sea-level change: A review and look forward: Sedimentology, v. 47, p. 2–48, doi:10.1046/j.1365-3091.2000.00008.x.

Dalman, R., Weltje, G.J., and Karamitopoulos, P., 2015, High-resolution sequence stratigraphy of fluvio–deltaic systems: Prospects of system-wide chronostratigraphic correlation: Earth and Planetary Science Letters, v. 412, p. 10–17, doi:10.1016/j.epsl.2014.12.030.

Gilbert, G. K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Hoyal, D.C.J.D., and Sheets, B.A., 2009, Morphodynamic evolution of experimental cohesive deltas: Journal of Geophysical Research, v. 114, F02009, doi:10.1029/2007JF000882.

Jerolmack, D.J., and Paola, C., 2010, Shredding of environmental signals by sediment transport: Geophysical Research Letters, v. 37, L19401, doi:10.1029/2010GL044638.

Jerolmack, D.J., and Sadler, P., 2007, Transience and persistence in the depositional record of continental margins: Journal of Geophysical Research, v. 112, F03S13, doi:10.1029/2006JF000555.

Karamitopoulos, P., Weltje, G.J., and Dalman, R., 2014, Allogenic controls on autogenic variability in fluvio-deltaic systems: Inferences from analysis of synthetic stratigraphy: Basin Research, v. 26, p. 767–779, doi:10.1111/bre.12065.

Martin, J., Paola, C., Abreu, V., Neal, J., and Sheets, B., 2009, Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level: American Association of Petroleum Geologists Bulletin, v. 93, p. 503–533, doi:10.1306/12110808057.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005, The Phanerozoic record of global sea-level change: Science, v. 310, p. 1293–1298, doi:10.1126/science.1116412.

Nijhuis, A., Edmonds, D., Caldwell, R., Cederberg, J., Slingerland, R., Best, J., Parsons, D., and Robinson, R., 2015, Fluvio-deltaic avulsions during relative sea-level fall: Geology, v. 43, p. 719–722, doi:10.1130/G36788.1.

Vail, P.R., Mitchum, R.M., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea-level: Part 3. Relative changes of sea level from coastal onlap, *in* Payton, C. E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 63–82.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Methods in Exploration 7, 55 p.

von der Heydt, A., Grossmann, S., and Lohse, D., 2003, Response maxima in modulated turbulence: II. Numerical simulations: Physical Review E: Statistical, Nonlinear, and Soft Matter Physics, v. 68, 066302, doi:10.1103/PhysRevE.68.066302.

Wang, Y., Straub, K.M., and Hajek, E.A., 2011, Scale-dependent compensational stacking: An estimate of autogenic time scales in channelized sedimentary deposits: Geology, v. 39, p. 811–814, doi:10.1130/G32068.1.

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