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Key Points:
- Our work predicts which climatic, tectonic, and anthropogenic signals are potentially stored in stratigraphy
- We present theory that predicts the minimum magnitude for stratigraphic storage of sediment flux signals is a function of signal duration
- This threshold is scaled to the magnitude and time scales of autogenic processes and is validated by physical delta experiments

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A Stratigraphic Framework for the Preservation and Shredding of Environmental Signals

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Abstract The stratigraphic record contains unique information about past landscapes and environmental change. Whether landscapes faithfully transmit signals of environmental change to stratigraphy is unknown because autogenic processes, such as river avulsion, can obscure signals prior to long-term stratigraphic storage. We develop a theoretical framework that predicts when a sediment flux signal will be transferred from the landscape to stratigraphy. This threshold magnitude is a function of signal duration. The magnitude is set by the maximum rate of autogenic volume change of the landscape, which decreases with increasing time window. Physical delta experiments, specifically designed to test our theory, demonstrate that only sediment supply signals with a magnitude greater than the threshold are stored in stratigraphy, supporting our theory. This framework allows us to assess the fidelity of the stratigraphic record to archive past signals of environmental change and predict the short- and long-term impact of current anthropogenic forcing on landscapes.

Plain Language Summary We generate and validate a theory that predicts by how much sediment supply needs to vary in order to modify a landscape and store that signal in sedimentary deposits accumulating in the landscape. This theory predicts which ancient climatic or tectonic signals we can potentially reconstruct from geological data and whether human activity leaves a trace in the landscape that will be preserved in the geological record.

1. Introduction

The stratigraphic record is a unique archive of past environmental change (Ager, 1973; Allen, 2008a), but this database is still underutilized because of difficulties distinguishing controls on stratigraphic architecture. Stratigraphy is traditionally interpreted in terms of a volumetric balance between the rate of sediment supplied to a sedimentary basin and the rate of accommodation generated by tectonic subsidence and eustatic sea level change. Within this framework, changes in climate and/or tectonics can alter the production and flux of sediment through sediment routing systems (Allen, 2017). These “allogenic” supply signals then propagate to a sedimentary basin and influence basin-wide deposition rates (Armitage et al., 2011; Duller et al., 2010; Hampson et al., 2014; Overeem et al., 2001; Paola et al., 1992) and the structure of stratigraphic sections (Allen et al., 2013; Duller et al., 2012; Scotchman et al., 2015). Stratigraphic patterns linked to changes in this volumetric balance operate at time scales $>10^6$ years (Armitage et al., 2011; Duller et al., 2010; Paola et al., 1992). At time scales $<10^6$ years it is often difficult, but sometimes possible (Blum et al., 2018), to distinguish allogenic stratigraphic structure from structure generated by processes internal to a sediment routing system, which occur over similar time scales (i.e., autogenic processes; Li et al., 2016; Hajek & Straub, 2017).

Autogenic processes constantly reorganize the transport system, resulting in local sediment storage, bypass, and release (SSBR; Paola & Foufoula-Georgiou, 2001; Kim & Jerolmack, 2008; Paola, 2016), which causes “noise” in landscape structure (Jerolmack, 2011), the effect of which is to potentially “shred” (sensu Jerolmack & Paola, 2010) allogenic signals within landscapes prior to stratigraphic transfer. Matters are complicated further when we consider not only the horizontal propagation of allogenic signals across the surface, as described above, but also the vertical propagation through the Earth's surface and into the stratigraphic record (Foreman & Straub, 2017; Li et al., 2016). This very real “Earth surface barrier” has inhibited our ability to accurately glean past allogenic information from the stratigraphic record.

A clear and natural avenue to a generic solution set that can be used to discriminate between allogenic and autogenic stratigraphic structure is to bridge the gap that exists between Earth-surface morphodynamics and

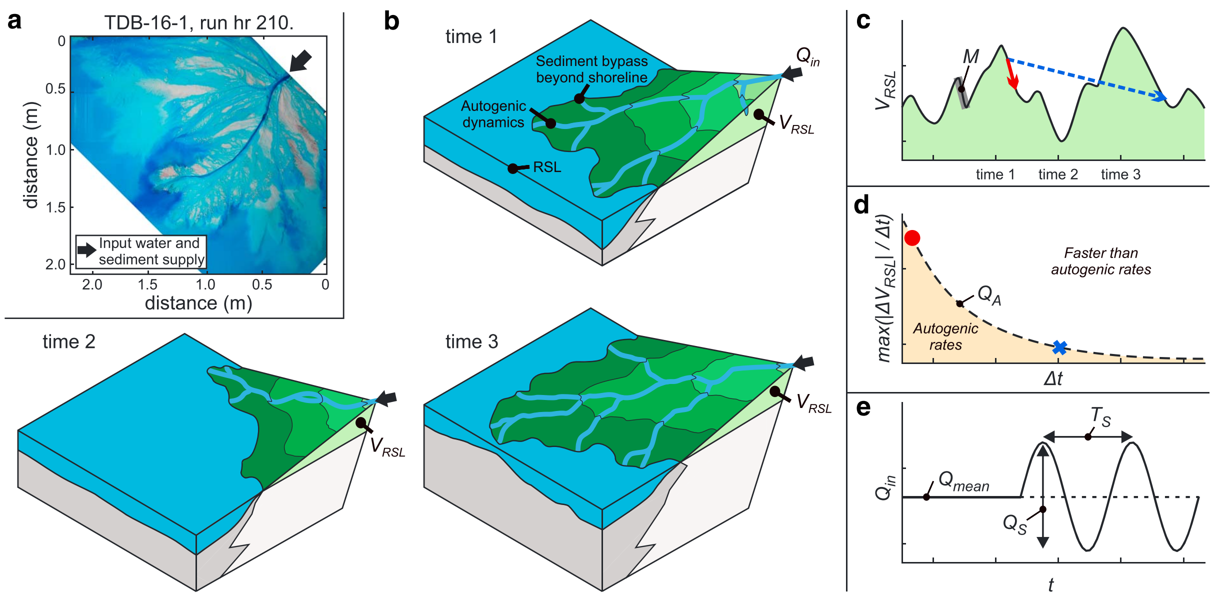

Figure 1. (a) Overhead image of an experimental delta. (b) Schematic aggradational delta at three different time steps. Even under constant sediment supply rate (Q_{in}), the volume stored above sea level (V_{RSL}) continually adjusts in response to autogenic dynamics. (c) Schematic of autogenic changes in V_{RSL}. The rate of V_{RSL} change generally decreases with the time window measured over (e.g., red vs. dashed blue arrow) and approaches zero over long time scales. (d) Schematic maximum rate of volume change (Q_A) for every possible time window of measurement. (e) Example of a cyclic sediment supply signal.

stratigraphy. Here we develop and test a new theoretical framework that delineates a threshold, set by morphodynamics, that must be surpassed if sediment supply signals are to be transferred to the stratigraphic record.

2. Theoretical Framework

Concepts that originated in the field of fluid mechanics (von der Heydt et al., 2003) and were later applied to granular avalanching systems (Jerolmack & Paola, 2010) suggest two parameters must be considered when developing a threshold for sediment supply signal transfer to stratigraphy: a time scale of autogenic saturation and a magnitude of autogenic SSBR. We recognize that the magnitude of autogenic SSBR is dependent on the time scale over which it is measured (Sadler, 1981) and so therefore the magnitude of a sediment supply cycle (SSC) necessary for stratigraphic storage is dependent on the duration of the cycle.

Previous studies suggest that the largest autogenic fluctuations set signal propagation and storage thresholds (Jerolmack & Paola, 2010; Li et al., 2016; Paola & Foufoula-Georgiou, 2001). This should also hold for stratigraphic storage of allogenic sediment supply signals. The maximum rate of autogenic change relates directly to the ability of an individual system to dissipate or accumulate an allogenic sediment supply signal. Here, an autogenic sediment flux change is defined by changes in terrestrial sediment volume over time, for systems experiencing constant forcing (Figures 1a–1c). As such, we define a derivative threshold, Q_A, as the maximum autogenic change in sediment volume stored in a system per unit of time. Q_A decreases with the measurement time window, with smaller values expected for longer time windows until autogenic variations approach zero over very long time scales (Figure 1d). This stratigraphic storage threshold is novel, as we recognize that the magnitude of a sediment supply signal necessary for sediment storage is dependent on the periodicity of the signal, which is in contrast to earlier studies that propose independent magnitude and periodicity thresholds (Jerolmack & Paola, 2010; Li et al., 2016).

To enable comparison between laboratory and field-scale sedimentary systems, we define two normalization parameters that encapsulate autogenic dynamics. The time window of measurement is normalized by the compensation time scale, T_c, while Q_A is normalized by a new autogenic cycle derivative, M. T_c is an estimate of the maximum time scale of autogenic organization in stratigraphy (Sheets et al., 2002; Wang et al., 2011). It also approximates the maximum time necessary to bury a particle to a depth that is no longer susceptible to erosion from autogenic processes (Straub & Esposito, 2013; Straub & Foreman, 2018). It can be estimated as H_c/r, where H_c equals a maximum channel depth and r equals the long-term aggradation rate. T_c has been used as a temporal threshold for the transfer of relative sea level (RSL) and climate proxy signals (Foreman & Straub, 2017). We use T_c to define a dimensionless time, $T^*=t/T_c$.

M represents the maximum rate of change in sediment volume stored in an environment over a full period of sustained autogenic volume growth or loss (Figure 1c). In other words, M equates to the maximum observed rate of volume change between a trough in a time series of sediment volume and the subsequent peak, or vice versa. M is used to define a dimensionless sediment flux, $Q^*=Q/M$. We can express a dimensionless version of Q_A as $Q_A^*=Q_A/M$.

With the framework outlined above, we predict that an allogenic sediment supply signal with a duration or periodicity, T_s, will be transferred to stratigraphy when the magnitude, Q_s, exceeds Q_A, measured over a time window equal to T_s (Figures 1d and 1e). This can be restated in dimensionless form: signal transfer will take place if the dimensionless change in supply rate Q_s^* exceeds the Q_A^* threshold, measured at $T^*=T_s^*$.

3. Methods

3.1. Setup of the Experiments

To test our theoretical framework, we explore the transfer thresholds for SSCs in a suite of physical laboratory experiments. In each experiment a delta developed in a basin that experienced a constant rate of accommodation generation through steady base-level rise, constant input water discharge and constant sediment mixture (Figure 1a). Topography was measured at high temporal and spatial resolutions relative to system morphodynamics to monitor sediment volume changes on the delta.

Experiments were conducted in the Tulane University Delta Basin, which is 4.2 m long, 2.8 m wide, and 0.65 m deep. Sea level was set to rise at 0.25 mm/hr and is controlled to submillimeter-scale resolution. Sediment (mean flux = 3.9×10^{-4} kg/s) and water (1.7×10^{-4} m^3/s) were mixed and fed from a point source. A cohesive sediment mixture with particles ranging from 1 to 1,000 μm (D_{50} = 67 μm) mimics earlier experimental work (Hoyal & Sheets, 2009).

Steady base level rise initiated after the shoreline prograded 1.1 m from the source. In each experiment, the combination of sediment feed rate and base-level rise maintained the shoreline at an approximately constant location through the course of the experiment, with fluctuations associated with autogenic and allogenic dynamics. Topography in all experiments was mapped once an hour with a FARO Focus3D-S 120 laser scanner on a 5-mm horizontal grid in the down and cross basin directions with a vertical resolution < 1 mm.

3.2. Building a Supply Signal Regime Diagram

To characterize time scales and magnitudes of autogenic SSBR events, we use a control stage of experiment TDB-12-1. During this stage the terrestrial delta volume was in dynamic equilibrium with the input sediment flux and rate of accommodation production (r=0.25 mm/hr). From a distribution of channel depths on the delta, we approximate H_c with the 95th percentile depth (12.2 mm) and estimate T_c=49 hr. In 900 run hours ($18.4T_c$) the experiment produced a deposit that was $>18H_c$ thick. While no attempt was made at upscaling our results, extensive work demonstrates the "unreasonable effectiveness" (Paola et al., 2009) of experimental deltas due to the scale independence of many processes, including channelization.

Given our focus on the transfer of sediment supply signals to terrestrial stratigraphy, we quantify our hypothesized relationship between Q_A^* and T^* using a time series of deposit volume stored above sea level (Figure 2a). This terrestrial volume (V_{RSL}) varies due to changes of the surface slope and the location of the shoreline, which are dictated by autogenic SSBR on the delta top. We calculate Q_A for time windows that increase from $0.02T_c$ to $4T_c$ by steps of $0.02T_c$ (1 hr). Autogenic episodes of V_{RSL} growth or loss are characterized by a range of durations that span up to $1.8T_c$ but have a mean period of $0.4T_c$. We measure $M = 9.7 \times 10^{-8}$ m^3/s $\approx 0.3Q_{in}$ from an autogenic V_{RSL} cycle with a duration of $\approx 0.3T_c$ (Figure 2a).

We observe a decrease in Q_A^* as a function of T^*, which is well approximated by an exponential decay of the form $Q_A^* = ae^{-bT^*}$ (Figure 2b). We hypothesize that allogenic sediment supply signals with a combination of periodicity and magnitude that plot well above the Q_A^* threshold will leave behind detectable evidence of

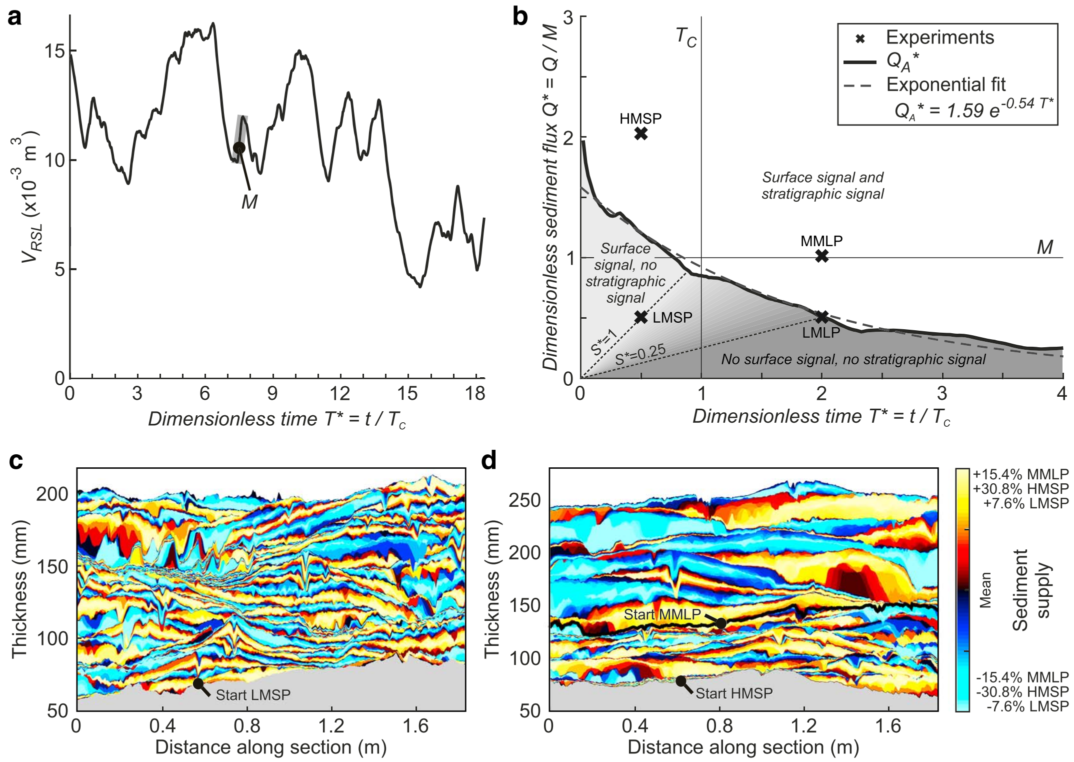

Figure 2. Construction of a regime diagram from autogenic volumetric changes. (a) Plot of terrestrial volume (V_{RSL}) versus time for the control stage. Normalization parameter M is derived from the highlighted stage. (b) Q_A^* versus measurement window (T^*). For each time window, we calculate Q_A^* from n=900-Δt samples. Q_A^* is well approximated by an exponential fit (R^2=0.98). Crosses mark combinations of periodicity and peak-to-peak amplitude for cyclic experimental stages. We test Q_A^* as a threshold for allogenic supply signals to be stored in stratigraphy. Acceleration parameter S^* is discussed in the discussion section. (c and d) Semicircular synthetic stratigraphic sections located at 0.7 m radius from the delta apex as if looking downstream. Stratigraphy is color-coded according to supply conditions during deposition. Panel c shows stratigraphy formed by signals of low magnitude and short period (LMSP), and panel d shows both high-magnitude short period (HMSP), and low-magnitude long period (LMLP) stages at the base and top, respectively.

allogenic signals in stratigraphy, while those that plot below Q_A^* will leave behind no detectable evidence in stratigraphy; that is, the signals are shredded.

3.3. Testing the Threshold

To test our proposed threshold, we explore the results from four additional experimental stages, each of which shared the same set of forcing conditions as the control stage with the exception of Q_{in}, which was varied following sinusoidal cycles (Figure 2b; Table 1). Periodicities of all cycles in any given stage was equal to either $2T_c$ or $0.5T_c$. Similarly, Q_s values were set to be either $2M$ or $0.5M$. While Q_{in} temporally varied, the mean supply rate (Q_{mean}) in each stage was equal to the control stage.

The allogenic SSCs were designed to systematically explore the joint influence of cycle period and magnitude relative to T_c and M, respectively (Figure 2b; Table 1). Natural sediment supply histories are more complex than our sinusoid, but we specifically use a simple experimental setup to leverage existing time series analysis methods. Our hope is that the concepts developed here can be easily modified for other classes of signals.

4. Results

We begin our signal hunt by exploring the time series of terrestrial sediment volume, equivalent to those used to define Q_A from the control stage. Theoretically, V_{RSL} is susceptible to supply signals by recording the combined effect of changes in transport slope and shoreline position. The equilibrium transport slope of a fan-delta is a function of the ratio of sediment to water supply (Parker et al., 1998; Whipple et al., 1998). Altering this ratio forces terrestrial transport slopes to adjust through deposition and/or incision,

Table 1
Sediment Supply Characteristics for Each Experimental Stage

Experiment	Stage	Time (hr)	Q_S (kg/hr)	t_S (hr)	Q_S^*(-)	Ts^* (-)	S^*(-)
TDB-12-1[a]	Control	385-1,285	—	—	—	—	—
TDB-16-1[b]	Low-magnitude short period (LMSP)	140-630	0.22	24.5	0.5	0.5	1
TDB-16-2[c]	Low-magnitude long period (LMLP)	140-630	0.22	98	0.5	2	0.25
TDB-16-3[d]	High-magnitude short period (HMSP)	140-385	0.87	24.5	2	0.5	4
TDB-16-3[d]	Medium-magn. long period (MMLP)	385-875	0.43	98	1	2	0.5

[a]Li and Straub (2017). [b]Toby and Straub (2019a). [c]Toby and Straub (2019b). [d]Toby et al. (2019).

which may have a measurable impact on resulting stratigraphy (Sun et al., 2002). Altering the balance between sediment supply and accommodation generation can drive transgression or regression of shorelines (Muto & Steel, 1997). On short time scales these effects may be obscured by autogenic SSBR.

We construct periodograms by calculating the fast Fourier transform of a time series of V_{RSL} to explore when supply signals consistently produce measurable geomorphic responses (Figure 3a). This time series is extracted from surface topography scans taken at a 1-hr resolution. All periodograms share a background structure characterized by power growth as a function of period, similar to that expected from time series with the presence of temporal correlation. Focusing first on short period signals, we observe spectral peaks that are significantly higher than spectral noise levels at the imposed period of the allogenic SSCs for both high- and low-magnitude experimental stages. The periodogram from the LMLP stage displays no significant peak at the imposed signal period. Interpretation of the MMLP stage is somewhat complicated as a broad peak is observed that centers at a time scale slightly below the imposed periodicity (Figure 3a).

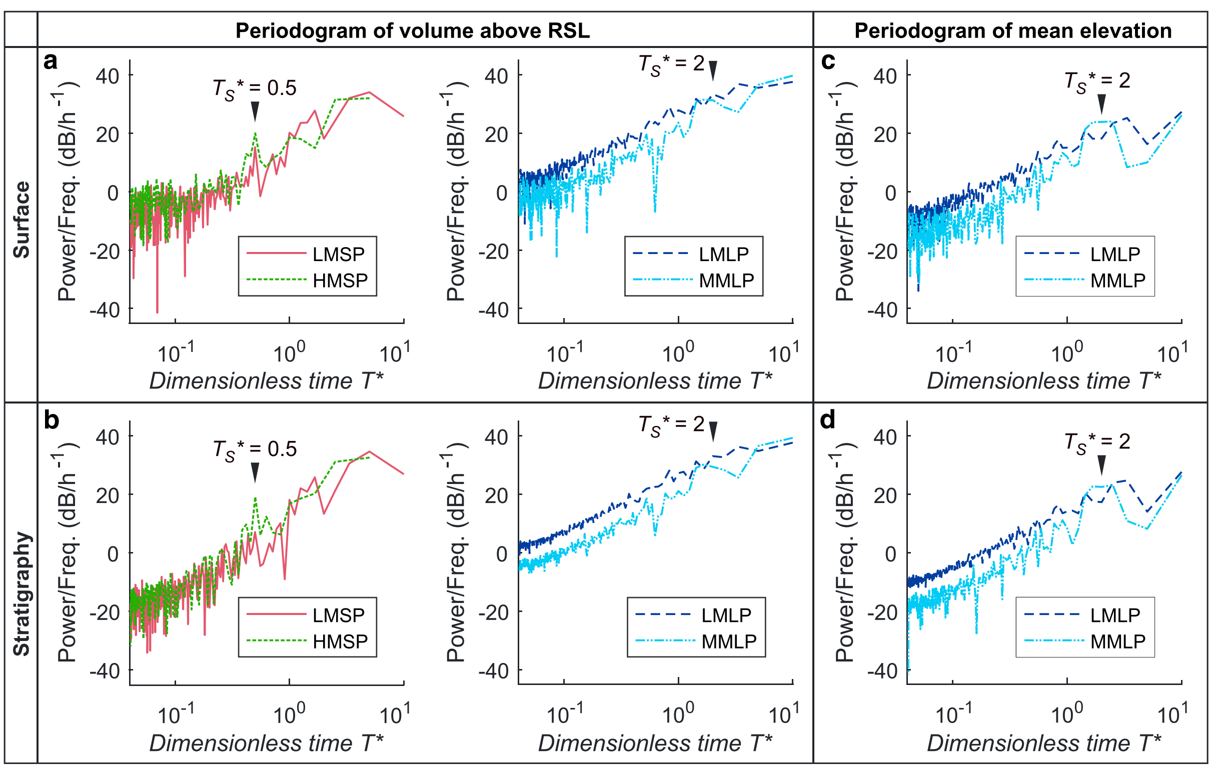

Figure 3. Periodograms of terrestrial volume (a and b) and mean elevation (c and d) for sediment supply cycle experiments. Panels (a) and (c) are based on topography data, and panels (b) and (d) on synthetic stratigraphy. Peaks in the periodograms from the geomorphic surface data sets, at periodicities corresponding to those of imposed sediment supply cycles (black arrows), show signal transfer for all stages except low-magnitude long period (LMLP). The stratigraphic data only shows signal transfer at the imposed sediment supply cycle periodicities in stages high-magnitude short period (HMSP) and medium-magnitude long period (MMLP). RSL = relative sea level; LMSP = low-magnitude short period.

Next we document the transfer of signals to the stratigraphic record using stacked topographic scans clipped for erosion (Figures 2c and 2d), which we refer to as synthetic stratigraphy (Li et al., 2016; Martin et al., 2009). Periodograms of paleo-terrestrial volume, generated from synthetic stratigraphy (Figure 3b), indicate that the observed peak in the surface data from the HMSP stage was transferred to the subsurface, while the observed LMSP peak is absent in the stratigraphic data. The spectra of stratigraphic data from the LP stages are similar to the geomorphic spectra.

The analysis of stages with SP supply cycles, outlined above, supports our hypothesized stratigraphic storage threshold, Q_A^*. While both SP stages exhibit allogenic signals in their geomorphology, only the HMSP signal, which plots above our transfer threshold, gets stored in the stratigraphy. To further test if the signals of LP stages are linked to the frequency of the SSCs, we perform an additional analysis on a time series of mean delta elevation relative to sea level. This is calculated by dividing V_{RSL} by the terrestrial area. We observed clear peaks at the imposed allogenic supply period in periodograms from both the geomorphology and stratigraphy of the MMLP stage, while no peaks in excess of spectral noise levels are observed in the LMLP stage (Figures 3c and 3d).

5. Discussion

5.1. Storage of Geomorphic Signals in Stratigraphy

Our experimental results broadly support the existence of a stratigraphic transfer threshold of sediment supply signals based on time and space scales of autogenic processes. All experimental stages whose SSC characteristics place them above our Q_A^* threshold are recorded in the synthetic stratigraphy, while SSCs that fall below or on our Q_A^* threshold lack stratigraphic signals of supply cycles (Figure 2b).

One interesting observation is that some allogenic SSCs induce a geomorphic surface signal that is absent in stratigraphy (e.g., LMSP stage), while other allogenic cycles produce neither geomorphic surface nor stratigraphic signals (e.g., LMLP stage). These results suggest that the ability of an SSC, for a given magnitude, to produce a geomorphic surface response decreases as the cycle period increases. We propose that a signal acceleration term is governing this behavior. Acceleration is given by the temporal derivative of sediment supply, which here is a cosine function. Prior studies recognized the importance of an acceleration term for stratigraphic signals, specifically the completeness of the stratigraphic record (Sadler & Strauss, 1990). The general idea is that a rapid change in sediment supply, even if small in total magnitude, can trigger a transient response at the Earth's surface, as the system is unable to remain in equilibrium with forcing conditions (Postma, 2014). If the period of the signal is short, it might not produce a thick enough sedimentary response to withstand reworking prior to burial beneath the active surface. A longer signal of the same magnitude might not trigger a transient response, as the system is able to remain in equilibrium with the forcing while the change in equilibrium states might not be large enough, relative to the stochastic dynamics, to produce a detectable signal.

Following Sadler and Strauss (1990), we simplify acceleration by taking the ratio of signal magnitude and period and define dimensionless signal acceleration as $S^*=Q_s^*/T_s^*$ (Table 1). Given that LMSP produced a geomorphic response and LMLP did not, we suggest that a signal acceleration threshold value must exist between $0.25<S^*<1$ (Figure 2b) but more experiments are necessary to converge on a specific threshold.

Diffusional models of sediment transport indicate that the propagation of sediment flux signals attenuates with downstream distance (Paola et al., 1992). However, a critical aspect of our findings is that not all surface signals are stored within the stratigraphic record. While more proximal locations might have stronger signals propagating over the geomorphic surface, we note that archiving of these signals also depends on the long-term accommodation generation.

5.2. Field-Scale Supply Signal Storage

Our theoretical framework could guide the interpretation of stratigraphy for sediment supply signals. Here we illustrate implications of our threshold for field-scale allogenic cycles triggered by tectonic, climatic, and anthropogenic influences. For simplicity purposes, we consider sediment supply signals of duration T_c, which are generally on the order of 10^4-10^5 years for sedimentary basins (Li et al., 2016; Straub & Wang, 2013). We note that T_c can vary with downstream distance as a result of changing channel depths and spatially varying accommodation production rates. We suggest utilizing an upper limit to T_c in the environment of interest for prediction of storage thresholds, as it gives the most conservative prediction. Field estimates of T_c may follow from an analysis of compensational stacking patterns or channel unit thickness distributions (Trampush et al., 2017).

While our focus here is on signals close to T_c, estimation of storage thresholds at other time scales can be estimated by taking advantage of the exponential relationship between ${Q_A}^*$ and T^*. The magnitude of Q_A likely depends on allogenic conditions such as landscape cohesion (Caldwell & Edmonds, 2014; Li et al., 2017) and flashiness of a system's hydrograph (Esposito et al., 2018; Fielding et al., 2018), among other physical variables, and requires further exploration. At a time scale of T_c, Q_A for our control stage is approximately $1/3Q_{in}$.

Several recent studies highlight how the buffering of signals due to deterministic processes in erosional landscapes limits our ability to decode time series of sediment flux for the true timing and magnitude of tectonic signals (Armitage et al., 2013; Li et al., 2018; Mudd, 2017). For example, results from a suite of numerical experiments loosely scaled to Basin and Range catchments suggest that periodic changes in tectonic uplift rate by a factor of 10 are significantly buffered if cycle period is much less than the landscape response time, $t_R > 10^6$ years (Li et al., 2018). As a result, the predicted magnitude of SSCs leaving the erosional catchment, for tectonic uplift periods between 10^4 and 10^5 years, is below 5% of the mean outlet sediment flux. The ratio of Q_A to Q_{in} from our experiments would suggest that signals exiting Basin and Range catchments should be prone to shredding in adjacent sedimentary landscapes prior to stratigraphic storage. As t_R in erosional landscapes scales with drainage area, signals from larger catchments will be more prone to stratigraphic shredding (Allen, 2008b).

Next we consider climate signals with durations between 10^4 and 10^5 years, the obvious choice for discussion being climate response to orbital forcings. Blum and Hattier-Womack (2009) calculate that a change in temperature due to Milankovitch-scale orbital forcing may result in 20-50% change in sediment yield according to the empirical BQART model (Syvitski & Milliman, 2007). The ratio of Q_A to Q_{in} at a time scale of T_c from our experimental data set suggests that SSC characteristics might fall close to our proposed threshold. As such, signal transfer may (or may not) be possible. Here we stress that our regime diagram presents a theoretical threshold for signal storage. Practical limitations to field stratigraphic data sets challenge our ability to detect subtle signals.

Finally, our observation that a fast change in sediment supply is more effective at causing a landscape response implies that anthropogenic signals are a good candidate to trigger a response in the landscape. Current climate change is occurring at a fast rate (Zeebe et al., 2016), and, if continued for a sufficient amount of time, its signal will be transferred to stratigraphy. Likewise, sediment trapping by dams causes fast and significant changes in sediment yield (Blum & Roberts, 2009). Even though human influences emerged in the very recent past, the speed and magnitude by which the sediment supply changed is unlikely to be matched by autogenic processes, making stratigraphic storage of the Anthropocene ever more likely.

6. Conclusions

We developed a novel theoretical framework that successfully predicts the conditions necessary for the stratigraphic storage of sediment supply signals. The importance of this finding is twofold: It (1) enables stratigraphers to quantitatively justify paleo-environmental interpretations and (2) offers a new direction for Earth scientists to explore time-dependent thresholds in landscapes.

Acknowledgments

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References

Ager, D. V. (1973). *The nature of the stratigraphical record*. New York: Wiley.

Allen, P. A. (2008a). From landscapes into geological history. *Nature*, *451*(7176), 274–276. https://doi.org/10.1038/nature06586

Allen, P. A. (2008b). Time scales of tectonic landscapes and their sediment routing systems. *Geological Society, London, Special Publications*, *296*(1), 7–28. https://doi.org/10.1144/SP296.2

Allen, P. A. (2017). *Sediment routing systems: The fate of sediment from source to sink*. Cambridge, United Kingdom; New York, NY: Cambridge University Press. https://doi.org/10.1017/9781316135754

Allen, P. A., Armitage, J. J., Carter, A., Duller, R. A., Michael, N. A., Sinclair, H. D., et al. (2013). The Qs problem: Sediment volumetric balance of proximal foreland basin systems. *Sedimentology*, *60*(1), 102–130. https://doi.org/10.1111/sed.12015

Armitage, J. J., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2011). Transformation of tectonic and climatic signals from source to sedimentary archive. *Nature Geoscience*, *4*(4), 231–235. https://doi.org/10.1038/Ngeo1087
Armitage, J. J., Jones, T. D., Duller, R. A., Whittaker, A. C., & Allen, P. A. (2013). Temporal buffering of climate-driven sediment flux cycles by transient catchment response. *Earth and Planetary Science Letters*, *369*, 200–210. https://doi.org/10.1016/j.epsl.2013.03.020
Blum, M., Rogers, K., Gleason, J., Najman, Y., Cruz, J., & Fox, L. (2018). Allogenic and autogenic signals in the stratigraphic record of the deep-sea Bengal Fan. *Scientific Reports*, *8*(1), 7973. https://doi.org/10.1038/s41598-018-25819-5
Blum, M. D., & Hattier-Womack, J. (2009). *Climate change, sea-level change, and fluvial sediment supply to deepwater depositional systems, External Controls on Deep-Water Depositional Systems*, *SEPM Special Publication* (Vol. 92, pp. 15–39). https://doi.org/10.2110/sepmsp.092.015
Blum, M. D., & Roberts, H. H. (2009). Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience*, *2*(7), 488–491. https://doi.org/10.1038/ngeo553
Caldwell, R. L., & Edmonds, D. A. (2014). The effects of sediment properties on deltaic processes and morphologies: A numerical modeling study. *Journal of Geophysical Research: Earth Surface*, *119*, 961–982. https://doi.org/10.1002/2013jf002965
Duller, R. A., Whittaker, A. C., Fedele, J. J., Whitchurch, A. L., Springett, J., Smithells, R., et al. (2010). From grain size to tectonics. *Journal of Geophysical Research*, *115*, F03022. https://doi.org/10.1029/2009JF001495
Duller, R. A., Whittaker, A. C., Swinehart, J. B., Armitage, J. J., Sinclair, H. D., Bair, A., & Allen, P. A. (2012). Abrupt landscape change post-6 Ma on the central Great Plains, USA. *Geology*, *40*(10), 871–874. https://doi.org/10.1130/G32919.1
Esposito, C. R., Di Leonardo, D., Harlan, M., & Straub, K. M. (2018). Sediment storage partitioning in alluvial stratigraphy: The influence of discharge variability. *Journal of Sedimentary Research*, *88*(6), 717–726. https://doi.org/10.2110/jsr.2018.36
Fielding, C. R., Alexander, J., & Allen, J. P. (2018). The role of discharge variability in the formation and preservation of alluvial sediment bodies. *Sedimentary Geology*, *365*, 1–20. https://doi.org/10.1016/j.sedgeo.2017.12.022
Foreman, B. Z., & Straub, K. M. (2017). Autogenic geomorphic processes determine the resolution and fidelity of terrestrial paleoclimate records. *Science Advances*, *3*(9), e1700683. https://doi.org/10.1126/sciadv.1700683
Hajek, E. A., & Straub, K. M. (2017). Autogenic sedimentation in clastic stratigraphy. *Annual Review of Earth and Planetary Sciences*, *45*(1), 681–709. https://doi.org/10.1146/annurev-earth-063016-015935
Hampson, G. J., Duller, R. A., Petter, A. L., Robinson, R. A., & Allen, P. A. (2014). Mass-balance constraints on stratigraphic interpretation of linked alluvial–coastal–shelfal deposits from source to sink: example from Cretaceous Western Interior Basin, Utah and Colorado, USA. *Journal of Sedimentary Research*, *84*(11), 935–960. https://doi.org/10.2110/jsr.2014.78
Hoyal, D. C. J. D., & Sheets, B. A. (2009). Morphodynamic evolution of experimental cohesive deltas. *Journal of Geophysical Research*, *114*, F02009. https://doi.org/10.1029/2007JF000882
Jerolmack, D. J. (2011). Causes and effects of noise in landscape dynamics. *Eos, Transactions American Geophysical Union*, *92*(44), 385–386. https://doi.org/10.1029/2011EO440001
Jerolmack, D. J., & Paola, C. (2010). Shredding of environmental signals by sediment transport. *Geophysical Research Letters*, *37*, L19401. https://doi.org/10.1029/2010GL044638
Kim, W., & Jerolmack, D. J. (2008). The pulse of calm fan deltas. *Journal of Geology*, *116*(4), 315–330. https://doi.org/10.1086/588830
Li, Q., Benson, W. M., Harlan, M., Robichaux, P., Sha, X. Y., Xu, K. H., & Straub, K. M. (2017). Influence of sediment cohesion on deltaic morphodynamics and stratigraphy over basin-filling time scales. *Journal of Geophysical Research: Earth Surface*, *122*, 1808–1826. https://doi.org/10.1002/2017JF004216
Li, Q., Gasparini, N. M., & Straub, K. M. (2018). Some signals are not the same as they appear: How do erosional landscapes transform tectonic history into sediment flux records? *Geology*, *46*(5), 407–410. https://doi.org/10.1130/G40026.1
Li, Q., & Straub, K. M. (2017). TDB_12_1, SEAD. https://doi.org/10.5967/M03N21GX
Li, Q., Yu, L. Z., & Straub, K. M. (2016). Storage thresholds for relative sea-level signals in the stratigraphic record. *Geology*, *44*(3), 179–182. https://doi.org/10.1130/G37484.1
Martin, J., Paola, C., Abreu, V., Neal, J., & Sheets, B. (2009). Sequence stratigraphy of experimental strata under known conditions of differential subsidence and variable base level. *AAPG Bulletin*, *93*(4), 503–533. https://doi.org/10.1306/12110808057
Mudd, S. M. (2017). Detection of transience in eroding landscapes. *Earth Surface Processes and Landforms*, *42*(1), 24–41. https://doi.org/10.1002/esp.3923
Muto, T., & Steel, R. J. (1997). Principles of regression and transgression: The nature of the interplay between accommodation and sediment supply: Perspectives. *Journal of Sedimentary Research*, *67*(6). https://doi.org/10.1306/D42686A8-2B26-11D7-8648000102C1865D
Overeem, I., Weltje, G. J., Bishop-Kay, C., & Kroonenberg, S. (2001). The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: A climate signal in sediment supply? *Basin Research*, *13*(3), 293–312. https://doi.org/10.1046/j.1365-2117.2001.00151.x
Paola, C. (2016). *A mind of their own: recent advances in autogenic dynamics in rivers and deltas*, *SEPM special publication* (Vol. 106, pp. 5–17). https://doi.org/10.2110/sepmsp.106.04
Paola, C., & Foufoula-Georgiou, E. (2001). Statistical geometry and dynamics of braided rivers. In M. P. Mosley (Ed.), *Gravel-Bed Rivers* (pp. 47–71). Wellington: N. Z. Hydrol. Soc.
Paola, C., Heller, P. L., & Angevine, C. L. (1992). The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory. *Basin Research*, *4*(2), 73–90. https://doi.org/10.1111/j.1365-2117.1992.tb00145.x
Paola, C., Straub, K., Mohrig, D., & Reinhardt, L. (2009). The "unreasonable effectiveness" of stratigraphic and geomorphic experiments. *Earth-Science Reviews*, *97*(1-4), 1–43. https://doi.org/10.1016/j.earscirev.2009.05.003
Parker, G., Paola, C., Whipple, K. X., & Mohrig, D. (1998). Alluvial fans formed by channelized fluvial and sheet flow. I: Theory. *Journal of Hydraulic Engineering*, *124*(10), 985–995. https://doi.org/10.1061/(Asce)0733-9429(1998)124:10(985
Postma, G. (2014). *Generic autogenic behaviour in fluvial systems: Lessons from experimental studies, From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin. International Association of Sedimentologists* (Vol. 46, pp. 1–18). Special Publications. https://doi.org/10.1002/9781118920435.ch1
Sadler, P. M. (1981). Sediment accumulation rates and the completeness of stratigraphic sections. *Journal of Geology*, *89*(5), 569–584. https://doi.org/10.1086/628623
Sadler, P. M., & Strauss, D. J. (1990). Estimation of completeness of stratigraphical sections using empirical data and theoretical-models. *Journal of the Geological Society*, *147*(3), 471–485. https://doi.org/10.1144/gsjgs.147.3.0471
Scotchman, J. I., Pickering, K. T., Sutcliffe, C., Dakin, N., & Armstrong, E. (2015). Milankovitch cyclicity within the middle Eocene deep-marine Guaso System, Ainsa Basin, Spanish Pyrenees. *Earth-Science Reviews*, *144*, 107–121. https://doi.org/10.1016/j.earscirev.2015.01.007

Sheets, B. A., Hickson, T. A., & Paola, C. (2002). Assembling the stratigraphic record: Depositional patterns and time-scales in an experimental alluvial basin. *Basin Research*, *14*(3), 287–301. https://doi.org/10.1046/j.1365-2117.2002.00185.x

Straub, K. M., & Esposito, C. R. (2013). Influence of water and sediment supply on the stratigraphic record of alluvial fans and deltas: Process controls on stratigraphic completeness. *Journal of Geophysical Research: Earth Surface*, *118*, 625–637. https://doi.org/10.1002/jgrf.20061

Straub, K. M., & Foreman, B. Z. (2018). Geomorphic stasis and spatiotemporal scales of stratigraphic completeness. *Geology*, *46*(4), 311–314. https://doi.org/10.1130/G40045.1

Straub, K. M., & Wang, Y. A. (2013). Influence of water and sediment supply on the long-term evolution of alluvial fans and deltas: Statistical characterization of basin-filling sedimentation patterns. *Journal of Geophysical Research:-Earth Surface*, *118*, 1602–1616. https://doi.org/10.1002/jgrf.20095

Sun, T., Paola, C., Parker, G., & Meakin, P. (2002). Fluvial fan deltas: Linking channel processes with large-scale morphodynamics. *Water Resources Research*, *38*(8), 1151. https://doi.org/10.1029/2001WR000284

Syvitski, J. P., & Milliman, J. D. (2007). Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. *The Journal of Geology*, *115*(1), 1–19. https://doi.org/10.1086/509246

Toby, S. C., & Straub, K. M. (2019a). TDB_16_1, SEAD. https://doi.org/10.26009/s0iorjdx

Toby, S. C., & Straub, K. M. (2019b). TDB_16_2, SEAD. https://doi.org/10.26009/s0xtyi86

Toby, S. C., K. M. Straub, R. Dutt, and A. Akintomide (2019), TDB_16_3, SEAD, https://doi.org/10.26009/s0c20606

Trampush, S. M., Hajek, E. A., Straub, K. M., & Chamberlin, E. P. (2017). Identifying autogenic sedimentation in fluvial-deltaic stratigraphy: Evaluating the effect of outcrop-quality data on the compensation statistic. *Journal of Geophysical Research: Earth Surface*, *122*, 91–113. https://doi.org/10.1002/2016JF004067

von der Heydt, A., Grossmann, S., & Lohse, D. (2003). Response maxima in modulated turbulence. II. Numerical simulations. *Physical Review E*, *68*(6), 066302. https://doi.org/10.1103/Physreve.68.066302

Wang, Y., Straub, K. M., & Hajek, E. A. (2011). Scale-dependent compensational stacking: An estimate of autogenic time scales in channelized sedimentary deposits. *Geology*, *39*(9), 811–814. https://doi.org/10.1130/G32068.1

Whipple, K. X., Parker, G., Paola, C., & Mohrig, D. (1998). Channel dynamics, sediment transport, and the slope of alluvial fans: Experimental study. *Journal of Geology*, *106*(6), 677–694. https://doi.org/10.1086/516053

Zeebe, R. E., Ridgwell, A., & Zachos, J. C. (2016). Anthropogenic carbon release rate unprecedented during the past 66 million years. *Nature Geoscience*, *9*(4), 325–329. https://doi.org/10.1038/ngeo2681