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Key Points:
- Temporal gaps within a time series of stratigraphic measurables severely modify the apparent temporal structure of autogenic processes
- This has practical implications for how we detect, interpret and reconstruct environmental signals from strata
- Using an estimate of completeness, we can predict the detectability of an environmental signal and reconstruct signal properties

Supporting Information:

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

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The Incomplete Record of Autogenic Processes Sets Limits on Signal Detectability

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Abstract Spectral analysis is a central tool regularly used by the scientific community to identify the presence of periodic processes within a time series of information, as spectral peaks at an imposed periodicity can be differentiated from internal (autogenic) variance. In scientific disciplines, such as seismology, the time series of information is of high temporal resolution. Hence, although temporal gaps are present, they do not impact the overall noise structure, meaning that the full spectrum of autogenic variance can be reconstructed. However, power spectra generated from stratigraphic information are affected by temporal incompleteness due to varying episodes of erosion and geomorphic stasis, which generate gaps over a range of scales. This removes information related to the natural and autogenic variability present within sediment-transport systems, which makes it challenging to accurately reconstruct the structure and strength of paleo-surface processes, which defines the detectability of past environmental signals. We explore how incompleteness impacts the temporal structure of autogenic noise within power spectra, and how this influences the detectability of spectral spikes related to environmental signals. We utilize a sediment flux time series from a physical rice pile and progressively degrade these data to mimic varying degrees of stratigraphic incompleteness. We find that incompleteness strongly influences the timescales and spectral structure of autogenic noise evident, and can render signals over all periodicities undetectable within a highly incomplete time series. This offers the ability to confidently justify the interpretation of subtle environmental signals from field measurements and understand the records that may best preserve paleoenvironmental variability.

Plain Language Summary Information about past environmental conditions is recorded in layers of ancient sediment. This enables scientists to identify specific environmental events in Earth's past, in order to understand the impact of current and future environmental events. However, layers of sediment do not represent a complete record of time and environmental signals generated by these events can be mixed up with natural environmental fluctuations (noise). This means that the detection of the original environmental signal can be uncertain. To reduce this uncertainty, we must quantify the duration and magnitude of noise, allowing a threshold to be constructed above which we can be confident that the signal is real. Constructing this for stratigraphy is difficult as strata contain temporal gaps over a wide range of scales, which makes the detection of past environmental signals challenging to the extent where many real signals could be deemed undetectable. We studied how the incompleteness of stratigraphy influences the structure of noise preserved in stratigraphy and how accurately environmental signals can be detected. We show that incompleteness is a major factor as to why a time series of stratigraphic information rarely records the full structure of noise, which consequently affects the detection and reconstruction of environmental signals.

1. Introduction

The internal dynamics within sediment-transport systems (STSs) are characterized by local episodes of sediment storage and release that occur naturally, known as autogenic processes, which are ubiquitous across all landscapes and generate stochastic fluctuations in sediment transport in the absence of external (allogenic) forcing (Hajek & Straub, 2017; Jerolmack, 2011; Jerolmack & Paola, 2010; Kim & Jerolmack, 2008; Paola, 2016; Pelletier et al., 2015; Romans et al., 2016; Straub et al., 2020). Stochastic sediment transport resulting from autogenic processes generates noise within a STS, and the resultant stratigraphy, and limits the predictability of STS dynamics (Ganti et al., 2014; Hajek & Straub, 2017; Jerolmack, 2011; Jerolmack & Paola, 2010; Paola, 2016; Romans et al., 2016; Van De Wiel et al., 2011). The duration and magnitude of autogenic processes within STSs determine the structure and timescales of autogenic noise present (Griffin et al., 2023; Hwa & Kardar, 1992; Jerolmack & Paola, 2010). Autogenic noise has a distinct tripartite structure composed of three noise regimes

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delimited by two autogenic timescales. The first regime comprises temporal correlation (red noise) over short timescales, where spectral power increases as a function of period. The second comprises no correlation (white noise) over intermediate timescales, where the spectral power plateaus. The third regime comprises anti-correlation (blue noise) over long timescales, where spectral power decreases as a function of period (Griffin et al., 2023; Hwa & Kardar, 1992). Whilst the tripartite structure should be evident in all stochastic natural systems, the presence of all three noise regimes depends on the relationship between the autogenic timescales; where these timescales converge, power spectra may only display red and blue noise (Griffin et al., 2023).

The two autogenic timescales denote temporal thresholds for the degradation and detectability of sediment flux signals generated by external environmental perturbations (Griffin et al., 2023; Jerolmack & Paola, 2010). Whilst signal degradation severely reduces the amplitude in comparison to the input signal ("shredding"), signals can undergo no modification but be rendered undetectable if the signal magnitude is similar to that of autogenic processes (Griffin et al., 2023; Jerolmack & Paola, 2010). Therefore, characterizing the temporal structure of autogenic processes from a time series of stratigraphic information enables the accurate reconstruction of paleo-surface processes, and allows theoretical frameworks which predict the degradation and detectability of sediment flux signals in both landscapes and strata to be fully utilized (Jerolmack & Paola, 2010; Toby et al., 2019).

Theoretical frameworks for signal degradation and detection rely on the full characterization of the structure of autogenic processes within a specific STS. This has been achieved for an exquisitely preserved time series of sediment flux and preserved deposition rates measured from physical experiments (Griffin et al., 2023; Hajek & Straub, 2017; Jerolmack & Paola, 2010; Toby et al., 2019). However, a time series of stratigraphic information is inherently incomplete owing to the presence of hiatuses over a variety of spatiotemporal scales from laminae to basin-scale unconformities, which reduce the preservation of autogenic processes within vertical sections (Ager, 1973; Davies et al., 2019; Foreman & Straub, 2017; Jerolmack & Sadler, 2007; Kemp, 2012; Sadler, 1981; Schumer & Jerolmack, 2009; Sommerfield, 2006). Within all geomorphic environments, variations exist in the duration of depositional, stasis (non-deposition) and erosional events driven by autogenic reorganization, which generates hiatal surfaces with a range of frequencies and durations (Hajek & Straub, 2017; Kim & Jerolmack, 2008; Sadler, 1981; Sommerfield, 2006; Straub & Foreman, 2018; Straub et al., 2020; Strauss & Sadler, 1989; Tipper, 2015; Trampush et al., 2017). As a result, part of the original autogenic signal is removed and imposed sediment flux signals can be distorted (e.g., Burgess et al., 2019; Foreman & Straub, 2017; Trampush & Hajek, 2017), making it challenging to accurately reconstruct sediment-transport processes and detect environmental signals from landscapes and strata (Kemp, 2012, 2016; Kemp & Sexton, 2014; Miall, 2015; Paola et al., 2018; Straub et al., 2020; Tofelde et al., 2021). Furthermore, limits on our ability to date strata mean sediment age is often assigned by linear interpolation between dated horizons (Abels et al., 2010; Ramos-Vázquez et al., 2017), providing additional challenges to the incompleteness problem by distorting the apparent representation of time in strata relative to true time (Barefoot et al., 2023; Trampush & Hajek, 2017). Hence, fundamental questions exist regarding the reliability of strata as an archive of past and future environmental change.

Analysis of a time series of stratigraphic information assumes a priori that the original full signal of autogenic noise is present and can be reconstructed without deeply considering the impact of incompleteness. Instead, the preserved noise is measured and assumed to accurately characterize the full spatiotemporal scales of autogenic processes within landscapes and strata. Griffin et al. (2023) found that a time series of surface processes generates power spectra with tripartite spectral structure; however, it is hypothesized that the lack of blue noise in stratigraphic measurables could result from incompleteness, and/or the assumption of linear sedimentation rate (Figure 1). This means that the punctuated chronology generated as a result of stratigraphic incompleteness could significantly distort the record of autogenic processes (Davies et al., 2019). This has secondary consequences for the detectability of environmental signals, which could be significantly reduced due to incompleteness, meaning periodic signals could be defined as statistically insignificant or missed entirely (Foreman & Straub, 2017; Griffin et al., 2023; Straub et al., 2020). Although this is predicted, the relationship between signal detectability and stratigraphic incompleteness, and a framework to predict signal detectability as a function of incompleteness and input signal properties has not yet been established (Burgess et al., 2019; Foreman & Straub, 2017; Trampush & Hajek, 2017). Understanding how incompleteness affects the preserved structure of autogenic processes is of fundamental importance for establishing robust confidence limits for signal detectability within environmental parameters.

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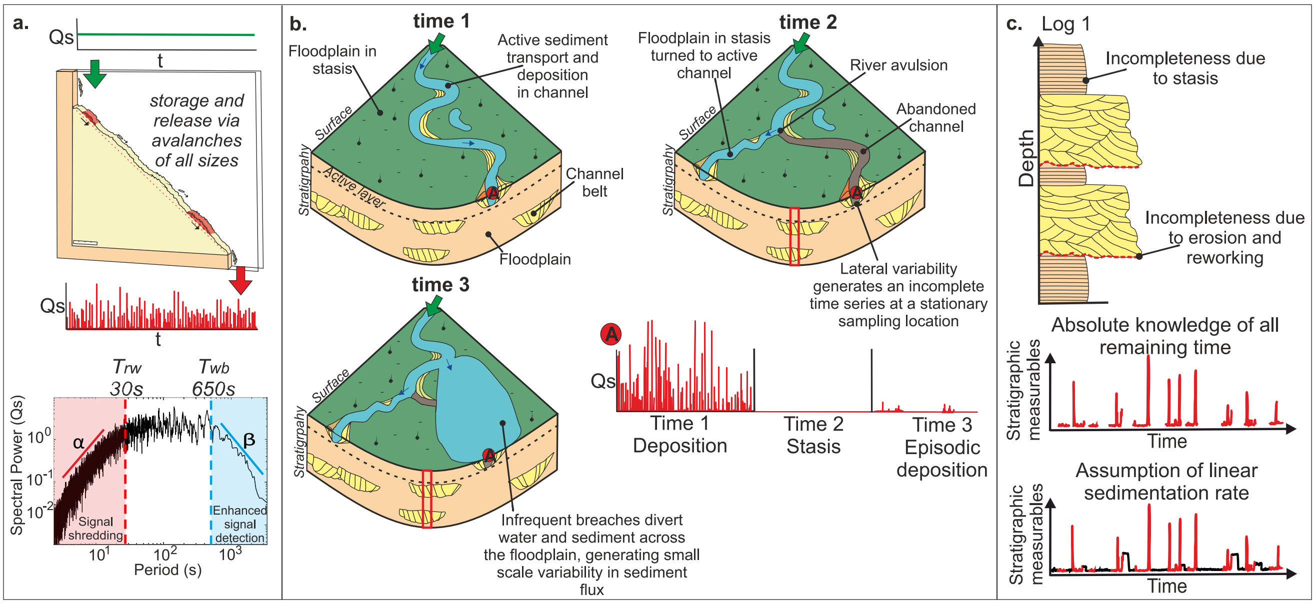

Figure 1. The nature of autogenic processes and stratigraphic incompleteness (a) Schematic illustration of the physical rice pile run under a constant input rate, highlighting the stochastic sediment flux time-series generated, comparable to a time-series of preserved deposition rates produced from natural systems. This generates power spectra with tripartite spectral structure defining two autogenic timescales, T_{rw} *and* T_{wb}. (b) Autogenic dynamics within the Earth's surface promote constant system reorganization, causing episodes of deposition, erosion and stasis (non-deposition), generating an incomplete time series of sediment flux at a stationary sampling location, defined by the red circle. (c) Sedimentary log taken from the red rectangle in panel (b). Time series of stratigraphic information containing temporal gaps and accumulating under variable sedimentation rates. If the absolute ages of all remaining sediment are known, the time series contains gaps of varying duration. To overcome this, the time series is bound by sparsely dated horizons under the assumption of a linear sedimentation rate between these points.

Here, we quantify (a) how incompleteness modifies the preserved record of autogenic surface processes and (b) how incompleteness influences the detectability and apparent degradation of environmental signals from a time series of sediment flux. To do this, we utilize a physical rice pile as an idealized STS, from which a time series of sediment flux is generated at discrete time intervals. The rice pile can provide a basis from which natural STSs and strata can be understood, as the complex internal dynamics which arise from storage and release along a 1D path elucidate the nature of autogenic processes in field scale systems (Bak et al., 1987; Frette et al., 1996; Griffin et al., 2023; Jerolmack & Paola, 2010). The distribution of these sediment flux events within the rice pile is heavy tailed, which has also been measured and theorized for many field scale systems. However, the statistics of these fluxes are not linked to the same processes at play in field-scale systems; hence, we do not focus on the specific processes but rather the ramifications of having a stochastic time series of sediment flux bound by process timescales and finite size effects. Although the rice pile does not directly generate strata, it produces a time series of sediment flux from a single location, which is a measurable attribute that links both Earth surface processes and strata (Toby et al., 2022). The time series generated is comparable to a time series of stratigraphic measurables collected from a 1D vertical section, which provides insight into the complex internal dynamics operating up-system of this location (Figure 1). Physical rice piles have been utilized to generate theoretical frameworks for the signal degradation and detection in STSs (Griffin et al., 2023; Jerolmack & Paola, 2010). Here, we advance this framework to understand the effect of incompleteness on the structure of autogenic noise and the detectability of environmental signals. This will provide a robust framework that can be used to predict the ability of various geomorphic environments to record evidence of external environmental perturbations.

2. Materials and Methods

2.1. Experimental Design

We use a suite of rice pile experiments presented by Griffin et al. (2023). These experiments have precisely controlled boundary conditions and generate a time series of efflux which is 100% complete compared to the incomplete time series generated from stratigraphic measurables. The experimental apparatus is constructed of two vertical parallel glass sheets 37.5 cm long, positioned 2.6 cm apart (Figure 1a). Rice was fed (influx) to the

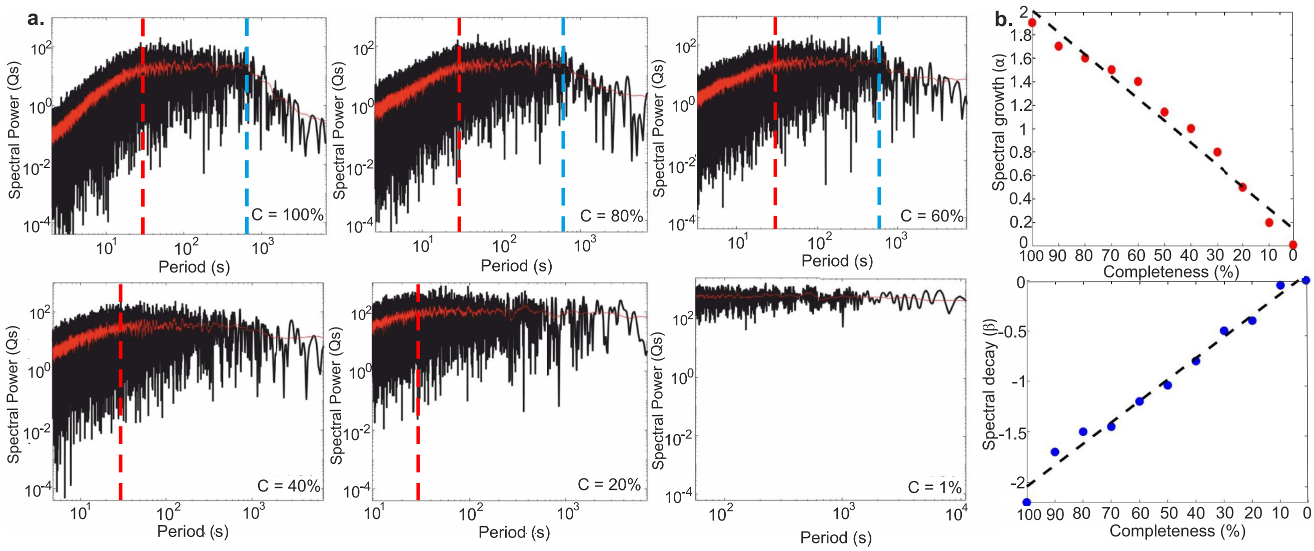

Figure 2. The temporal structure of autogenic processes evident from a time series containing temporal gaps of varying duration (a). Power spectra generated from a time series of efflux from the control experiment (influx rate of 0.37 g s^{-1}), where time is systematically removed in 10% intervals as a proxy for stratigraphic incompleteness. The full spectrum is shown in black, and the mean spectra generated by applying a moving mean (window = 50 datapoints) to the spectra are shown in red. The vertical dashed lines denote the autogenic timescales, T_{rw} (red) and T_{wb} (blue). The percentages in each panel denote the percentage completeness. Due to the temporal gaps, power spectra are generated using the Lomb-Scargle periodogram. (b) Variations in the spectral gradient (see Figure 1) of the red noise regime (spectral growth; top) and the blue noise regime (spectral decay; bottom) as a function of completeness.

pile from a dry particle feeder (Schenk Accurate) positioned 8 mm from the top surface, allowing a rice pile to form at a critical angle so that a dynamic topographic equilibrium was achieved. Over the suite of experiments, influx was defined between a minimum and maximum range (0 and 0.78 g s^{-1}) controlled at 1 s intervals via a computer connected to the sediment feeder which directly feeds the pile. Efflux was measured at approximately 1 s intervals using an Ohaus EX12002 balance (accuracy and precision of 0.1 g). The balance has a maximum mass of 12 kg, and all experiments were run until the balance was saturated. The dimensions of rice grains used in the experiments have a diameter of 2.5 ± 0.5 mm, length of 8 ± 0.5 mm and an average mass of 0.02 g. The experimental set-up is similar to that of the physical rice pile of Frette et al. (1996).

We first utilize the control experiment run with a constant influx rate of 0.37 g s^{-1}. The influx rate denotes the mean rate of the sediment feeder, and the experimental run time (9 hr) defines the time to saturate the balance at the specified influx rate. This experiment was used to quantify the effect of stratigraphic incompleteness on the spectral structure of autogenic processes and to generate confidence bands to quantify signal detectability within power spectra of tripartite geometry.

To quantify the effect of incompleteness on signal detectability and apparent signal degradation, we utilize 36 experiments run with cyclic influx (where influx rate follows a sinusoid) of different periods and amplitudes. To achieve parity with the control experiment, a mean influx rate of 0.37 g s^{-1} was attained for all cyclic experiments. Nine periodicities were chosen to cover the range of autogenic timescales present (Figure 1): 6, 12, 24, 48, 100, 250, 500s, 1000 and 2000s. Signal amplitude was chosen as percentages of the mean feed rate (0.37 g s^{-1}) increasing in 25% intervals from 25% (0.0925 g s^{-1}) to 100% (0.37 g s^{-1}).

2.2. The Removal and Interpolation of Time Within a Time Series

2.2.1. Removing Time From a Time Series

The spectral structure of autogenic processes has been quantified from a 100% complete time series (Griffin et al., 2023); we explore the implications of imperfect sampling on the temporal by systematically removing data from the time series. The sediment flux time series generated from the rice pile is limited to positive values and zeros; positive values are analogous to depositional events and zeros are analogous to stasis events. This is comparable to a time series of preserved deposition rates generated from natural systems.

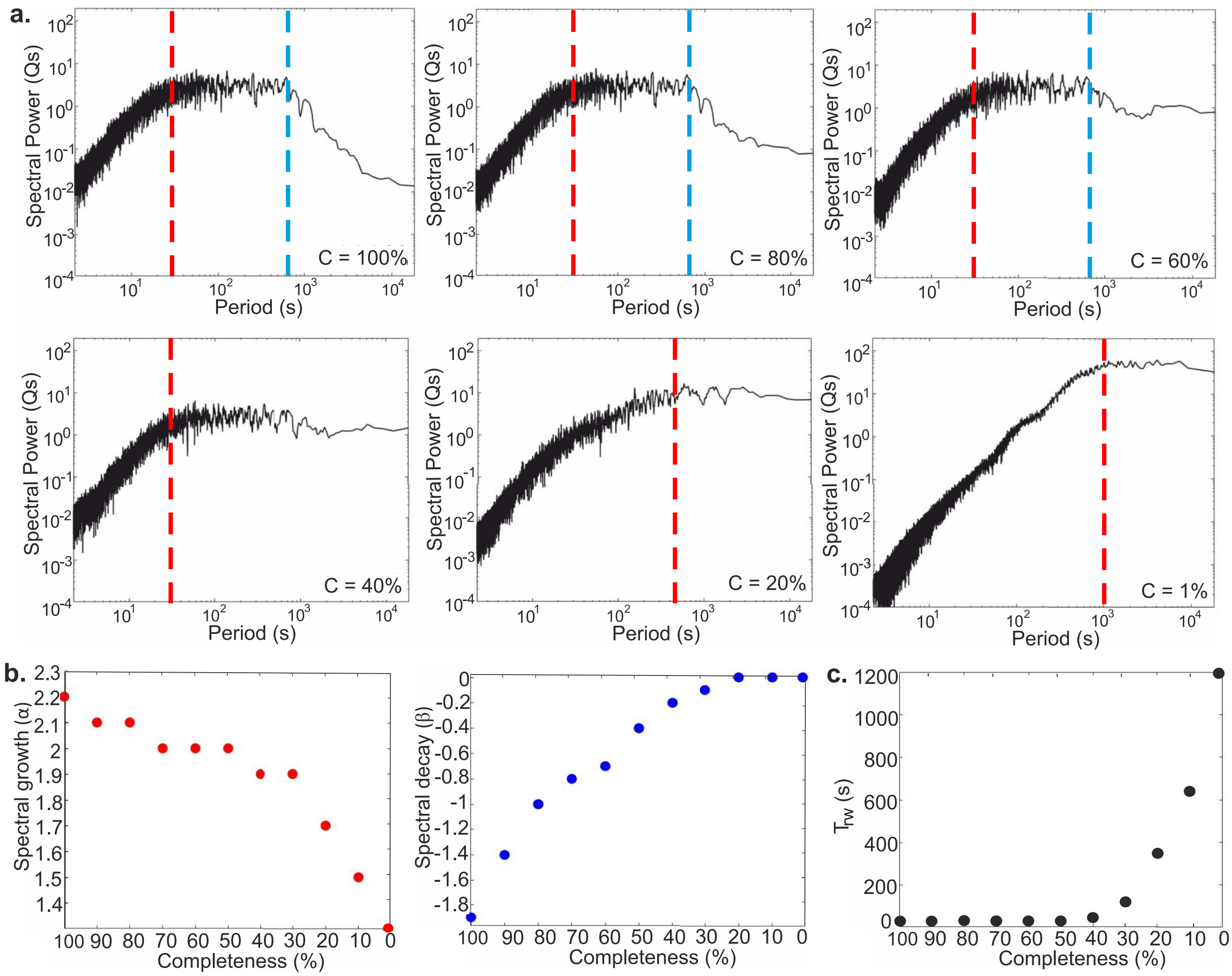

Figure 3. The temporal structure of autogenic processes evident from a time series where the temporal gaps have been removed through interpolation using the assumption of linear sedimentation rate (a) Power spectra generated from a time series of efflux from the control experiment (influx rate of 0.37 g s^{-1}) where time has been systematically removed in approximately 10% intervals as a proxy for stratigraphic incompleteness. The vertical dashed lines denote the autogenic timescales, T_{rw} (red) and T_{wb} (blue). The percentages in each panel refer to the completeness of the time series. Power spectra have been generated using the multi-taper method (MTM) with two tapers. (b) Variations in the spectral gradient of the red noise regime (left) and the blue noise regime (right) as a function of completeness. (c) Variations in T_{rw} as a function of completeness.

Physical experimental results suggest that the duration of depositional events (t_k) on deltas exhibits an exponential distribution (Ganti et al., 2011):

$$\mathrm{PDF}(t_k) = \lambda e^{-\lambda t_k}$$

Where λ is a rate parameter which defines the mean number of events in an interval, here set to 0.5, so the mean duration of depositional episodes is generally lower than the mean duration of temporal gaps (Ganti et al., 2011). This distribution defined the amount of time kept at each iteration.

Conversely, stasis events (t_r) within a system exhibit a truncated Pareto distribution (Ganti et al., 2011):

$$\mathrm{PDF}(t_r) = \frac{\alpha \gamma^{\alpha} t_r^{-\alpha-1}}{1 - \left(\frac{\gamma}{\nu}\right)^{\alpha}}$$

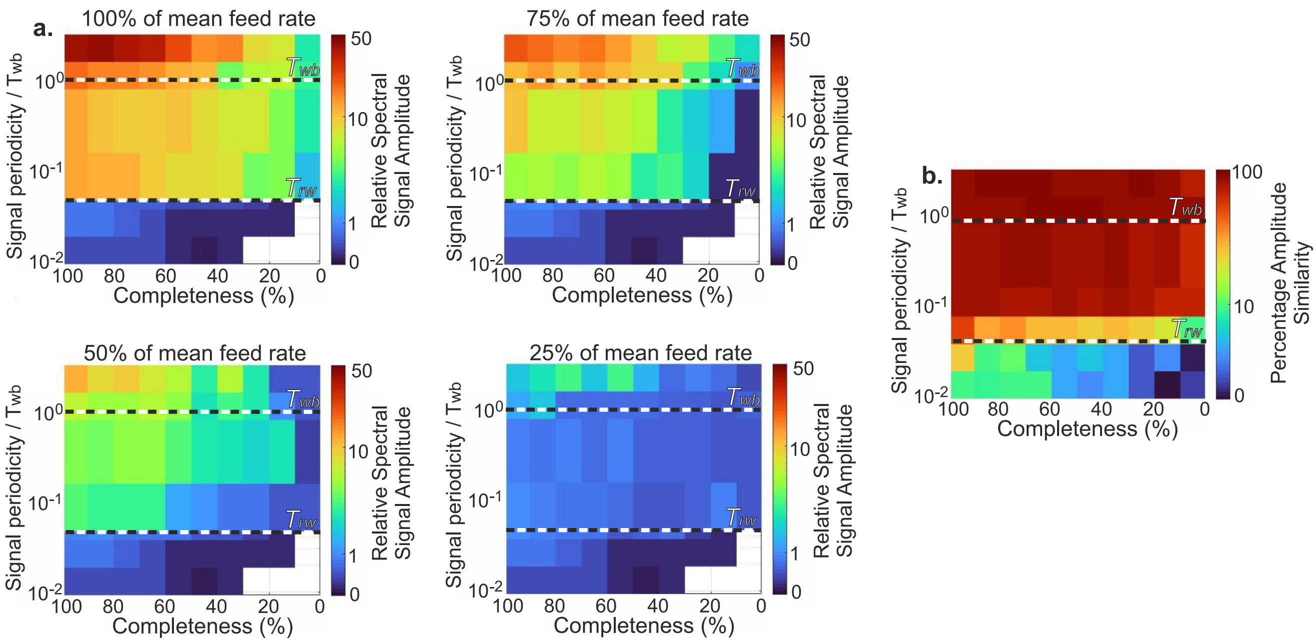

Figure 4. Signal detectability from time series containing temporal gaps of varying duration. Each subplot includes data from nine experiments where the input signal periodicity varied between 6 and 2,000 s. (a) The combined effects of signal periodicity, amplitude and stratigraphic completeness on signal detectability. Signal amplitude decreases at 25% intervals. (b) Apparent signal degradation from time series containing temporal gaps of varying duration. Signal degradation is not influenced by signal amplitude (Griffin et al., 2023); hence, apparent signal degradation is only quantified for signals with amplitudes equivalent to 100% of the mean feed rate.

Where α is the tail index which controls the shape of the distribution, γ is the smallest time step removed (here, set to 1) and υ is the truncation parameter, which defines the largest time step removed (here, set to 650s), which is equivalent to the longest autogenic timescale, T_{wb}, which is 650s in the rice pile control experiment (Griffin et al., 2023). This distribution defines the amount of time removed at each iteration.

To generate an incomplete time series, a random number from within the limits of the exponential distribution is generated, defining the number of time steps kept. Following this, a random number from within the limits of the truncated Pareto distribution was generated, defining the number of time steps removed. This pattern was repeated for the full length of the time series. Completeness was systematically varied between 100% and 1% by changing the tail index (α) of the truncated Pareto distribution between 3 and 0.05 respectively. We acknowledge this is not exactly akin to how stratigraphy is generated; as we utilize the overall percentage completeness of a time series, we believe this is comparable to natural systems that produce time series with similar overall completeness. This method allows us to explore the impact of incompleteness on both the spectral structure of autogenic processes and signal detectability.

The new discrete time series, generated by removing proportions of time, contains gaps of varying duration. This variable discretization of time resembles the record of autogenic processes recorded in stratigraphy that could be produced if the absolute ages of all sediment present were known. To generate power spectra from a time series containing gaps of varying duration, we use the Lomb-Scargle Periodogram, which is the best available technique to compute periodicity directly from unevenly sampled data (VanderPlas, 2018).

2.2.2. Interpolation Using an Assumption of Linear Sedimentation Rate

The lack of age constraint within stratigraphy means that generating a time series with absolute knowledge of time is improbable. Instead, the section in question can be bound by sparsely dated horizons under the assumption of a linear sedimentation rate between these points. This method is applied to produce linearly sampled time series from many environmental measurables (Hofstra et al., 2008; Martínez-Graña et al., 2016; Sadler, 1981; Wu et al., 2013). We utilize both methods to compare the spectral structure of autogenic processes and signal detectability generated from time series containing temporal gaps to the record influenced by the assumption of

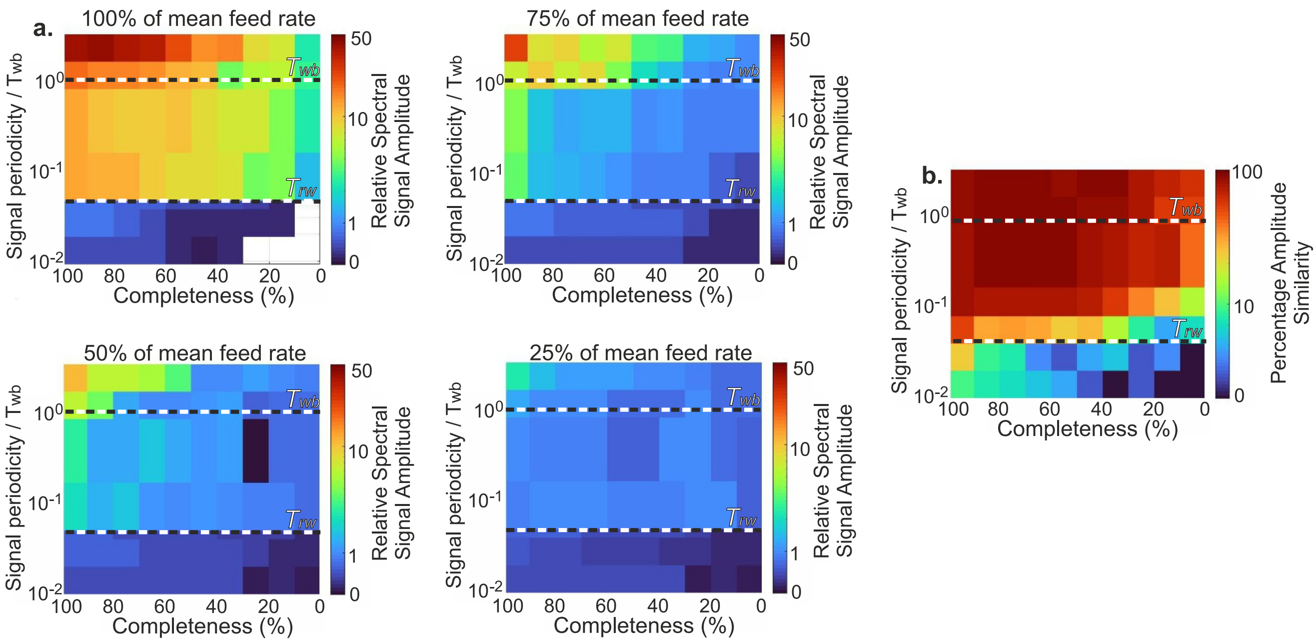

Figure 5. Signal detectability from time series where the temporal gaps have been removed through interpolation using the assumption of linear sedimentation rate. Each subplot includes data from nine experiments where the input signal periodicity varied between 6 and 2,000 s. (a) The combined effects of signal periodicity, amplitude and stratigraphic completeness on signal detectability. Signal amplitude decreases in 25% intervals. (b) Apparent signal degradation from time-series where the temporal gaps have been removed through interpolation using the assumption of linear sedimentation rate. Signal degradation is not influenced by signal amplitude (Griffin et al., 2023); hence, apparent signal degradation is only quantified for signals with amplitudes equivalent to 100% of the mean feed rate.

linear sedimentation. We interpolate the degraded time series onto a time interval of 1 s between the first and last-time steps using the nearest neighbor method, where the interpolated value at the query point is the value at the nearest sample grid point. If linear sedimentation rate is assumed in a time series of stratigraphic measurables, beds bounding significant temporal gaps are thicker than average and are hence overrepresented in the apparent time. The method of interpolation chosen aims to mimic this. To generate power spectra from the linear time series, we utilize the multi-taper method (MTM) with 2 tapers (Thomson, 1982).

2.3. Signal Detectability and Apparent Signal Degradation

To make a statistical statement about the presence or not of an influx signal in power spectra, a statistical model with a good fit to the background noise spectrum must be applied from which confidence bands are generated (Vaughan et al., 2011).

As blue noise is present within the power spectra, the commonly utilized autoregressive lag 1 (AR1) model provides a poor approximation of the spectral structure (Figure S1 in Supporting Information S1). We overcome this by constructing a spectral model and a suite of associated confidence bands for power spectra of tripartite structure through adaptation of the bending power law (BPL) model (McHardy et al., 2004; Vaughan, 2010; Vaughan et al., 2011) to account for two spectral gradient breaks. The BPL model optimizes the best fit of the function to the data and smoothly changes from one power law to another (McHardy et al., 2004):

$$S_{\mathrm{BPL}} = \frac{Nf^{-\beta}}{1 + \left(\frac{f}{f_b}\right)^{\gamma-\beta}}$$

Where S is the power at a given frequency, f, N is a power-law normalization factor, f_b is the frequency associated with the bend in the power-law from one trend described with a slope of β to a second trend described by a slope of γ.

We augment this equation to account for two bends in the power spectra and generate the double bending power law (DBPL) model;

$$S_{\mathrm{DBPL}} = \frac{Nf^{-\beta}}{1 + \left(\frac{f}{f_{b1}}\right)^{-\beta} + \left(\frac{f}{f_{b2}}\right)^{\gamma-\beta}}$$

Where S_{DBPL} is the spectral power at a given frequency, f, β is the slope of the power law at high frequencies, γ is the slope of the power law at low frequencies and f_{b1} and f_{b2} are the frequencies of the two bends. This equation assumes that the slope of the power law at intermediate frequencies is zero (white noise). This spectral model provides a strong statistical fit to the power spectra generated from the physical rice pile (Figure S2 in Supporting Information S1).

To quantify the signal detectability, the 95% confidence band generated from the DBPL model was applied to the power spectra. The ratio between the power of the signal spike and the power of the 95% confidence band at the imposed periodicity was quantified: if this ratio exceeds one, a signal is considered statistically detectable.

To quantify the amount of apparent signal degradation due to incompleteness, we stack the efflux time series into lengths equal to the input period, and take the mean of the efflux for each second over the imposed periodicity. From this, we gain a mean ensemble efflux to which we fit a sine wave with a period equal to the known input and return an amplitude and phase based on the signal present in the mean ensemble efflux. We compare the amplitude of the signal evident in the ensemble efflux to that of the known input signal and quantify a percentage similarity (Griffin et al., 2023).

Data is removed from the time series randomly; hence, the detectability and apparent degradation of a sinusoidal sediment flux signal is dependent on the exact data points removed. Whilst 2 time series may have the same completeness, different parts of a sinusoidal signal may be removed each time, which influences signal degradation and detectability. To quantify a representative detectability and apparent degradation for each incompleteness interval, the time series was degraded randomly 5 times and an average detectability and apparent degradation was quantified. Five iterations are the minimum number required to stabilize the trends seen in Figures 4 and 5.

3. Results

3.1. Incompleteness on the Structure of Autogenic Processes

Firstly, we quantify the temporal structure of autogenic processes evident within stratigraphy using a time series containing temporal gaps of varying duration (Figure 2). This provides an understanding of how incompleteness alone influences the spectral structure of autogenic processes. When power spectra are generated from a time series which is between 100% and 35% complete, all three noise regimes (red, white and blue noise) are present. As completeness decreases beyond 50%, the temporal range of the red noise regime is gradually reduced as short time scales are progressively removed from the power spectra; this is indicated by T_{rw} moving progressively to the left as completeness decreases (Figure 2a). In contrast, the timescales over which blue noise persists are consistently present. As completeness decreases, the gradient of spectral growth (red noise) and spectral decay (blue noise) both decrease at a linear rate, meaning the structure of these noise regimes becomes increasingly difficult to distinguish. When completeness is reduced to 50%, the structure of blue noise is lost, rendering the power spectra to white noise over all timescales greater than T_{rw}. This is indicated by T_{wb} disappearing as completeness decreases below 50% (Figure 2a). As completeness is reduced to below 35%, short timescales continue to be removed from the power spectra; at 15% complete, all timescales less than T_{rw} are removed, rendering the power spectra to solely white noise.

Secondly, we quantify the structure of these processes evident within an incomplete time series where the temporal gaps have been removed through interpolation using the assumption of linear sedimentation rate. This is analogous to a time series of stratigraphic information (Figure 3). When the time series is between 100% and 35% complete, all three noise regimes (red, white and blue noise) are present within the power spectra. The timescales over which both red noise and blue noise persist are consistently present. Although the structure of the red noise regime remains easily distinguishable with decreasing completeness, identifying blue noise is difficult when completeness is reduced to 50% as the gradient of spectral decay (blue noise) decreases. When completeness is below 50%, the structure of blue noise is lost, rendering the time series to white noise over all timescales greater than T_{rw}. This is indicated by T_{wb} disappearing as completeness decreases below 50% (Figure 3a). As completeness is reduced to below 35%, T_{rw} gradually increases from 30 s to more than 1,000 s as high-frequency noise is added to the time series via interpolation. This is indicated by T_{rw} moving progressively to the right as completeness decreases (Figure 3a).

3.2. Incompleteness on the Detectability of Environmental Signals

Firstly, we quantify signal detectability from a time series containing temporal gaps of varying duration (Figure 4), which provides insight into how incompleteness alone influences signal preservation. Signals with periodicity less than T_{rw} are undetectable over all amplitudes within a complete time series due to signal shredding and are therefore undetectable over all amplitudes within a time series which is incomplete to any degree (Griffin et al., 2023). High amplitude signals (100% of the mean feed rate) with periodicity between T_{rw} and T_{wb} are detectable within a complete time series. As completeness decreases, signal detectability also decreases, but high amplitude signals over these periodicities remain detectable within a time series over all levels of completeness (Figure 4a). As the amplitude of these influx signals is reduced, signal detectability decreases and medium amplitude signals (50% of the mean feed rate) with periodicity between T_{rw} and T_{wb} can be rendered undetectable in a time series with low completeness. Low amplitude input signals (25% of the mean feed rate) with periodicity between T_{rw} and T_{wb} are undetectable within a complete time series as they are obscured by autogenic noise (Griffin et al., 2023); hence, these signals are undetectable within a time series which is incomplete to any degree (Figure 4a). Long period signals with periodicity greater than T_{wb} show enhanced detectability (Griffin et al., 2023); hence, high amplitude long period influx signals remain highly detectable within time series over all levels of completeness. Although long period signals remain detectable within a highly complete time series as signal amplitude is reduced, long period, low amplitude signals (i.e., 25% of the mean feed rate) can be rapidly rendered undetectable as completeness decreases below 50% (Figure 4a).

Secondly, we quantify the detectability of signals from a time series where the temporal gaps have been removed through interpolation using the assumption of linear sedimentation rate. This is analogous to a time series of stratigraphic information (Figure 5). Overall, a divide in signal detectability is evident when completeness is approximately 50%. This is intuitive, as approximately half the time series, and hence, the influx signal, is removed and replaced with high-frequency noise. Signals with periodicity less than T_{rw} are undetectable over all amplitudes within a complete time series due to signal shredding by autogenic processes and are therefore undetectable over all amplitudes within a time series which is incomplete to any degree (Griffin et al., 2023) (Figure 5). High amplitude signals with periodicity between T_{rw} and T_{wb} are detectable within a complete time series. As completeness decreases, signal detectability also decreases, but high amplitude signals over these periodicities remain detectable within a time series overall levels of completeness (Figure 5a). As the amplitude of the influx signal is reduced, signal detectability reduces dramatically, where medium amplitude signals show minimal detectability even within a highly complete time series. Low amplitude input signals are undetectable within a complete time series as they are obscured by autogenic noise (Griffin et al., 2023); hence, these signals are undetectable within a time series which is incomplete to any degree. Signals with periodicity greater than T_{wb} show enhanced detectability when completeness is high (Griffin et al., 2023); however, as completeness is reduced to below 50%, it becomes difficult to differentiate signals from autogenic noise. As the amplitude of the influx signal is reduced, the detectability of these long-period signals significantly reduces, where low amplitude long-period signals are rendered undetectable when completeness is below 80% (Figure 5a).

Although the overall trends in signal detectability between both sets of time series (e.g., Figures 4 and 5) show similarity; signal detectability is significantly reduced over all periodicities and amplitudes as a result of interpolation using the assumption of linear sedimentation rate. This detectability reduction mainly affects signals with periodicity between T_{rw} and T_{wb}, and long-period signals beyond T_{wb} are only minorly affected.

3.3. Incompleteness on the Apparent Degradation of Environmental Signals

Autogenic processes degrade sediment flux signals when the signal amplitude is less than T_{rw} (Griffin et al., 2023; Jerolmack & Paola, 2010). Given this, we explore the apparent degradation experienced by environmental signals due to incompleteness. Here, apparent degradation refers to the amplitude reduction experienced due to incompleteness. This is analogous to the amplitude reduction as a result of signal shredding (Griffin et al., 2023).

For both data sets (Figures 4b and 5b), signals with periodicity less than T_{rw} experience a severe degradation in amplitude due to signal shredding and are therefore severely degraded within a time series which is incomplete to any degree (Griffin et al., 2023) (Figures 4b and 5b). Signals with periodicity greater than but close to T_{rw} experience a gradual increase in degradation as completeness decreases, where they are severely degraded when completeness is low. Although degraded, these signals can still be reconstructed by stacking the time series over all levels of completeness. Long period signals above T_{rw} and T_{wb} experience minimal degradation until completeness is low (i.e., <30%), where the recoverable signal amplitude is approximately half of the known input amplitude.

4. Discussion

4.1. Incompleteness on the Colors of Noise Preserved in Sediment-Transport Systems

The tripartite spectral structure of autogenic processes is evident from a time series of high temporal resolution (Griffin et al., 2023); however, the spectral structure of these processes preserved in stratigraphy is rarely representative of their true character. Whilst we turn to strata as an archive of Earth's surface processes and environments, this record is inevitably incomplete (Paola et al., 2018; Sadler, 1981; Schumer & Jerolmack, 2009; Straub & Esposito, 2013; Straub & Foreman, 2018; Vendettuoli et al., 2019), which hinders and warps our interpretation of the spatiotemporal scales of autogenic dynamics present within a STS.

Stratigraphers have long known that all stratigraphic sections are incomplete (Ager, 1973; Hutton, 1788; Sadler, 1981); hence, efforts have been made to understand the circumstances which allow for the reconstruction of environmental signals from incomplete records, encompassing both autogenic timescales and the properties of environmental signals (e.g., Foreman & Straub, 2017; Kemp & Sexton, 2014; Trampush et al., 2017). However, the impact of incompleteness on the spectral structure of autogenic processes has not been deeply considered as the preserved noise is assumed to accurately characterize the full spatiotemporal scales of autogenic processes within landscapes and strata. We show the importance of also understanding the noise removed in the process. As completeness decreases, the preserved record is less faithful to the full spectrum of autogenic processes, hindering our ability to reconstruct paleo-surface processes. However, the structure of the resulting power spectra can provide stratigraphers with an approximate evaluation of completeness, from which the full spectral structure can be estimated. Quantifying the change in spectral growth and decay as a function of completeness allows us to infer the structure and strength of paleo-surface processes from an incomplete record and hence to some extent recreate the autogenics within a STS.

Although blue noise is common in power spectra generated from a time series of Earth surface processes with sufficient duration (e.g., Benavides et al., 2022; Lazarus et al., 2019; McKean & Roering, 2004), evidence of this regime within power spectra generated from stratigraphic measurables is generally rarer (e.g., Aziz et al., 2008; Taylor Perron & Huybers, 2009; Vaughan et al., 2011) (Figure 6). Our results suggest this is predominantly due to stratigraphic incompleteness filtering the preservation of surface processes, where one effect is to remove evidence of blue noise. The magnitude of the autogenic events associated with this spectral regime generates a system-scale response (e.g., the largest autogenic events within a system of a defined size). However, the rarity of these events within a STS renders them more likely to be removed (Ganti et al., 2020) or at least significantly reduced in scale from a time series of stratigraphic measurables. The removal of the Elwha Dam in Washington, USA released 20 million tons of sediment, generating a huge sediment wave downstream and initiating a rapid aggradational response (Ritchie et al., 2018). Although the response to this event was large, the associated geomorphic imprint rapidly waned, and channel incision dispersed the deposits of the initial sediment wave (East et al., 2018), which could massively reduce the stratigraphic evidence of this event. Furthermore, the sedimentary record at one locality in a STS may not record evidence of all sediment-transport events as the signal may not be of sufficient magnitude to propagate and deposit downstream. For example, a 500 million ton sediment pulse generated in response to knickpoint collapse on the Rio Coca in Ecuador occurred in the upstream reach but is likely undetectable at the mouth of the Amazon (Barrera Crespo et al., 2024). Field evidence over a range of scales suggests that stratigraphy is more likely to record mundane, common transport conditions (Ganti et al., 2020). This means that small-scale sediment-transport events can be removed entirely from the record, but their high frequency allows for regularity in preservation. Although the time series in question may not record the full extent of autogenic processes, this does not mean they are absent within the system; care must be taken to differentiate these concepts. To ensure the most accurate reconstruction of autogenic dynamics within a STS, we must aim to

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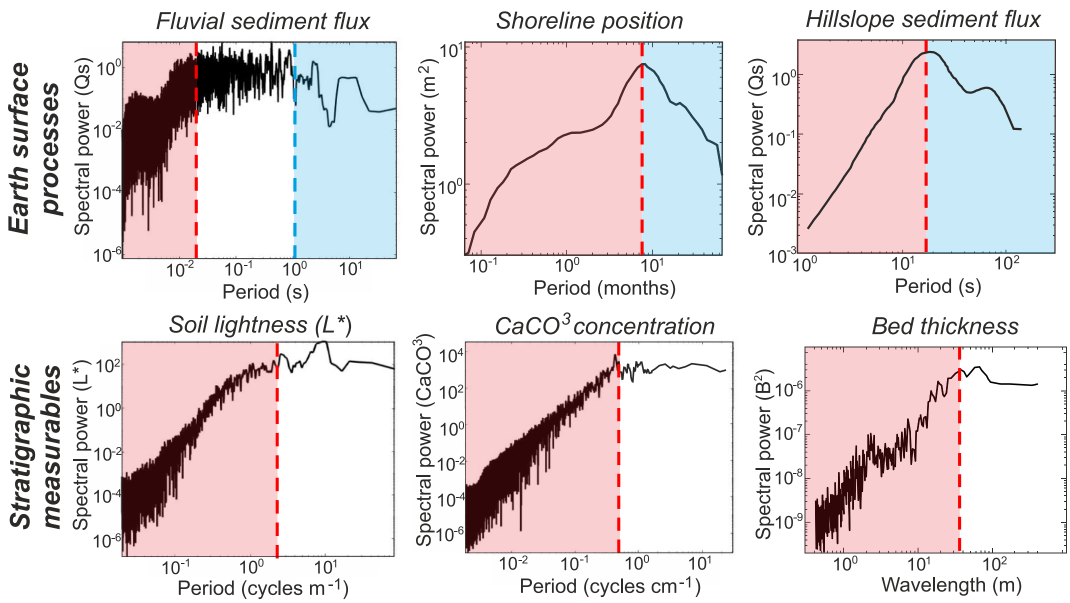

Figure 6. The spectral structure of autogenic processes preserved within surface and stratigraphic measurables. *Top*: Power spectra generated from time series of surface processes, where all spectra show evidence of red and blue noise, hypothesized to be universal. Data taken from Benavides et al. (2022), Lazarus et al. (2019), and McKean and Roering (2004). *Bottom*: Power spectra generated from a time series of stratigraphic measurables, where the full spectral structure of autogenic processes is not present in the majority of the spectra shown. Data taken from Aziz et al. (2008), Vaughan et al. (2011), and Taylor Perron and Huybers (2009).

reduce the requirement to interpolate a time series as much as possible. Absolute knowledge of time is unattainable; instead, a high sampling resolution allows temporal gaps to be minimized and results as much as possible from incompleteness alone. This will allow scientists the ability to identify and account for as many unconformities as possible, as well as develop techniques to improve the messy conversion from space to time (Barefoot et al., 2023).

The preservation of blue noise within power spectra generated from a time series of stratigraphic information (either physical measures or chemical data as a proxy for an environmental change) is infrequent, but we highlight that some studies find evidence of blue noise (Figure 6) (Abels et al., 2013; Dunkley Jones et al., 2018; Kurokawa et al., 2019; Liu et al., 2023; Pas et al., 2020). However, blue noise is often discounted to apply the autoregressive lag 1 (AR1) spectral estimation model. The ease of visually identifying the noise regimes present within power spectra is dependent on how the data is displayed (Figure 7). Power spectra generated from stratigraphic measurables are commonly displayed with a linear frequency axis, which allows the alleged periodicity to be equated to cycles per meter. This impedes the identification of the noise regimes present. In this case, blue noise appears as a sharp drop in power at low frequencies that is easily missed, especially when the rest of the power spectra appear to resemble a sloping continuum from low to high frequencies common with a red noise process (Weedon, 2003). This can explain the common thought that stochastic variations in sediment transport are characterized in power spectra by red noise, where the spectral rollover to white noise is thought to define the upper limits of stochasticity within a STS (Jerolmack & Paola, 2007, 2010; Meyers, 2012; Vaughan et al., 2011; Weedon, 2003). Instead, displaying the same data with a logarithmic period axis allows the full spectral structure to be visualized and interpreted with more clarity (Figure 7). Therefore, the tripartite spectral structure of autogenic processes may not be as rare as thought, but rather misinterpreted. We must now look beyond the traditionally assumed Gaussian noise models and instead establish realistic expectations of the structure of autogenic variability produced and also preserved in the stratigraphic record (Grove et al., 2022; Tu et al., 2023). This highlights the requirement to understand the true temporal structure of autogenic processes within a system, and how to best analyze the data before inverting spectra for paleo-surface process interpretation and signal detectability. Accounting for blue noise within power spectra generated from stratigraphic measurables has significant implications for generating estimates of spectral background structure from which confidence bands are produced to determine the presence of environmental signals (Hajek & Straub, 2017; Vaughan et al., 2011). The AR1 model, which assumes that

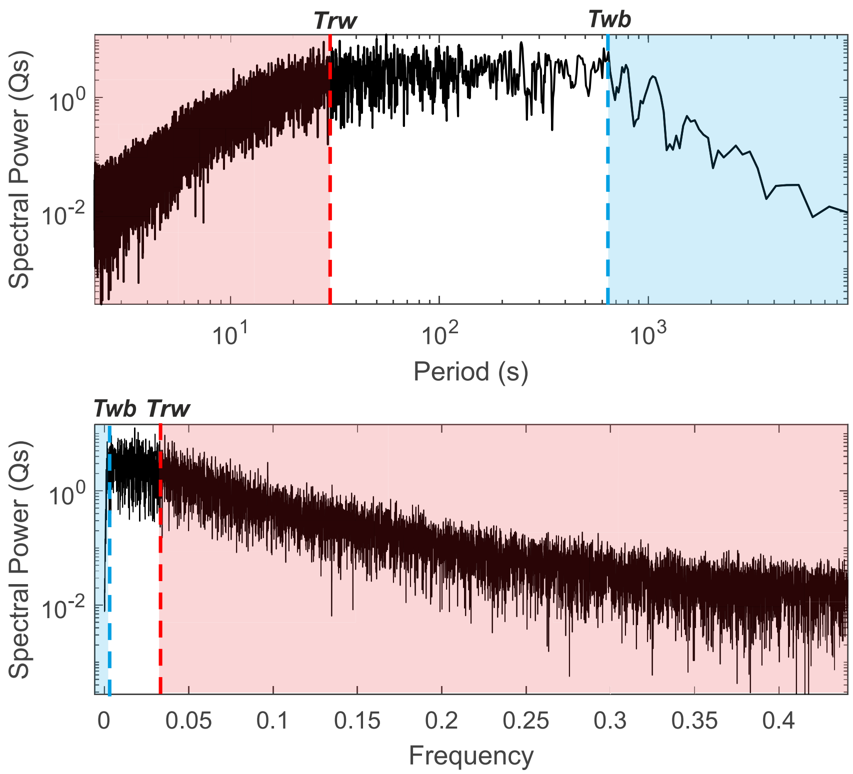

Figure 7. Power spectra generated from the control experiment (influx rate of 0.37 g s^{-1}) with both autogenic timescales, T_{rw} and T_{wb}, highlighted. *Top*: Power spectra plotted as a function of period with a logarithmic *x*-axis. The tripartite spectral structure is evident. *Bottom*: Power spectra plotted as a function of frequency with a linear *x*-axis. The spectra appear to resemble a sloping continuum from low to high frequencies common with a red noise process; however, the presence of blue noise is evident at low frequencies by the sharp drop-off in spectral power.

power spectra only contain red noise over high frequencies and white noise over low frequencies, is commonly applied to all power spectra generated for paleoclimate analysis as the presence of blue noise is often overlooked. If the AR1 model is applied to power spectra that contain blue noise, the model would generate confidence bands where the expected power at low frequencies will be underestimated relative to the true power of the spectra. This means that the transition to blue noise could be confused with a statistically significant periodicity, resulting in false positives and spurious signals (Hajek & Straub, 2017).

Although incompleteness has minimal impact on the spectral structure of autogenic processes until a time series is less than 50% complete at common discretization timescales, we do not include other time-reducing effects. Alongside incompleteness, low measurement resolution and/or the utilization of short temporal records can further hinder the preservation of autogenic processes. Although blue noise should be evident within a time series of moderate completeness, in reality, evidence of the full tripartite spectral structure may be removed if the time interval of measurement is shorter than the maximum autogenic timescale, or due to the short time series studied. Whilst the length of the time series available from stratigraphic measurables is bound by outcrop availability or the length of core extracted, to achieve the best estimate of autogenic spectral structure, the measurement resolution utilized should be considered carefully to allow for the most thorough temporal sampling. Although we can control these factors to some extent, a time series of stratigraphic measurables is already substantially hindered if the time series is significantly incomplete. Further work should focus on understanding the effects of measurement resolution on the structure of autogenic processes and work to define an optimal measurement resolution for stratigraphic time series analysis.

4.2. Quantifying Signal Detection and Degradation From an Incomplete Record

To overcome poor age constraints within stratigraphic sections, sediment age is linearly interpolated between sparsely dated horizons (Abels et al., 2013; Ramos-Vázquez et al., 2017); however, incompleteness and

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substantial interpolation can hinder our ability to differentiate signal degradation and detection timescales. The loss of blue noise from power spectra due to incompleteness impedes our ability to quantify T_{wb}. This means that the maximum timescale of autogenic organization and the timescales of faithful signal preservation over all amplitudes cannot be quantified (Griffin et al., 2023). However, this timescale has been predicted to be of similar magnitude as the compensation timescale, T_c (Griffin et al., 2023). T_c can be defined from stratigraphy (Wang et al., 2011), hence allowing for the approximation of T_{wb}. The substantial interpolation of stratigraphic time series can drive the red-to-white noise transition (e.g., T_{rw}) to longer timescales (Figure 3), extending the duration of apparent correlation due to the addition of high-frequency noise via interpolation. This generates an apparent spectral T_{rw}, which can be over an order of magnitude larger than the true T_{rw}, and hence, an apparent shredding regime. If T_{rw} is known, this extended red noise regime can be differentiated into true and apparent red noise and the true shredding timescales can be defined. However, the reliance on power spectra to quantify T_{rw} means that signals with periodicity over all apparent red noise timescales will appear shredded when incompleteness renders them undetectable.

Incompleteness also has direct ramifications for the detectability and reconstruction of environmental signals from stratigraphic measurables. Incompleteness has been described as having power-limiting effects on signals (Kemp, 2012), where the power of the signal spike is significantly diminished when compared to the signal spike from a complete time series. Therefore, a signal that only just breaches the 90% confidence band is the best we can hope for (Hilgen et al., 2015; Kemp, 2012). We show that when the absolute ages of all sediment present in the time series are known, the impact of incompleteness on signal detectability is minimal. The direct effects of incompleteness are less than previously described (e.g., Hilgen et al., 2015; Kemp, 2012) and instead, poor geochronology and the assumption of a linear sedimentation rate cause a significant reduction in signal detectability. The assumption of linear sedimentation rate can cause signals to be undetectable from within a highly incomplete time series unless the signal is of high amplitude or the periodicity exceeds T_{wb}. This means that many meso-timescale environmental forcings (those with periodicity less than $T_{wb,}$ and span timescales between 10^1 and 10^4 years (Sheets et al., 2002)) may experience a severe detectability decrease, and hence be difficult to detect within a time series.

Furthermore, Blum and Hattier-Womack (2009) calculated that a change in temperature due to Milankovitch scale climatic forcing may result in a change in sediment yield of 20%–50% according to the empirical BQART model (Syvitski & Milliman, 2007). This would generate a low amplitude sediment flux signal with an amplitude of 25% of the mean feed rate; we show that such signals are rendered undetectable within highly incomplete time series. If the time series of interest becomes incomplete over timescales comparable to known environmental signals, the assumption of a linear sedimentation rate causes a severe detectability decrease where these signals may be rendered undetectable in the time series. This challenges our ability to extract subtle environmental signals from field measurements with limited exposure and current methods (Straub et al., 2020; Toby et al., 2019).

However, we highlight that the amplitude of the spectral peak present within an incomplete time series will always be the minimum spectral amplitude for the signal in question. This could result in evidence of signals being missed within a power spectrum as the signal power has been reduced to a magnitude similar to the power of autogenic noise. Due to the detectability reduction with decreasing completeness, if a measurable response is produced from an incomplete time series, the true signal would naturally produce a much larger response. Although true, this must still be treated with caution. The 95% confidence band denotes the 95th percentile of the data; hence, 5% of the noise will consistently breach the confidence band. If part of the transport system noise occurs at a periodicity of known external forcing (e.g., Milankovitch-forced climatic periodicity), then it could be assumed as periodicity and justified due to the spectral amplitude reduction. To overcome this, a simplistic remedy was proposed by defining a detection threshold where the probability of false detections is low: the global (99.95%) confidence band (Vaughan et al., 2011). This is a strong statistical solution; however, the power reduction due to incompleteness could mean signals cannot always be detectable at this level (Meyers, 2019). Whilst low significance levels may lead to false positive signals, high significance levels could lead to false negative signals, and generate competing problems (Hilgen et al., 2015). We highlight the use of T_{wb} as the timescale of faithful signal transfer, even from highly incomplete stratigraphic sections (Griffin et al., 2023). However, a pathway for future work is to quantify from field data whether the raised detection threshold is too harsh for detecting signals from incomplete records, and how much this threshold should be raised to produce a realistic and accurate signal detectability threshold.

Incompleteness impacts signal degradation less than signal detectability, but removing time from a time series still has consequences for reconstructing environmental signals. Although we show that signals with periodicity above T_{rw} still resemble the known input signal over all degrees of completeness, when completeness is low (e.g., below 20%) the reconstructed signal amplitude can be degraded to half of the true signal amplitude. This amplitude reduction is not as severe as the amplitude reduction caused by signal shredding, but this apparent degradation combined with the apparent increase in T_{rw} could allow these signals to appear shredded. We highlight that these signals have not experienced shredding by autogenic processes but have been degraded in amplitude by incompleteness, which affects the structure of the signal recorded in a time series. These signals could potentially be reconstructed if the signal periodicity (e.g., the periodicity of Milankovitch-scale orbital forcing) was known. Therefore, multiple realizations of the time series could be stacked at this periodicity, which could aid the reconstruction of environmental signals rendered undetectable by incompleteness. However, interpolation onto a linear sedimentation rate brings significant error into the reconstructed time series as the proportions of the input signal preserved in each time interval are not linear, making this method generally unfeasible. Methods to improve the signal detectability from a time series of stratigraphic information without using linear interpolation have been suggested (e.g., Trampush & Hajek, 2017), however, a pathway for future work is to investigate the effect of various methods of interpolation on signal detectability.

4.3. Detection and Reconstruction of Sediment-Supply Signals From Stratigraphic Measurables

The theoretical framework can be used to guide the interpretation of sediment-supply signals from a time series of stratigraphic measurables, provided we have knowledge of stratigraphic completeness, the properties of the input signal and the compensation timescale, T_c. Over short timescales (10^1–10^3 years), completeness is set by the maximum magnitude of fluctuations in sedimentation, controlled by the internal stochastic dynamics of a STS. However, over long timescales (10^4–10^5 years), completeness shows little variation as sedimentation is controlled by subsidence, resulting in a completeness exponent close to 1 (Jerolmack & Sadler, 2007). To highlight differences between STS, we note that channelized depositional environments generally have shallower short-term completeness exponents than non-channelized depositional environments; by concentrating sedimentation into a narrow zone, channels increase the rapidity and noisiness of sediment accumulation (Jerolmack & Sadler, 2007). Using the short-term completeness exponents for different depositional environments, and using half the period of the imposed signal as the minimum discretization timescale (according to the Nyquist sampling theorem), we can ascertain an estimated completeness for a time series of stratigraphic measurables that might contain an imposed signal.

This framework can be applied in two ways depending on whether the information sought is an estimate of signal detectability (forward application) or signal properties (inverse application). Both applications can be applied to time series of information which contain temporal gaps (Figure 4) and those which have undergone interpolation (Figure 5). The rice pile only allows for the analysis of surface fluxes due to the lack of subsidence. When applying this framework to a time series of stratigraphic information, we suggest normalizing the 3D space by the compensation timescale, T_c, which represents the maximum timescale of autogenic organization within stratigraphy and marks the transition from transient to persistent rates of sedimentation (Straub et al., 2020). Hence, T_c is the smallest discretization timescale necessary to obtain a complete stratigraphic record (Straub et al., 2020).

The forward application of this framework provides an estimate of signal detectability and the ratio of the signal spike to the 95% confidence band. This provides more certainty when identifying potential signals from a time series of stratigraphic information. The estimated ratio of the signal spike to the 95% confidence band generated can be for either a time series which contains temporal gaps (e.g., Figure 4), or a time series where temporal gaps have been removed by linear interpolation (e.g., Figure 5). The benefit of this is that it allows for the detectability of the original signal to be compared to the expected detectability after linear interpolation. As an example, we can utilize Figure 5 to approximate whether a 40 kier Milankovitch signal will be detectable within a power spectrum generated from a linearly interpolated time series of stratigraphic measurables from the Mississippi Delta. The y-axis of Figure 5 requires knowledge of signal periodicity (40 kyr). To quantify signal amplitude, and hence utilize the correct amplitude subplot, we assume a change in sediment input flux (signal amplitude) of approximately 50% (Blum & Hattier-Womack, 2009). The x-axis of Figure 5 requires an estimate of stratigraphic completeness. The database of depositional environments provides a short-term incompleteness exponent for delta's of $\propto = 0.44$, allowing us to estimate completeness as: $C = a\left(\frac{\text{discretization dt}}{T_C}\right)^{\propto}$, where a is approximately 1, the discretization dt is half input signal periodicity (20 kyr), and T_c is the compensation timescale; 200 kyr for the Mississippi Delta (Li et al., 2016). Using these values, we calculate a completeness of $C = 36\%$ for the Mississippi Delta. We can then place the signal within all three axes of the framework to estimate the expected ratio of the signal spike to the confidence band. We estimate this ratio as ~1.5; this signal would breach the confidence band but detectability is low.

The inverse application of this framework provides an estimate of the true amplitude of the imposed signal, which is generally difficult to quantify first-hand. Although identification of signal periodicity takes precedence in cyclostratigraphy, we provide a novel method to quantify the imposed signal amplitude, which is commonly unknown. As an example, we can utilize the trends in Figure 5 to approximate the absolute amplitude of a Milankovitch signal identified within a power spectrum generated from a linearly interpolated time series of soil lightness taken from the Bighorn Basin, USA (Abels et al., 2013), where a spectral spike that breaches the 99% confidence band is evident. Because of the linear interpolation of stratigraphic information onto a regular time series, we emphasize that the ratio input will be the minimum signal detectability. The *y*-axis of Figure 5 requires knowledge of signal periodicity (20 kyr). To place the signal within the colored matrix, we utilize the known ratio of the signal spike to the confidence band (~2). The *x*-axis of Figure 5 requires an estimate of stratigraphic completeness. The depositional environment of this strata has been interpreted as channelized alluvial plain (Abels et al., 2013), providing a short-term completeness exponent of $\propto = 0.17$, allowing us to estimate completeness as: $C = a\left(\frac{\text{discretization dt}}{T_C}\right)^{\propto}$, where a is approximately 1, the discretization dt is half the input signal periodicity (10 kyr), and T_c is the compensation timescale; 67 kyr for the Bighorn Basin (Straub et al., 2020). Using these values, we calculate a completeness of $C = 72\%$ for the Bighorn Basin. We can then place the signal on the correct amplitude subplot to estimate the expected signal amplitude. We estimate this to be 25% of the mean feed rate.

We stress that the framework presented is merely a guide for the signal detectability within stratigraphic measurables. Time series of stratigraphic information from different locations within the same STS may have similar estimated completeness, but the instances of time preserved may differ, and hence change the exact signal preserved. In the framework presented, the time series was degraded randomly 5 times to stabilize the trends and an average detectability and apparent degradation was quantified. Although we utilize the average detectability and apparent degradation for this framework, we find that for the same degree of completeness, signal detectability can range by ±7% and signal degradation by ±10% depending on the time intervals removed in each iteration. Hence, we highlight the uncertainty in these estimations. This framework can provide a conceptual path forward for signal detection from stratigraphic measurables; however, this needs to be tested within field scale systems. Application of this framework allows stratigraphers the ability to quantitatively justify the interpretation of environmental signals in landscapes and strata and also offers a new direction for defining robust confidence limits for signal detectability.

5. Conclusions

- Incompleteness and the linear interpolation of time between dated horizons distort the true autogenic signal, hence defining the true nature and timescales of autogenic processes can be improbable when completeness is low.
- The preservation of the true autogenic signal within stratigraphic measurables is problematic; however, the ease of visually identifying the structure of autogenic noise can be impeded by how the data is displayed. This highlights the requirement to understand how to analyze stratigraphic data before inverting spectra for paleosurface process interpretation and signal detectability
- Incompleteness has consequences for signal detectability, where signals over all periodicities can be rendered undetectable if completeness is low. However, poor constraints on time hinder signal detectability further.
- We develop a framework that can predict signal detectability and reconstruct signal properties using an estimate of completeness, which enables stratigraphers to quantitatively justify the presence of environmental signals within stratigraphic measurables. This provides better constraints on the structure of autogenic processes evident from landscapes and strata, but also improves understanding of the records in which information about paleoenvironmental variability may be best preserved.

Data Availability Statement

All data needed to evaluate the conclusions in the paper are present in the paper. Data from the suite of experiments discussed in the manuscript are accessible through the Harvard Dataverse, where all data are under the data set Rice Pile Experiments conducted at Tulane University in 2022 (Griffin & Straub, 2023).

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