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Key Points:

- If sediment dispersal changes through time and time is interpolated from long-term rates, one will misestimate durations from strata
- Misestimation is not inevitable in the strata. Some changes in sediment dispersal result in distortion, while others do not
- Geologic clues that indicate the degree of sediment localization are key to diagnosing stratigraphic sections with substantial distortion

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
E. A. Barefoot,
eabarefoot@gmail.com

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Author Contributions:
Conceptualization: Eric A. Barefoot, Kyle M. Straub
Funding acquisition: Eric A. Barefoot, Kyle M. Straub
Investigation: Eric A. Barefoot
Methodology: Eric A. Barefoot, Kyle M. Straub
Resources: Kyle M. Straub
Software: Eric A. Barefoot
Supervision: Jeffrey A. Nittrouer, Kyle M. Straub
Validation: Eric A. Barefoot, Kyle M. Straub
Visualization: Eric A. Barefoot

Sedimentary Processes and the Temporal Resolution of Sedimentary Strata

Eric A. Barefoot[1], Jeffrey A. Nittrouer[2], and Kyle M. Straub[3]

[1]Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, IN, USA, [2]Department of Geosciences, Texas Tech University, Lubbock, TX, USA, [3]Earth and Environmental Sciences Department, Tulane University, New Orleans, LA, USA

Abstract An appealing strategy for reconstructing the timing and tempo of paleoenvironmental change from sedimentary strata is to linearly interpolate between marker beds of known age. This method requires significant assumptions, but more advanced age modeling methods are usually not feasible. We used experiments to explore how changes in sedimentary processes invalidate these assumptions and affect estimates of time from the strata. When sedimentary processes changed to favor widespread deposition, we found that measuring time linearly systematically overestimated time duration from the resulting strata (time dilation) and misestimated the beginning and end of geologic intervals (phase shifting). When simple age models must be used for sedimentary strata, geologic evidence for transient changes in spatial sediment dispersal may help identify sections of dilated and shifted time, and better resolve time in sedimentary strata.

Plain Language Summary Sedimentary rocks can be used to measure the amount of time that passed between events in Earth history. Since it is rare to find layers of rock whose age can be measured, one needs a simplifying assumption: the thickness of sedimentary rocks is proportional to the amount of time that passed. In other words, the sediment accumulated relatively steadily, and gaps are short relative to the duration of interest. In this study, we show that this approach incorrectly dates events in the timeline, and erroneously inflates time durations. The bias is most significant when a change in environmental conditions causes sediment to spread more widely across the landscape than it did before. The bias is not as pronounced when sediment deposits are localized. Clues and context from sedimentary rocks may help reveal whether sediment was spreading widely or locally in the past. Using this evidence, geologists will be able to identify sections where simplifying assumptions will not hold, and can apply appropriate corrections.

1. Introduction

Sedimentary rocks are the main geologic archive used to reconstruct paleoclimate, tectonic motions, and the history of life on Earth (Paola et al., 2018). Measuring the magnitude and duration of environmental change is crucial for understanding how Earth systems interact to maintain a habitable planet (Kirtland Turner, 2018). The most commonly-used age models assume relatively steady, continuous sedimentation to interpolate linearly between marker beds of known age. That is, gaps should be short compared to the interval of interest, and distributed uniformly in the stratigraphic column. When these assumptions do not hold, establishing a timeline from sedimentary strata is not straightforward.

Issues of timing and duration are central to interpreting many consequential events in Earth's history. For example, explaining the cause of the Cretaceous-Paleogene (K-Pg; ~65 Ma) mass extinction (Schoene et al., 2019) depends on the relative timing of the Deccan Traps eruptions (Keller et al., 2009; Schoene et al., 2015) versus the Chicxulub impact (Schulte et al., 2010; Sharpton et al., 1992). In another case, estimates for the duration and tempo of the Paleocene-Eocene Thermal Maximum (PETM; ~55.6 Ma) (Kirtland Turner, 2018) are essential for understanding how the global climate responded to past changes in the carbon cycle (Zachos et al., 1993). As a third example, the shape, duration, and magnitude of the Shuram carbon isotope excursion (CIE) at ca. 570 Ma are very challenging to constrain (Knoll et al., 1986; Le Guerroué et al., 2006), and yet the CIE is widely used as a chronostratigraphic marker to measure the timing of major evolutionary, tectonic, and climatic changes occurring in the Ediacaran period (Fike et al., 2006; Halverson et al., 2005; Williams & Schmidt, 2018).

The fundamental limit to overcoming these uncertainties and reconstructing geologic time in sedimentary rocks is the temporal incompleteness of strata (Sadler, 1981; Trampush & Hajek, 2017). Sedimentary strata

Writing – original draft: Eric A. Barefoot
Writing – review & editing: Jeffrey A. Nittrouer, Kyle M. Straub

contain unconformities due to both external (allogenic) factors and internal (autogenic) unsteadiness (Davies & Shillito, 2018; Jerolmack & Sadler, 2007; Rogers, 1998).

We use the term "unconformity" throughout to refer to gaps in the stratigraphic record of any duration, due to any cause. Allogenic changes in environmental boundary conditions (e.g., sea level, tectonic uplift) that erode or starve basins of sediment leave unconformities in the stratigraphic column. Within a geologic basin, emergent internal (i.e., autogenic) sediment transport dynamics focus erosion and deposition in some portions of the basin while other regions receive no sediment at all (Davies & Shillito, 2021; Ganti et al., 2011; Straub & Foreman, 2018; Straub et al., 2009). As a result, for a given stratigraphic column, geologic time does not advance up section linearly. Instead, periods of inactivity and erosion are interspersed with bursts of sediment accumulation (Paola et al., 2018; Schumer et al., 2011; Tipper, 2015).

Layers of known age are uncommon, which makes it challenging to calibrate age models to account for sections of missing time in sedimentary strata. In the absence of other information, the default approach is to interpolate linearly between layers of known age, which inherently assumes that the sediment accumulation rate between them is steady and constant (Abels et al., 2010; Jarochowska et al., 2020; Westerhold et al., 2009; Wilf et al., 2003). This approximation is best applied to environments where the short-term variability of sediment accumulation is small compared to the long-term accumulation rate, such as lacustrine or abyssal sediments (exemplified in Figure 1—light blue line) (Foreman & Straub, 2017; Trampush & Hajek, 2017). While lakes and the deep oceans are important archives for tracing the behavior of Earth systems, they represent a subset of the available sedimentary rock archive. Important insights can be gained if paleoenvironmental interpretations with improved timescales are applied to terrestrial and marginal marine environments with highly variable sedimentation rates. In these environments, sediment accumulation rates fluctuate according to both the processes internal to the system itself (autogenic), as well as externally-imposed (allogenic) environmental conditions like sediment supply (Bryant et al., 1995; Gaeuman et al., 2005; Lane et al., 1996; Yu, 2002), base level (Chadwick et al., 2020; Muto, 2001; Salter et al., 2018; Syvitski & Saito, 2007), and hydrograph variability (Colombera et al., 2017; Esposito et al., 2018; Fielding et al., 2018; Leary & Ganti, 2020).

There are a variety of age-modeling approaches that exploit the signatures of allogenically-forced increases or decreases in sedimentation rate to sharpen age models. They include: (a) incorporating lithological variation to better infer accumulation rates (Kominz & Bond, 1990; Trauth, 2014), (b) using visual correlation (Zachos et al., 2005) and dynamic time warping algorithms to align records from disparate locations (Ajayi et al., 2020; Hay et al., 2019; Lisiecki & Lisiecki, 2002), and/or (c) aligning records with orbital cyclicities (Aswasereelert et al., 2013; Aziz et al., 2008; Meyers & Sageman, 2007; Röhl et al., 2007). These approaches, though, assume that sedimentation is continuous across large sections of the stratigraphic column, and assume unconformities are long-lived and rare. Moreover, because the stochasticity of sediment accumulation changes with allogenic forcing, the number and concentration of undetected unconformities may also covary in tandem with the environmental conditions (Figure 1—bottom row).

Because we lack the ability to directly measure the amount of unrecorded time in a stratigraphic column, assumptions like steady, continuous sedimentation will remain a practical means for estimating the timing and tempo of past climate, tectonics, and biological evolution. However, it is essential (a) to quantify how these assumptions impact our reconstructions of geologic time, and (b) to investigate how their influence can be mitigated.

2. Experiment Design

Herein, we use idealized sedimentary experiments with high-resolution age control to examine how changes in environmental boundary conditions affect reconstructions of geologic history when the linear time assumption does not hold. We use the term "event" throughout this paper to mean any interval of time in Earth's history whose beginning and end can be demarcated by evidence within the strata. Examples could include the interval between the first and last occurrence of index fossils, an isotope excursion measured from benthic foraminifera, or a shift from oxic to anoxic seawater.

To represent a generic sedimentary environment with well-characterized dynamics, we used an experimental basin (Li et al., 2016) where sediment and water flow created channelized surfaces (Hoyal & Sheets, 2009), and imposed net aggradation by steadily raising the water level in the basin over the full duration of the experiment. Throughout, we held the long-term average water and sediment supply constant, but imposed floods of varying

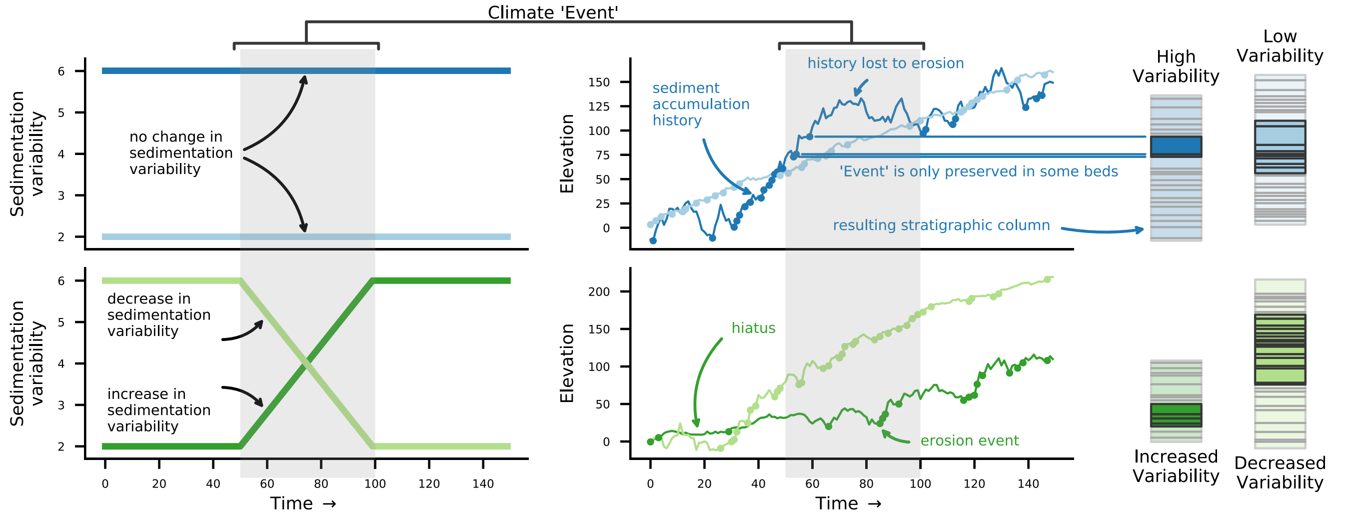

Figure 1. Sediment accumulation histories for four hypothetical scenarios. The left-hand panels show the coefficient of variation for sedimentation; the sediment accumulation histories are shown in the right-hand panels. The resulting stratigraphic columns are shown on the far right of each row. On the top row, the sedimentation variability for each scenario is a constant function of time (blue lines), whereas on the bottom row, the variability either increases or decreases during a geologic event (green lines). The beds in the resulting strata that were deposited during the climate event are highlighted in each column. Existing theory demonstrates that—when averaged over an ensemble of columns—estimates of timing and duration are unbiased for the cases in blue (Foreman & Straub, 2017; Trampush & Hajek, 2017). If steady sediment accumulation is assumed between dated horizons located at the top and bottom of each stratigraphic column, the perceived duration of the event in the dark green column would be compressed relative to its true duration, and the event in the light green column would be dilated. Either way, the result is unreliable estimates of the timing and duration of the event.

amplitudes. The flood amplitude (Q_v) was defined as the ratio of the maximum discharge (Q_{max}) to the minimum discharge (Q_{min}), $Q_v = Q_{max}/Q_{min}$, such that the average water discharge was equivalent for different values of Q_v (see supplement for details). We controlled the spatial and temporal variability of sedimentation in the basin by engineering transitions between low- and high-amplitude flood regimes.

In these experiments, floods dispersed sediment across the surface; flood amplitude controlled how far away from a channel it dispersed. Under the high-amplitude flood regime ($Q_v = 3$), two main processes spread sediment widely across the surface. First, vigorous sheet flow during floods transported sediment away from channels and across the basin surface, depositing extensive channel-margin deposits. Second, high-amplitude floods promoted more frequent avulsions and accelerated channel migration (Barefoot, Nittrouer, & Straub, 2021; Esposito et al., 2018). In contrast, sediment dispersal under a low-amplitude flood regime ($Q_v = 1.5$) tended to be localized. During low-amplitude floods, sluggish overbank flows were incapable of transporting sediment far away from channels. This reduced channel mobility and focused sediment accumulation in the region adjacent to the channel (Barefoot, Nittrouer, & Straub, 2021).

We engineered transitions between the two flood regimes. Flood amplitude either diminished or intensified, and each transition took place over a prescribed duration. We call flood intensification "positive transitions" and diminishing floods "negative transitions." Each interval of positive or negative transition constitutes a geologic "event" whose duration and timing can be measured. Additionally, we compared the results to data from a control experiment, where flood amplitude remained unchanged throughout the entire experiment (Li et al., 2017; Li & Straub, 2020). For the control experiment, we chose an arbitrary window of a fixed duration to be the event of interest.

Throughout the experiment, we acquired topographic data and images of the sediment surface at high temporal frequency. Practically speaking, the smallest unconformity we can measure in our experiments spans the duration between two topographic scans. We located each event in the strata by identifying the stratigraphic horizons that marked the beginning and end of each event. For negative and positive flood transitions, the marker horizons of the event are the beginning and end of the transition. For the control experiment, the marker horizons were chosen so that events of the same duration could be compared to the flood transitions.

For each event, we picked a random set of stratigraphic columns from the experiment, simulating the process of taking a sediment core. We chose only those columns where the sediment thickness during the event was non-zero (see Supporting Information S1 for a discussion of this choice and its implications). The columns were sampled at a regular spatial interval, much in the same way that one would sample a physical sediment core. The apparent duration of each event was measured using a linear time assumption (i.e., continuous sedimentation) between the bottom and top horizons of known age. We consider the apparent duration of the event as measured assuming linear time (t_m) relative to the true imposed duration (t_x), and name the ratio of the two a "time dilation factor" ($t^* = t_m/t_x$), where t^* values >1 represent apparent time dilation and t^* values <1 represent apparent time compression. We also measured the apparent timing of the event onset, and compared it to the value we prescribed. Again assuming linear time, we compute an apparent time lag (ϕ), where values greater than zero indicate a lag, and values less than zero indicate a lead. For the remainder of the manuscript, we call this a "phase shift." We also use the general term "time distortion" to refer to the combined action of time dilation and phase shifting.

We normalized the imposed timing and duration of each event by a characteristic autogenic timescale. In the short run, accumulated sediment packages were uneven in thickness. Over the long run, the locus of deposition moved, and successively emplaced packages of sediment compensated for uneven short-term deposition (Ganti et al., 2011; Straub et al., 2009). Compensation occurs in nearly all net-depositional environments, and one may estimate a compensation timescale (T_c), defined as the ratio of the characteristic landscape relief (l) and the long-term aggradation rate (r); $T_c = l/r$ (Wang et al., 2011). This timescale is a property of the sedimentary dynamics; it reflects the time required for the largest and longest-lived autogenic sedimentation variability to average out. We use this timescale as a normalization factor because T_c is readily measurable in natural sedimentary systems, and allows a means to scale our experimental observations.

3. Process-Induced Apparent Time Dilation, Compression, and Phase Shifting

In all our experiments (positive, negative, and control), we observed that linear time interpolation generated apparent time dilation when the event of interest was short relative to the compensation timescale ($t_x = 1/4T_c$, see Figure 2). For intermediate length events ($t_x = 1/2T_c$), the reconstructed event time trended toward $t^* = 1$, indicating that the average perceived duration was equivalent to the true event duration (no time dilation). For the longest events ($t_x = T_c$), the reconstructed event time appeared shorter than the true duration ($t^* < 1$) indicating apparent time compression. In this way, the temporal sampling resolution of the stratigraphic record changed systematically with the duration of the geologic event itself. The dependence on apparent event duration on the true duration is a consequence of the Sadler effect (Sadler & Strauss, 1990), where the apparent accumulation rate increases as shorter time windows are measured. That is, we expect this dilation and compression simply because the stratigraphic column is incomplete, with many undetectable hiatuses.

There are differences between the control experiment and the experiments where we manipulated flood amplitude. Apparent time dilation in positive transitions (flood intensification) exceeded time dilation in the control experiment (>90% probability for all treatment levels, Figure 3). In other words, during time intervals when floods intensified, the resulting sediment package was thicker on average than a similar time interval when conditions did not change. If a linear age model were applied to reconstruct the duration of positive flood transition events, it would overestimate the true elapsed time by as much as 30%. This effect is above and beyond what would be expected due to the Sadler effect alone.

Our experiments also show an apparent time phase shift in the positive flood transitions. When using a linear time assumption, the apparent onset of the event in the strata leads the true onset by about $1/2T_c$ on average ($\phi \approx -1/2T_c$); there is no clear trend with the event duration (Figure 2).

Both of these outcomes are asymmetric. Negative flood transition events are statistically indistinguishable from the control. When floods diminished in intensity, the apparent duration of the event is the same as corresponding events in the control experiment, and they do not lead or lag the true event onset (Figure 3).

4. Morphodynamic Controls on Stratigraphic Sampling

To explain why increasing flood amplitude created an apparent time dilation and phase shift in the stratigraphic record—but decreasing it had no effect—we examined how sedimentary processes responded to transient changes in flood amplitude.

In the absence of external forcing, our experimental landscapes converged on a dynamic equilibrium, where the roughness and morphology remain statistically similar over long intervals of time. The equilibrium topography formed by low-amplitude floods contrasts strongly with the equilibrium topography formed by high-amplitude

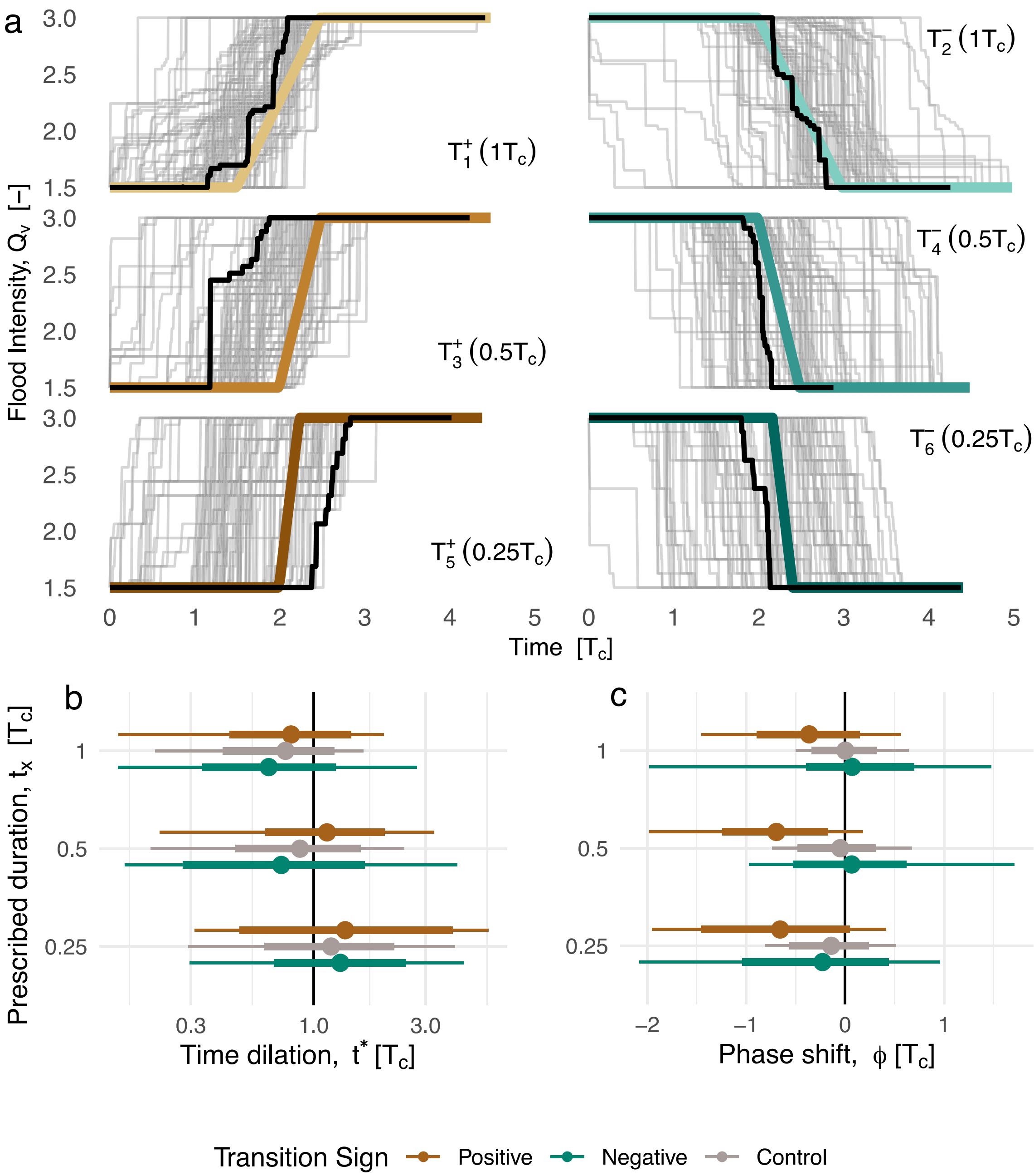

Figure 2. Panel (a) shows the experimental events, with prescribed changes in flood amplitude in color. Example reconstructions using linear time interpolation are shown in gray for an ensemble of 25 randomly selected stratigraphic columns. An individual reconstruction is highlighted in black for each. Panel (b) shows the time dilation, t^*, calculated for the control experiment, as well as the experiment with positive and negative transitions. The mean is shown by a point, the thick horizontal line comprises 66% of the data, and the thin line 95% of the data. In general, the reconstructed duration of flood regime transitions is longer than the true value for abrupt transitions, and appears shorter for gradual transitions. Panel (c) shows the phase shift, ϕ, with the same convention. The phase shift observations indicates that event onset time leads the true onset for positive events, but not negative events or the control.

floods (Figure 4). Localized deposition during the low-amplitude flood regime constructed surfaces marked by short wavelength roughness features like ridges and levees. By widely dispersing sediment, high-amplitude flooding constructed smooth topography lacking ridges or swales (Barefoot, Nittrouer, & Straub, 2021).

At the beginning of each flood-regime transition event, the equilibrium topography of the prior regime formed the initial condition for the next interval of landform development. This surface remained until it was either eroded, or buried under new sediment. In this way, the equilibrium topography of the prior regime was juxtaposed with the sediment transport dynamics of the subsequent regime. Gradual events (~T_c) allowed the landscape to adjust

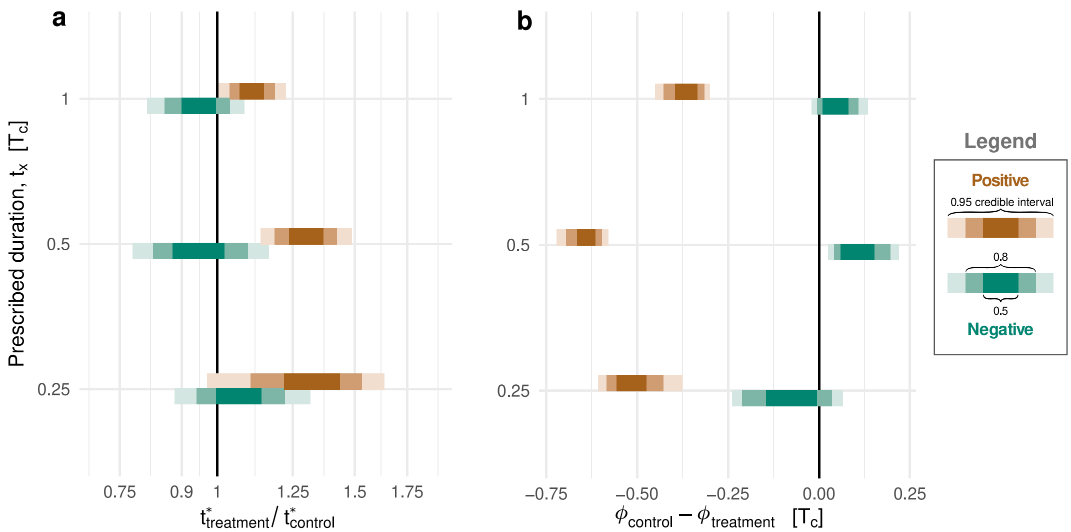

Figure 3. In panel (a), we use a one-way ANOVA to quantify the ratio of time dilation for the control experiments (no change in flood amplitude) versus the positive and negative events (increase or decrease in flood amplitude); that is, $t^*_{\text{treatment}}/t^*_{\text{control}}$. In panel (b), a one-way ANOVA is used to quantify the difference in phase shift between the control experiment, and the positive and negative treatments; that is, $\phi_{\text{control}} - \phi_{\text{treatment}}$. Both ANOVAs were fit using a Bayesian framework; here we visualize the posterior estimates of the mean difference, where the color intensity indicates the quantile intervals of the samples. If the posterior distributions overlap unity in panel (a), then estimates of the event duration cannot be statistically distinguished from the control. This is the case for all of the negative treatments (teal). In contrast, all of the positive treatments (brown) plot greater than one, indicating that there is a greater than 90% probability these events are dilated relative to the control experiment. In panel (b), if the posterior distributions group around zero, then they are statistically indistinguishable from the control. Positive treatments all fall below zero, indicating a apparent leading phase shift, whereas negative treatments cluster around zero.

from one state to another while erosion and deposition continuously maintained equilibrium; conversely, abrupt events ($<T_c$) were marked by pronounced, and long-lived disequilibrium (see supplement).

During positive events, increasingly intense floods and mobile channels promoted widespread sediment distribution, which was deposited upon rough topography built by low-amplitude flooding. As a result, there were abundant topographic swales to trap and accumulate sediment, and the flow possessed sufficient energy to distribute sediment into them. In the opposite case (negative events), progressively weaker floods and less mobile channels promoted localized sediment deposition, which accumulated on a smooth surface generated by high-amplitude flooding. Accordingly, sediment deposition was confined to the area adjacent to the channel during negative events (Figure 4).

This hysteresis is the origin of the asymmetric impact on stratigraphic time dilation and phase shift (Figure 3). In the case of positive events, sediment accumulation is spatially widespread, and there is ample storage space, so evidence of the transition event is preserved throughout the basin, resulting in a thicker section than would be expected under steady accumulation. Moreover, the onset of the event is lower in the stratigraphic column than would be expected with steady sediment accumulation, producing an apparent phase lead. In the case of negative events, sediment accumulates in a narrow region around the channel at rates comparable to the control experiment, but some regions of the basin receive no sediment, and many stratigraphic columns contain unconformities spanning the entire event.

5. Reconstructing Time in Dynamic Sedimentary Archives

Our experiments demonstrated that temporary changes in sediment deposition patterns can alter the completeness of the resulting stratigraphic column. By assuming linear time accumulation between dated horizons under these circumstances, geologic events appear to start too early in the stratigraphic column, and unfold over a longer interval of time than they did in reality. The apparent time dilation effect is especially pronounced when the event is abrupt relative to the autogenic dynamics of the sedimentary system.

However, this apparent time distortion is not always present, and under some circumstances, linear time assumptions produced accurate estimates. The key distinguishing factor between these scenarios is the spatial pattern of

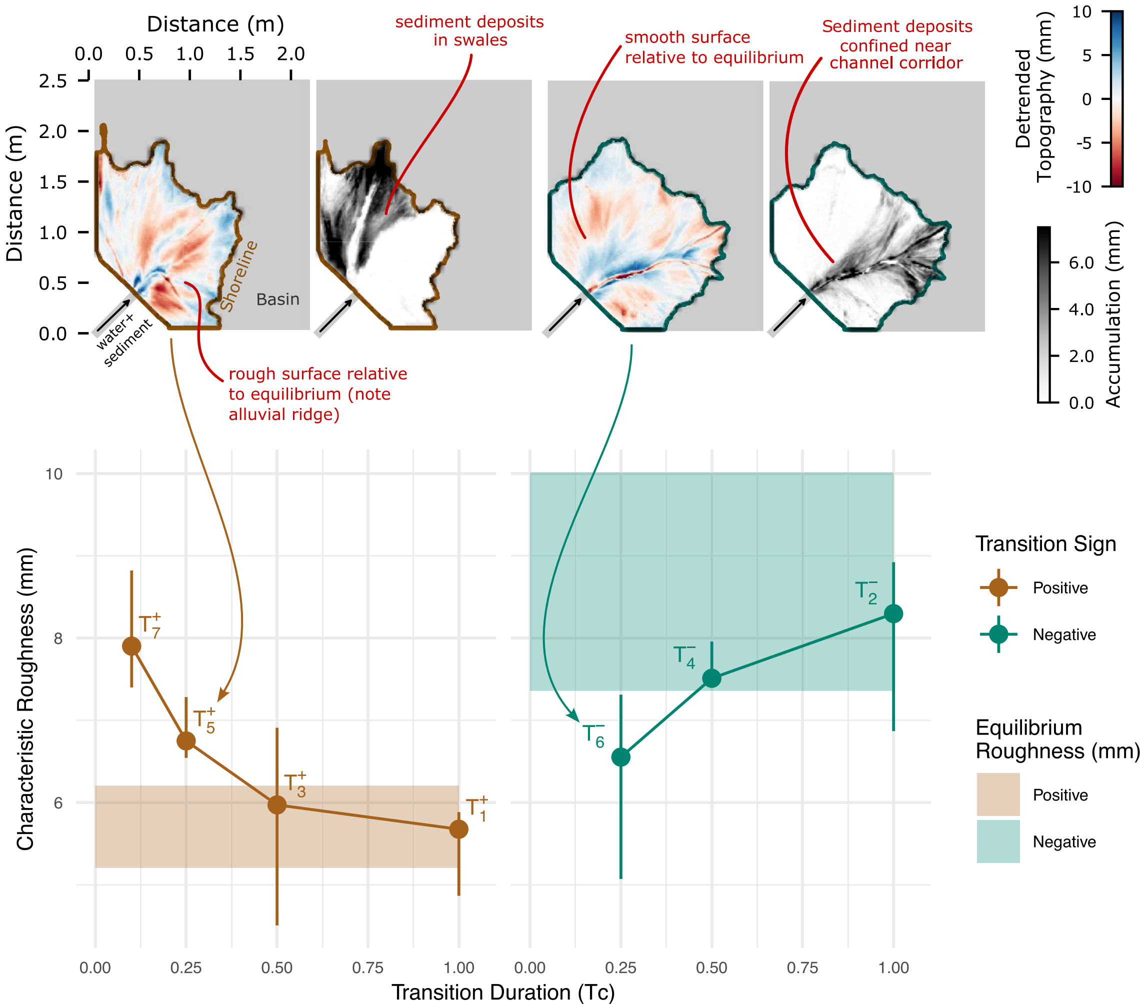

Figure 4. Red-blue maps shows topography roughness (ridges and swales) as deviations from the overall conical deposit shape, and isopach maps show deposition in grayscale for 10 hr immediately following the transition event. Gray background shows the experimental basin, and the arrow indicates the water and sediment inlet, the shoreline is drawn on the map. The characteristic surface roughness is the standard deviation of the red-blue maps, and panels immediately following each transition. The duration of the preceding transition is given on the x-axis in units of T_c. Ranges of equilibrium values for roughness during low and high-intensity flooding are given by shaded regions. Abrupt transitions possess roughness values more typical of the preceding flooding regime, whereas gradual transitions are marked by roughness values in the range of equilibrium values. The two transitions shown in the maps (T_5^+ and T_6^-) are indicated with the teal and brown arrows.

sediment deposition before, during, and after the event. When sediment deposition is localized and confined to a limited area before the event, then during the event becomes progressively widespread, extreme distortion results. When the opposite occurs, distortion is minimized. We propose that sedimentological indicators of localized versus widespread sediment dispersal can be used to identify sections where linear-time assumptions are unlikely to hold, and also to predict the nature of the time distortion in those sections.

Care must be taken when working with small samples or individual cores. Our results reveal that time distortion is predictable on average, but distortion varied substantially from core to core. Small sample sizes lack predictive power; combining age models from many stratigraphic columns will produce the most accurate reconstructions. While acquiring many cores from the same sedimentary system is often impractical, one could in principle use the statistical models presented here to estimate a prediction interval for an individual core and estimate the uncertainty. Ultimately, with additional investigation and careful application, these results could be used to arrive at improved age models for sedimentary strata.

There are many events in the Earth's past where sediment dispersal patterns change as a result of environmental perturbations. For example, in fluvial sedimentary basins where the PETM has been documented, intensified flooding and/or enhanced sediment supply from surrounding mountains commonly resulted in widespread sand

and conglomerate deposition (Barefoot, Nittrouer, Foreman, et al., 2021; Foreman et al., 2012). Relative to the compensation timescale estimated in these basins, the PETM onset is relatively short. Current best estimates indicate that the carbon isotope excursion (CIE) that marks the onset of the PETM could have been as brief as 5 kyr (Kirtland Turner, 2018). In many of the terrestrial basins where the PETM has been studied (e.g., the Bighorn (Foreman, 2014), Piceance (Foreman et al., 2012), and Tremp-Graus (Colombera et al., 2017)), this is anywhere from 1/2 to 1/10th of the basin's compensation timescale (T_c). As a result, the apparent duration of the PETM CIE onset measured from locations like these may be substantially dilated and/or phase shifted (Aziz et al., 2008).

The effects we have described here almost certainly lurk in the sedimentary records of other depositional environments, where biological and geochemical proxies are used to establish the chronology of major events in Earth history. The suite of sedimentological and geological context clues that might indicate time distortion will vary across sedimentary basins and depositional environments. Nonetheless, our experiments suggest a way forward in these circumstances: one should try to distinguish between episodes where sediment deposition is focused in small areas or spread widely across the depositional system.

Marine turbidity currents, for example, can cycle between episodes of relative confinement (where sediment accumulates in a localized area) and unconfinment (where sediment accumulates in large sheets) (Pyles, 2008; Romans et al., 2011). Submarine channels confine themselves by building levees via suspension fallout. Fluctuating sea level can disconnect submarine channels from the upstream continental shelf, and starve the system of suspendible sediment. Ultimately, disconnected channels cannot build levees, and they tend to deposit sediment in unconfined sheets (Romans et al., 2011). The degree of confinement can be inferred after the fact by studying the resulting turbidite deposits (Malkowski et al., 2017). Based on our results, we speculate that within packages with similar degrees of confinement, linear time assumptions will hold. Across the boundaries, linear time likely does not hold for transitions from relatively confined to unconfined sedimentation.

Our experiments suggest a general rule: environmental change that shifts sediment deposition patterns from localized to widespread deposition is likely to distort the preservation of geologic time. However, this need not be the only, or even the most important way that shifting sedimentary processes affect the temporal resolution of stratigraphy. Importantly, there are also feedbacks and interactions between sediment deposition patterns and the biogeochemical markers that stratigraphers use to reconstruct paleoenvironmental histories. It will remain a challenge to untangle multiple different effects from a common cause (Holland, 2016; Peters, 2005, 2006). For example, a change in sea level (Davies et al., 2009) may coincide with the last occurrence of a fossil in the strata, and sea level rise itself also affects sediment localization.

Our experiments isolate and quantify the effect of variable sedimentation rates and corresponding changes in stratigraphic architecture. The results demonstrate that apparent time dilation and phase shifts in sedimentary strata are predictable, and thus suggest that with sufficient information about the autogenic dynamics of an ancient sedimentary system, one can—in principle—separate the impact of changing stratigraphic architecture from environmental impacts on biogeochemical markers hosted in the sediment. Recent theoretical and methodological advances demonstrate how nested hierarchies of autogenic landforms elements interact to produce sedimentary structures. Combined with the experimental results here, these advances establish a framework for deriving quantitative constraints on the characteristic autogenic timescales and lengthscales of ancient sedimentary systems (Ganti et al., 2020; Greenberg et al., 2021; Leary & Ganti, 2020; Lyster et al., 2022). Our results should be used as a first step to leverage quantitative reconstructions of sedimentary autogenics to sharpen the temporal resolution of paleoclimate and paleontological archives when independent age constraints are sparse.

Data Availability Statement

The data that support this study can be downloaded at the following https://doi.org/10.5281/zenodo.8071771. Data are stored as three dimensional arrays, in HDF5 datasets. Analysis was conducted with a mix of R and Python 3, with statistical calculations completed using R and JAGS. Plots were created with Python and R/ggplot2, and all code are available from the same DOI as the data.

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