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Geomorphic stasis and spatiotemporal scales of stratigraphic completeness

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ABSTRACT

Alluvial stratigraphic records are notoriously incomplete. All stratigraphic sections within sedimentary basins experience varying episodes of erosion and geomorphic stasis during their accumulation. This has detrimental effects on the completeness of paleoclimatic and paleobiologic records. Here we evaluate the resultant stratigraphic incompleteness using a physical experiment with self-organized vertical scales of topography and lateral scales of geomorphic stasis. First, we document how stratigraphic completeness improves as the temporal discretization interval coarsens, and show that the primary cause of the missing time shifts from stasis to erosion as the discretization is coarsened. Second, we demonstrate that the debilitating effect of finer temporal resolution can be predictably offset by compositing records across a wider area, and present a new two-dimensional formulation of stratigraphic completeness. These findings imply systematic shifts in taphonomic preservation, and by extension, the quality of paleobiologic and paleoclimatic proxy records.

INTRODUCTION

Ideally, information contained in strata (e.g., geochemical proxies, fossils) is of a sufficient temporal resolution to address questions regarding how the Earth system responds to climate change events and at what pace taxa evolve and go extinct. Unfortunately, most stratigraphic records are riddled with gaps, typically referred to as stratigraphic hiatuses, due to geomorphic activity. This recognition of stratigraphic incompleteness dates back to Hutton's (1788) work on unconformities and Barrell's (1917) work on the rhythms of erosion/sedimentation processes. Yet quantifying incompleteness and relating it to geomorphic "rhythms" has remained an especially difficult problem in the centuries since its recognition.

In 1981, Sadler presented the first data that quantified the average completeness of stratigraphic records. Using a global data compilation, he showed a dependence of sedimentation rate on the time scale over which the rate was measured, which he linked to the accumulation of stratigraphic hiatuses. Subsequently, numerous studies have explored this "Sadler-Effect" using one-dimensional (1-D) numerical models wherein erosional and depositional events are sampled from probabilistic distributions (Strauss and Sadler 1989; Schumer and Jerolmack 2009). These models illustrate the likely shape of the statistical distributions of the paleoelevation fluctuations and hiatuses that construct the stratigraphic record. However, in many of these models, hiatuses only result from periods of erosion because the models dictate that the geomorphic surface must fluctuate during each time step.

Tipper (2015) recently referred to these as "busy" models of sedimentation and argued the "importance of doing nothing." He proposed that most locations in sedimentary systems, most of the time, are neither aggrading nor degrading, but are simply inactive. Although he may be correct, we currently lack data from modern systems to characterize how much time is missing due to stasis versus erosion. This characterization is the first goal of our study, and has implications regarding the taphonomic character of preservation for paleoclimatic and paleobiologic records on different time scales. A geomorphic surface in stasis can still accumulate "information" (e.g., soils, fossil concentrations), whereas erosion causes the loss of information.

The second goal is to build on concepts of 1-D stratigraphic completeness. Existing theory and stratigraphic simulations indicate the potential for substantial improvements in understanding the spatiotemporal characteristics of strata by constructing composite stratigraphic sections (Tipper, 1998). However, there is a critical lack of observational data from well-constrained case studies that evaluates the quantitative spatial relationships between geomorphic behaviors and stratigraphic completeness. Circumstantially, Sadler and Jerolmack (2015) pointed out that multiplication of globally averaged aggradation rates by progradation rates removes the accumulation rate dependence on the time scale of measurement. They attributed this to mass-conservation, inferring that erosion at proximal sites likely leads to progradation of a landform at more distal sites. This inference was further supported by Mahon et al. (2015), who demonstrated that the stratigraphic completeness of shorelines is generally greater than that of any 1-D location on a delta. Using an experiment, we are able to rigorously evaluate the phenomenon of spatially varying completeness, and develop a new quantitative framework for estimating the completeness of composite stratigraphic sections in channelized sedimentary systems.

METHODS

We examine the role of geomorphic stasis and stratigraphic completeness using a laboratory-scale, experimental delta subjected to known boundary conditions (Fig. 1A; Li and Straub 2017). The delta freely evolved under its own internal physics, with constant water discharge ($Q_{w,input} = 1.7 \times 10^{-4}$ m^3/s), sediment supply ($Q_{s,input} = 3.9 \times 10^{-4}$ kg/s), and the uniform generation of accommodation through base-level rise ($\overline{r}_{SL} = 0.25$ mm/h). Total runtime was 500 h, and the resultant fluviodeltaic stratigraphy can be thought of as dominated by autogenic processes. Experimental morphodynamics, similar to geomorphic processes operating in field-scale systems, produce elevation time series with correlation resulting from the movement of coherent landforms, and periods of stasis are the direct result of the experimental morphodynamics. Critically, our experimental setup allows monitoring of the geomorphic activity at high spatiotemporal resolutions relative to the morphodynamics, which is infeasible to measure in field-scale systems.

Topography was monitored once an hour with a laser scanner, resulting in digital elevation models with a 5 mm horizontal grid and a vertical resolution of ~0.5 mm (Fig. 1B). The laser scanner also collected digital images, which are co-registered with the topography (Fig. 1C). The input water was dyed red to aid identification of regions with active sediment transport versus stasis. Regions with active flow had at least some interaction of sediment with the bed over any single run hour.

We analyzed a transect extracted from the larger 3-D topographic data set. This transect is located 0.6 m from the source, approximately

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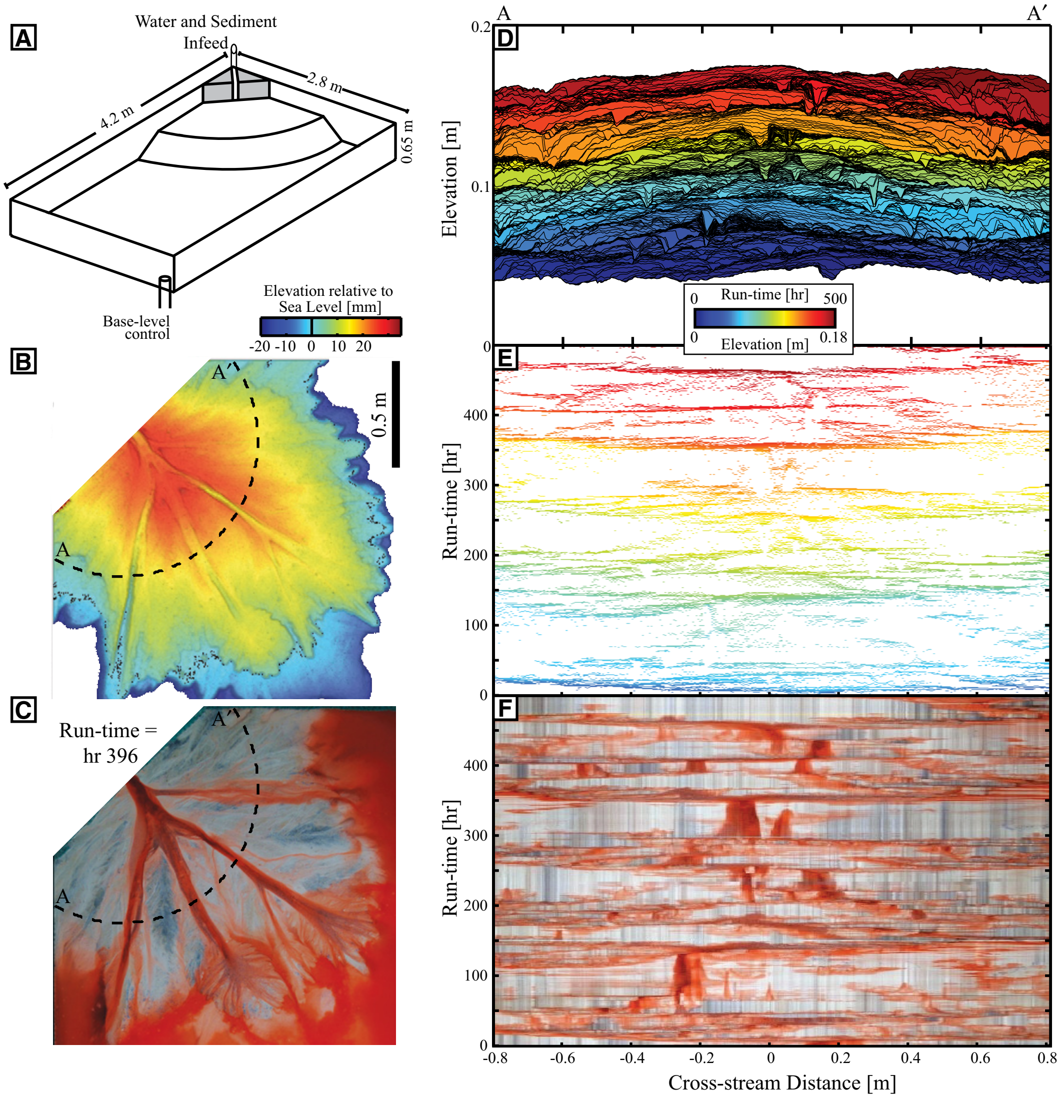

Figure 1. A: Schematic of experimental basin. B,C: Topographic map (B) and digital image (C) of experimental surface at run hour 396. Dashed line A-A′ indicates location of transect extracted for analysis. D: Cross section of synthetic stratigraphy generated from stacked digital elevation models, clipped for erosion. Deposit is colored by time of deposition with contours of constant time. E: Time-space matrix with color indicating preserved elevation. White regions represent stratigraphic hiatuses. F: Time-space map of experimental surface color.

halfway between the basin entrance and mean shoreline. We analyzed a strike section, as the statistics that characterize 1-D elevation fluctuation time series are relatively stationary across any given transect. In the field, outcrops of stratigraphy can take any orientation relative to the mean transport direction, but our hope is that this analysis will provide an initial scenario that can be expanded on in future studies.

Analysis of the section proceeded after topographic measurements were rounded to the nearest 0.5 mm. We stacked measurements of topography to construct a panel of synthetic stratigraphy, which requires clipping topography to remove deposits that are later remobilized during episodes of erosion (Fig. 1D). After constructing the synthetic stratigraphy, we limited our analysis to the first 450 run hours, to avoid strata not buried below the reworking zone. This allows us to generate pseudo-Wheeler diagrams and identify stratigraphic hiatuses (Fig. 1E). Finally, we used the digital images to construct a time-space map of the experimental surface color and used a threshold red-color intensity to identify time-space pairs in stasis versus active transport (Fig. 1F).

RESULTS

We generated a probability of exceedance distribution (PDE) to characterize durations of stasis on the geomorphic surface (Fig. 2A). This PDE was constructed from all 1-D time series of geomorphic surface color and compared to a similarly constructed PDE of stratigraphic hiatuses measured from the synthetic stratigraphy. While the PDEs have similar shapes, for a given duration of interest there are more hiatuses than episodes of stasis due to the contribution of erosional episodes (Fig. 2A). The shapes of the PDEs resemble truncated Pareto distributions, which appears to be a robust characterization of geomorphic stasis, as previous researchers have found similar distributions in experiments (Ganti et al. 2011). Truncated Pareto distributions are characterized by short-duration power-law decay trends that transition to more rapid decay trends above a critical truncation scale. In our data, we observe a "roll-over" in the PDE from the short to long duration trends approximately at the stratigraphic integral scale, T_i (Fig. 2A). T_i is equal to the depth of the larger channels that construct the geomorphic surface divided by a system's long-term aggradation rate (Wang et al. 2011). T_i approximates the time to bury a particle to a depth that is no longer susceptible to erosion from autogenic events. It has also been referred to as the "compensation timescale" as it captures a sedimentary system's tendency to systematically deposit in locations with accommodation. Our data suggest that T_i is the critical truncation scale for the Pareto distributions that characterize stasis in channelized sedimentary systems.

Next, we constructed PDEs for the width of regions in stasis on the geomorphic surface and of stratigraphic hiatuses for each time step (Fig. 2B). These spatial PDEs also resemble truncated Pareto distributions. Similar to T_i, we seek an autogenic truncation scale that characterizes the surface processes. We chose a scale, B_{D95}, equal to the 5th percentile of the PDE; in other words, 95% of the stasis episodes are narrower

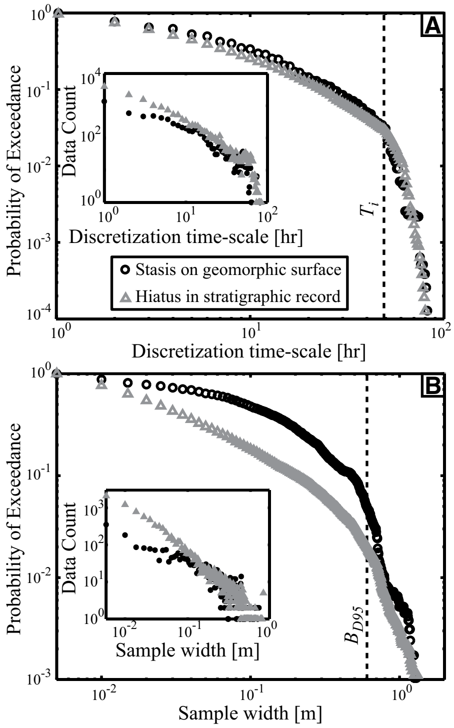

Figure 2. A: Probability of exceedance distribution (PDEs) presented in log-log space for geomorphic stasis and stratigraphic hiatus durations. Dashed line indicates estimated stratigraphic integral scale, T_i. Insert panel shows data count of stasis and hiatus episodes of a given duration. B: PDEs presented in log-log space for the width of geomorphic stasis episodes and hiatuses. Dashed line indicates estimated B_{D95} (the 5th percentile of the PDE) Insert panel shows data count of stasis episodes and hiatuses of a given width.

than this value. This percentile avoids statistical irregularities in picking the widest observed stasis window. The time-space map of surface color indicates that B_{D95} usually corresponds to situations when flow collapses into a single channel that runs approximately down the basin center (Fig. 1E).

We started the characterization of stratigraphic completeness, f_c, in one dimension. f_c is defined as the fraction of time intervals in a stratigraphic section, with a given temporal discretization, that preserve sediment over the thickness of the 1-D section. We tracked the increase in f_c as a function of a dimensionless time scale equal to $\delta t/T_i$ (t is time). We started by calculating f_c with $\delta t/T_i$ set to the temporal resolution of data collection. We then systematically coarsened the temporal discretization to a final resolution equal to $2T_i$. Similar to previous studies (Strauss and Sadler 1989), we find that f_c increases with the dimensionless time scale of discretization and saturates at 100% when $\delta t/T_i \geq 1$.

Next we explored the relative roles of stasis versus erosion for incompleteness. We identified all stratigraphic hiatuses for a record digitized at a given $\delta t/T_i$ and then explored if at any time between the start and end of the hiatus the point was covered by active flow. For example, when examining the cause of a hiatus in a record discretized at $\delta t/T_i = 0.5$, we explored if active flow covered that cell during any 1 h between the start and end of the hiatus. Given our data resolution, this helps ensure that a hiatus, labeled as stasis, was in fact in stasis during the entire interval. Hiatuses resulting from erosion that occurred between the start and end of an interval are then identified. These erosional hiatuses span intervals that include shorter-term periods of transient deposition and/or episodes of stasis. At short discretization intervals, the primary cause for incompleteness is stasis (Fig. 3A). This is in agreement with an analysis of the limit $\delta t/T_i \rightarrow 0$ at which the maximum theoretical completeness of a record is the fraction of the surface covered by active transport. Interestingly, as the temporal discretization interval coarsens, the relative fraction of the record missing due to erosion progressively increases. Longer time windows allow channels to translate laterally and rework previously deposited sediment between the start and end of any given interval. However, eventually the relative influence of long-term aggradation prevails, and the fraction of time steps missing due to both erosion and stasis decreases as the temporal discretization interval is further coarsened.

Our second goal was to understand how expanding the width of the field of observation, δx, improves recovery of temporal information from stratigraphy. We started this analysis by measuring f_c with $\delta t/T_i$ set to the resolution at which data were collected. We define a dimensionless sample width as $\delta x/B_{D95}$. For a given value of $\delta x/B_{D95}$, we ask if preserved deposition occurred in any grid cell in the field of observation: if yes, we considered that time step preserved. We find that f_c increases with dimensionless sample width and saturates at 100% when $\delta x/B_{D95} \geq 1$. The f_c dependence on both the dimensionless sample width and the dimensionless time scale of discretization indicates a 2-D completeness phase space (Fig. 3B). For each value of $\delta x/B_{D95}$, we calculated the value of $\delta t/T_i$ necessary to first reach 100% completeness, T_c^*. The power-law growth of completeness as a function of both $\delta t/T_i$ and $\delta x/B_{D95}$ suggest that T_c^* can be predicted using

$$\ln\left(T_c^*\right) = \frac{1}{\ln\left(\delta x / B_{D95}\right)}. \quad (1)$$

The advantage of Equation 1 is that, similar to our data, $T_c^* \rightarrow 1$ as $\delta x/B_{D95} \rightarrow 0$ and $T_c^* \rightarrow 0$ as $\delta x/B_{D95} \rightarrow 1$, and the two variables necessary to predict a discretization time scale to achieve 100% completeness can plausibly be estimated for field systems. We find good agreement between Equation 1 and our experimental data (Fig. 3B).

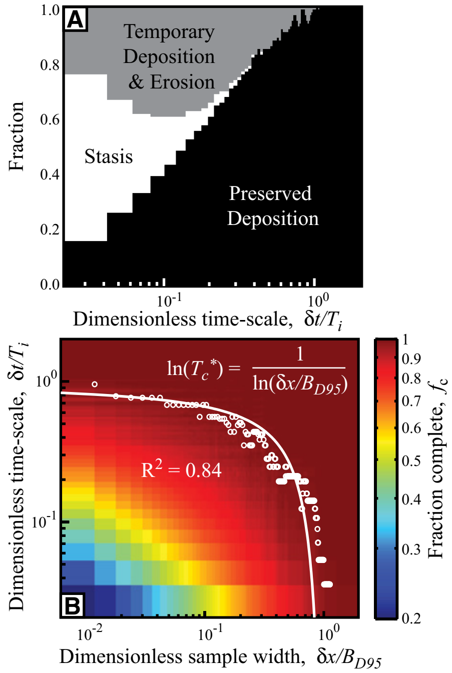

Figure 3. A: Stratigraphic completeness (black region), and the relative contributors to incompleteness (white for stasis, and gray for erosion) as functions of dimensionless time scale of discretization. B: Matrix defining how stratigraphic completeness changes as a function of dimensionless time scale of discretization and dimensionless sample width. Open circles reflect time scale necessary to reach 100% completeness for a given width of observation. Solid white line is defined by Equation 1, while R^2 value characterizes fit of Equation 1 to the data.

DISCUSSION

We return to Tipper's proposition that most stratigraphic hiatuses are the result of stasis on geomorphic surfaces. From a continuous time perspective, $\delta t \rightarrow 0$, our results support Tipper's proposition. As with most channelized settings, the ratio of channel to overbank area is small in our experiment, which results in widespread stasis at any point in time. However, records extracted from strata are always discretized and our results suggest the level of discretization determines the primary culprit for missing time. Geomorphic stasis is the primary cause for gaps in high-temporal-fidelity proxy records.

The observation that stasis dominates the generation of hiatuses on short time scales implies that many terrestrial fossil and climate proxy records are temporally complete, but time-averaged. The issue then is not signal loss, but signal condensation. Clear examples include climate-induced geochemical and morphologic changes during pedogenesis, stable isotopic compositions of authigenic minerals in sediments, trace fossil assemblages, and many fossil bone beds (Rogers and Kidwell 2000; Hasiotis et al. 2002; Sheldon and Tabor 2009). Our data provide a quantitative geomorphic justification for why isotope records from a single soil are representative of the climate rather than weather, and how fossil records can capture ecosystem structure. Indeed, the novel field of paleobiologic conservation essentially exploits this phenomenon and uses fossils accumulated on geomorphic surfaces in stasis over the past centuries to millennia to establish baseline ecosystem conditions and diversity before human disturbances (Kidwell 2015).

If on long time scales a single section can be complete, and on a short time scale a single bed or soil can be representative, how should we construct complete records over meso time scales? Many geological time-scale questions focus on stratigraphic records discretized at intermediate values of $\delta t/T_i$ which in field scales are likely on time scales of 10^3–10^5 yr (Foreman and Straub 2017). In these records, the stratigraphic filter is largely the result of erosion linked to the lateral migration of transport systems during any given time window. Thus, in these cases, quantifying f_c is essential in order for researchers to construct time series of paleoclimate and paleobiologic change and for comparison of these records against the rates and magnitudes of changes on modern Earth. Recent work suggests that these gaps, which result from stochastic morphodynamic processes, limit our ability to reconstruct paleoclimate events shorter than T_i from proxy records obtained from a single stratigraphic section (Foreman and Straub 2017), or produce spurious variability in the shape of a signal between multiple sections (Trampush and Hajek 2017).

Assuming f_c also increases as power-law functions of discretization time scale and lateral sample width in field systems (Equation 1), our results indicate that compiling separate sections with paleoclimate proxy records or fossil occurrences, with a density scaled to the half-width of the basin, helps improve f_c in a predictable fashion. For example, to obtain a record an order of magnitude of finer temporal resolution would require increasing the number of stratigraphic sections by an order of magnitude spread out across a basin. Intuitively, field researchers know that composite, overlapping sections improve completeness (Abels et al. 2013), but heretofore there were minimal direct observations of natural or experimental systems that rigorously justify this approach from a geomorphic process perspective.

Finally, although the stratigraphy presented here is purely autogenic, our observations imply that allogenic forcings (of which there are many) could predictably alter the parameter space that determines completeness. Any allogenic forcing that induces a shorter T_i and/or a narrower B_{D95} would reduce the vertical and lateral scales necessary to average over, in order to obtain greater completeness. The opposite changes in T_i and B_{D95} would expand the vertical and lateral scales needed to be considered.

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