CLIMATE MODELING

Autogenic geomorphic processes determine the resolution and fidelity of terrestrial paleoclimate records

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Terrestrial paleoclimate records rely on proxies hosted in alluvial strata whose beds are deposited by unsteady and nonlinear geomorphic processes. It is broadly assumed that this renders the resultant time series of terrestrial paleoclimatic variability noisy and incomplete. We evaluate this assumption using a model of oscillating climate and the precise topographic evolution of an experimental alluvial system. We find that geomorphic stochasticity can create aliasing in the time series and spurious climate signals, but these issues are eliminated when the period of climate oscillation is longer than a key time scale of internal dynamics in the geomorphic system. This emergent autogenic geomorphic behavior imparts regularity to deposition and represents a natural discretization interval of the continuous climate signal. We propose that this time scale in nature could be in excess of 10^4 years but would still allow assessments of the rates of climate change at resolutions finer than the existing age model techniques in isolation.

INTRODUCTION

Accurately reconstructing the true rates and magnitudes of past climate change depends on a dense temporal sampling of inorganic and organic proxy records (for example, $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, and TEX_{86}). Marine sediments are thought to provide a nearly continuous history of oceanic conditions on time scales of 10^2 to 10^3 years due to the steady accumulation of the sediment and associated preservation of the proxy material (for example, microfossil tests and organic matter) (*1*–*4*). Moreover, high-resolution age models can be constructed from abundant volcanic ashes, reversals of Earth's magnetic polarity, and biostratigraphic data, which enhance the fidelity of the paleoclimate time series (in the absence of major sea-level falls and carbonate dissolution) (*1*, *3*, *5*, *6*). Terrestrial paleoclimate records of the Plio-Pleistocene and Holocene exploit similar depositional behavior in lacustrine systems and annual to sub-annual accumulation of snow layers in ice sheets and limestone precipitation in speleothems (*7*–*9*). These terrestrial records also contain a suite of independent geochronometers that produce highly resolved age models (*7*–*9*). By integrating marine and terrestrial proxies, researchers have comprehensively tested paleoclimate models and identified the key atmospheric and oceanic processes operating during past climate change events (*10*, *11*). Furthermore, the rates and magnitudes of these past events can be reasonably compared to the instrument measurements of anthropogenic climate change because the sampling density in the time domain is frequent and well constrained.

A similar approach could also address the persistent questions regarding earlier Earth paleoclimates such as shallow latitudinal thermal gradients, CO_2 climate sensitivity, carbon cycle feedbacks, and extreme shifts in the hydrologic cycle (*12*–*16*). Detailed marine records are available for much of the Cenozoic era and portions of earlier geologic time, but terrestrial records are comparatively underdeveloped (*2*, *17*). Lacustrine strata are geographically restricted and typically isolated to relatively brief time intervals of suitable tectonic and climatic conditions (*18*). Ice cores and speleothems are unavailable. Thus, proxies found in alluvial sequences, predominantly floodplain strata, must be sampled to fully reconstruct paleoclimate. However, existing records have been developed and interpreted cautiously due to widespread opinion that alluvial strata are too incomplete to generate high-resolution paleoclimate data (*3*, *5*).

Alluvial stratigraphic records

Perhaps the most widely recognized phenomenon of stratigraphic incompleteness is the "Sadler effect," wherein sedimentation rates appear to slow the longer the time interval the rates are averaged over (*4*, *19*–*21*). This phenomenon is partially due to the accumulation of unconformities and partially to heavy-tailed distributions of time intervals of nondeposition (*4*, *19*). Compilations of sedimentation rates from a variety of marine and nonmarine depositional environments suggest that fluvial systems are the most incomplete and gap-filled on shorter time scales (*4*, *20*), which leads to the inference that they will poorly preserve climate proxies in comparison to their marine counterparts. However, the apparent dependence of sedimentation rate on the time interval observed may be a major factor only up until the point when tectonic subsidence begins to influence sedimentation patterns (*4*, *20*).

Within the source-to-sink paradigm of siliciclastic sedimentary systems, the terrestrial portion of the sediment routing system is often portrayed as a "transfer zone" between the erosional, mountain catchments (the source) and marine depositional basins (the sink) (*6*). In the extreme case, when there is an absence of subsidence in the alluvial portions of the system, sediment flux is transferred efficiently from the source to the sink, and there is no long-term preservation of environmental conditions on land due to a lack of accumulation. Intuitively then, as accommodation increases through subsidence, the capacity to record a greater proportion of time increases, as should the preservation potential of proxies hosted within the sedimentary strata.

However, the rate of subsidence is not the only parameter creating gaps and unconformities in sedimentation. Across any landscape, there will be variation in the frequency and magnitude of deposition, nondeposition, and erosion. In the case of fluvial and fluvio-deltaic systems, these events relate to a variety of processes that include, among others, channel avulsion, channel migration, bar dynamics, bedform movement, crevasse splaying, overbank flooding, and the storage-and-release patterns of the sediment from floodplains and channel banks. This means that deposition is unsteady across a variety of spatial and temporal scales in a given basin. Ultimately, these stochastic depositional

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and erosional events result in unsteady sedimentation rates and gaps in strata within any given stratigraphic section (*3–6*, *19*). In turn, this complicates the transformation of proxies sampled vertically from a rock outcrop into a time series of environmental change (Fig. 1, A and B).

Age models of alluvial deposition in deeper geologic time cannot resolve bed-scale deposition rates and very rarely resolve changes in deposition on time scales of 10^5 years and finer due to poor preservation and rarity of ash layers, magnetochrons, and fossils (*3*, *5*, *6*, *17*, *18*, *22*, *23*). In the absence of sufficient age constraints, researchers commonly assume linear sedimentation rates, an assumption known to be incorrect, between widely separated dated horizons (*3*, *5*, *17*, *18*, *22*). Thus, properly allocating the distribution of time in alluvial stratigraphy is a fundamental obstacle inhibiting our understanding of past climate states (*3*, *5*, *6*). Previous studies have attempted to rectify this problem using a variety of statistical approaches (*3*, *5*, *24*). Others have incorporated estimates on the time scales over which the proxies themselves form into the time series [for example, formation of soil nodules (*15*)]. We address the allocation of time in strata and the preservation of proxy records of environmental change by using recent insights into the physical structure of the stratigraphic record.

Autogenic variability and the compensation time scale

Geomorphic systems operate over a range of spatiotemporal scales in response to a variety of internal (autogenic) processes and external forcings. On short time scales (seconds to 10^3 years), deposition is controlled by local transport conditions and the topography generated by the alluvial system itself. This results in a largely stochastic stratigraphy (*6*, *22*, *25*). On long time scales (10^5 to 10^7 years), stratigraphy is controlled by basin subsidence, commonly generated by tectonics (*6*, *18*, *25–31*). On this time scale, stratigraphy is predictable, deterministic, and sedimentation continuous as long as subsidence persists. However, many important climatic phenomena occur on intermediate time scales (10^3 to 10^5 years) between the transitions from stochastic and deterministic deposition. The latter depositional record is desirable for proxy-based studies, making the identification of this threshold in stratigraphy critical for accurate and complete paleoclimate reconstructions.

Recent experimental and field studies have identified an autogenic "compensation time scale" (T_{comp}), which captures the time necessary for the channels of a fluvial or fluvio-deltaic system to visit and deposit across the basin and for subsidence to remove the deposits from the surficial zone of reworking by the alluvial system (*25–28*). In experimental basins, the spatial heterogeneity of the landscape can be described by the standard deviation of sedimentation across a basin, which decays as a power law trend over longer and longer time intervals of averaging (*25–28*). In field stratigraphic studies where precise age constraints for each bed are absent, the same decay occurs as the thickness of characteristic sediment packages increases (*23*, *25–29*). This vertical spatial heterogeneity across a landscape is determined by the complicated interaction of a variety of parameters including sediment grain size distribution, river discharge hydrograph, overbank flooding frequency, vegetation, and others. The landscape heterogeneity can be thought of as decreasing because the depositional system begins to "feel" the effects of subsidence and sedimentation gravitates toward filling the associated accommodation space. In experiments and some natural systems, the topographic roughness can be reasonably encapsulated by an estimate of the maximum flow depth of the system (*23*, *25–28*), although in some cases, larger depositional units, such as a characteristic depositional lobe size, may be more appropriate (*23*, *26*). T_{comp} can be quantified using this estimate of the topographic roughness of the alluvial system divided by the long-term sedimentation rate (*23*, *25–28*). This time scale will be an intrinsic feature of a depositional system and produces autogenic depositional patterns that actively fill stratigraphic gaps.

The compensation time scale has two major ramifications for paleoclimate studies. First, it appears to act as a low-pass filter for fluctuations

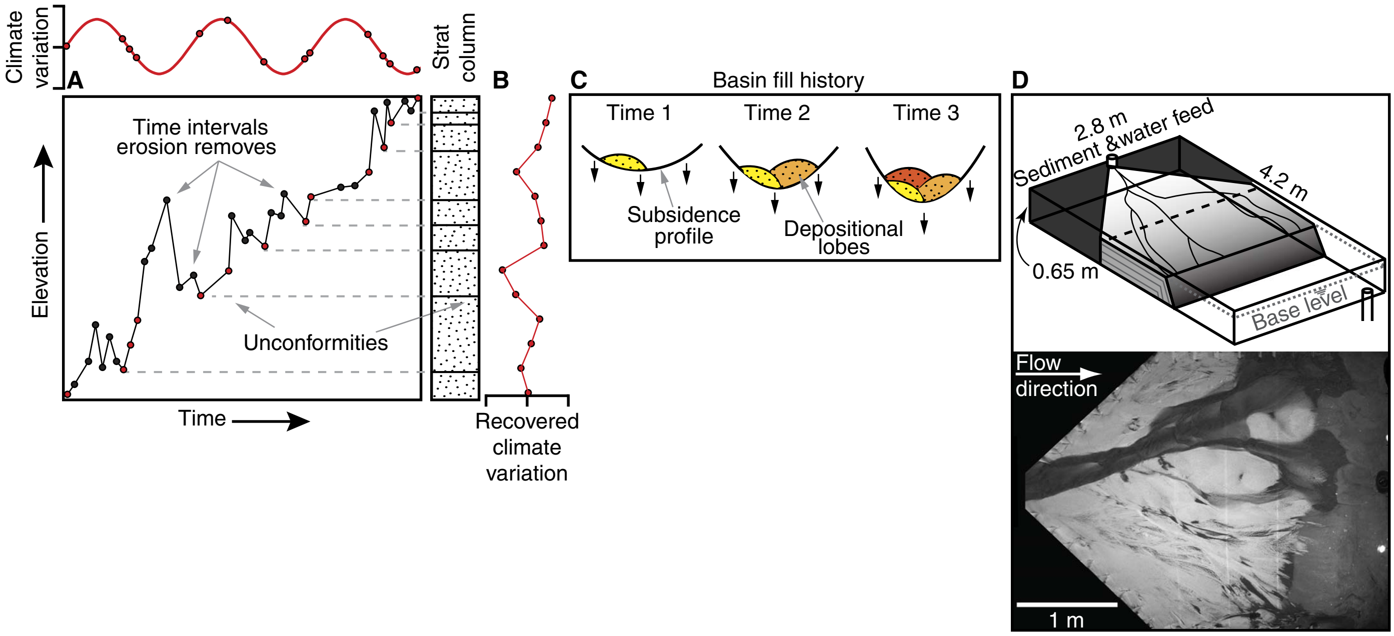

Fig. 1. Schematic example of time series recovered from stratigraphy and experimental setup. (**A**) Construction of stratigraphic column from individual depositional and erosional events of varying magnitude and rate. These geomorphic events discretize the proxies preserved in the resultant stratigraphy and the coeval time series of climatic variation [red circles are time periods represented in the recovered climate change record (**B**)]. (**C**) Illustration of compensation behavior in cross section as a basin subsides. (**D**) Schematic illustration and overhead photograph of the experiment (dashed line denotes the position of topography scans).

in relative sea level of shorter periods than T_{comp} and amplitudes smaller than the topographic roughness of the fluvio-deltaic system (*30*). Although similar experiments with cyclical changes in sediment flux and water discharge have yet to be performed, it is suspected that a similar buffering or "shredding" effect occurs (*27*, *31*). These observations suggest that in order for an allogenic forcing to be recognized as different from background stochastic depositional events in stratigraphy, the forcing must be of either longer duration and/or greater amplitude in comparison to T_{comp}.

The second major paleoclimate implication of the compensation time scale is developed herein. Although the geomorphic and stratigraphic communities have predominantly focused on inverting sediment flux signals to recover climatic information (*6*, *31*), the effects of T_{comp} on the geochemical proxy records hosted within the sedimentary layers themselves have been overlooked. We postulated that T_{comp} provides a natural integration time scale above which temporal uncertainties associated with stochastic geomorphic processes will no longer substantially affect the recovered time series of proxy-derived climate change. T_{comp} is the finest time scale upon which deposition can be considered steady within a basin (*28*), and we hypothesized that T_{comp} sets the finest temporal resolution the extracted climate time series can faithfully preserve. We use the topographic evolution of a delta in an experimental basin under constant boundary conditions and synthetic time series of oscillating climates to evaluate how proxy records may be modulated purely because of the stochastic and deterministic behavior of fluvio-deltaic depositional systems. We find that this modulation is only a factor if the period of climate oscillations occurs faster than twice the T_{comp} of the alluvial system. In these cases, the true signal is shredded and made unrecognizable from stochastic noise, but spurious climate signals can also be produced.

RESULTS

We tested our hypothesis using an aggrading fluvio-deltaic system within an experimental basin (Fig. 1D; see Materials and Methods). These experiments are extremely useful in uncovering scale-independent phenomena of alluvial and deltaic systems, including T_{comp} (*25–28*, *32*). Rapid sequential topographic scans of the evolving experimental surface track precisely which depositional events are preserved within the resultant stratigraphy. These specific depositional events of known timing and duration "sample" a separate time series of synthetic climate oscillations. Subsequently, the preserved beds are assigned to a new age based on linear interpolation between the start and end runtime of the experiment. Long-term net sedimentation rates are a priori known to be constant (an imposed boundary condition). We then compare the new time series generated from the hypothetical proxies hosted in the preserved sedimentary beds to the known values of the synthetic climate oscillations. One hundred stratigraphic sections were selected randomly along the scanned transect along the depositional strike for analysis. We investigated five climate scenarios that held the amplitude constant but varied the period of oscillation from $0.5 * T_{comp}$, T_{comp}, $2 * T_{comp}$, $3 * T_{comp}$, and $4 * T_{comp}$. We also evaluated scenarios wherein the climate was produced by a random number generator, with climate fluctuations equal to or less than the amplitude of the sinusoid. This time series was also subsampled on the basis of bed preservation and submitted to the same time series analysis. Finally, we submitted the individual bed thicknesses to the time series analysis, with the aim of determining whether the statistical analysis extracted cyclicity from the deposits we knew to be stochastically generated.

Note that the synthetic climate oscillations are not reflected in water discharge nor sediment flux variations provided at the experiment input. These parameters were held constant, and an imposed steady base-level rise produced a uniform and constant subsidence rate (see Materials and Methods). Undoubtedly, in natural alluvial systems, changes in climate will induce some concomitant shifts in discharge and sediment flux, which may, in turn, affect T_{comp}. However, the relationship between forcing and these inputs is not necessarily straightforward (*6*, *31*). In some cases, conflicting observations have been made from experimental and modeling studies depending on a variety of factors and starting assumptions (*6*, *29*, *31*, *33*). We evaluate these factors in more detail in Discussion and how they may influence the applicability of our results. For the time being, we have restricted our analysis here to illustrate the effects of a purely autogenic scenario before assessing more complicated scenarios involving sets of "nested hypotheses" regarding the characteristics of the catchments, the lag times between a catchment and a basin, among several other factors.

Our results show that as the period of climate oscillation progressively increases relative to the compensation time scale of the geomorphic system, the reconstructed time series more faithfully captures the underlying climate variation (Fig. 2). This includes more reliably capturing the full amplitude of the oscillation and proper placement of climatic extremes in absolute time, represented by in-phase oscillations of true and reconstructed climate time series (Fig. 2). We statistically analyzed each reconstructed paleoclimate record using REDFIT time series analysis, which specifically aims to address uneven sample distributions in the time domain (see Materials and Methods). The resulting power spectra show that when the period of climate oscillation is shorter than the compensation time scale, several statistically significant but spurious, paleoclimate oscillations are identified in some stratigraphic sections. This occurs even when the 99% confidence limit is used (Fig. 3A). In other sections, the climatic signal is "shredded" and unrecognizable from noise by the spectral analysis (Fig. 3B). Similar results are observed as the period of climate oscillation approaches the geomorphic compensation time scale (Fig. 3, A and B). In some cases, the time series analysis correctly identifies a single oscillation but incorrectly predicts its period (Fig. 3A). However, in most (~60%) of the sections, either the signal is shredded or multiple spurious events are identified. It is only when the period of climate oscillation is twice the period of the compensation time scale that the time series analysis accurately and reliably (that is, 100% of the sections) identifies true paleoclimate variability. Similar statistical results are obtained if the precise depositional times of the beds are used rather than the interpolated ages, but T_{comp} itself becomes the finest resolution to recover climate fluctuations (note that in nearly all field stratigraphic applications, bed-scale depositional ages are unobtainable). That is, knowing the precise age of each bed in a sedimentary succession (that is, a perfect age model) does not circumvent the problems associated with stochastic geomorphic processes.

We also produced random synthetic climate simulations that exhibited no structured secular variation and undertook the same statistical procedure after the time series had been subsampled by the individual beds. The purpose was to evaluate whether purely autogenic stratigraphy could artificially impose climate cyclicity from noise. In most cases (75%), the REDFIT time series analysis did not identify oscillations in the random climate time series (Fig. 4A). However, in a nontrivial number of cases (25%), the analysis did identify anomalous, spurious climate oscillations (Fig. 4, B and C). These spurious oscillations can occur at frequencies higher, lower, and, in rare cases, equal to the compensation

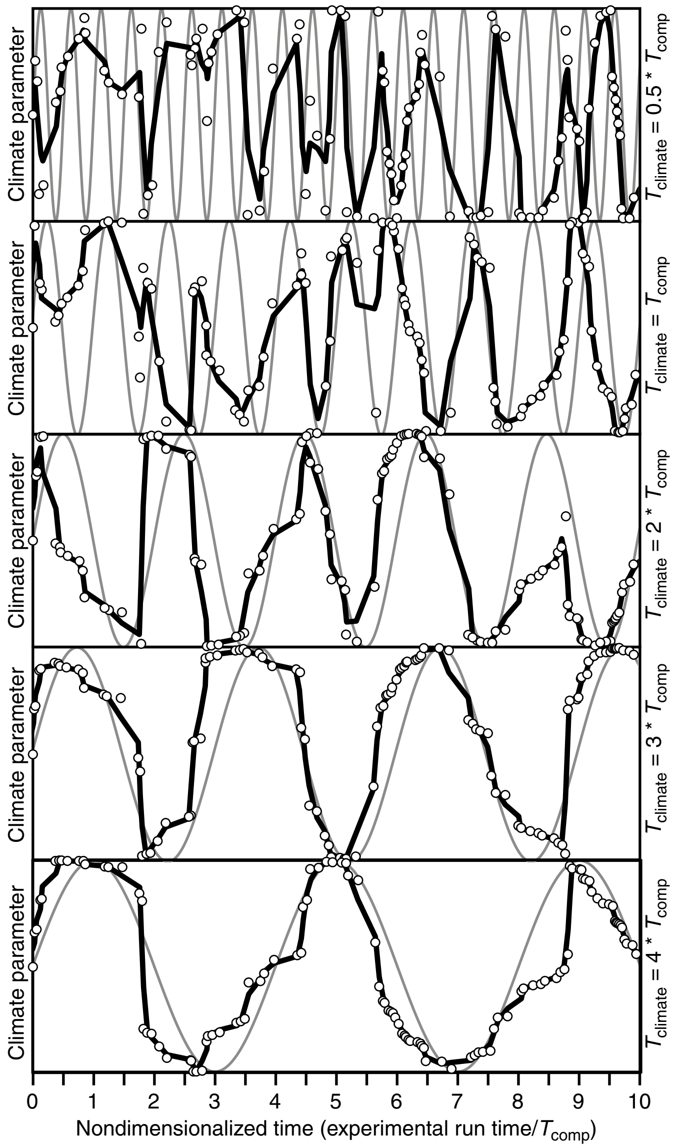

Fig. 2. Example time series of climatic changes. The true climate variation is shown as gray lines, and the climate time series produced by linear interpolation between depositional events by proxy data points are shown as white circles, with a three-point running average of proxy data points (black line).

time scale (Fig. 4, B and C). Finally, we evaluated any cyclicity in bed deposition by submitting the bed thickness metrics to the time series analysis. Approximately half of the sections showed no cyclicity, as expected (Fig. 4D), but half of the sections showed cycles in bed thickness at periods longer and shorter than the compensation time scale (Fig. 4E).

DISCUSSION

The inability of existing statistical methods to identify true climate variability when the change is "fast" ($T_{\text{climate}} < T_{\text{comp}}$) is due to the insufficient sampling of the time domain by the alluvial system. This is an expected result; climate fluctuations cannot be recorded if there is no sediment deposition and proxy preservation. However, for the case of $T_{\text{climate}} \approx T_{\text{comp}}$, there are sedimentary layers and associated proxies available. In these cases, the presence of false negatives in the time series analysis may indicate that alluvial processes act as low-pass filters on climate records. This occurs despite the fact that the climate fluctuations are highly structured (that is, more so than those in nature), the sediment flux is constant, and several discrete samples representing the time interval are available. The false negatives are likely related to the stochastic depositional and erosional events [that is, morphodynamic turbulence (*31*)], causing short-term departure from the long-term sedimentation rates used to construct the age model. The error in the time domain is sufficient to destroy the periodicity in the climate.

The presence of false positives and spurious signals when $T_{\text{climate}} \approx T_{\text{comp}}$ could suggest that the REDFIT analysis typically used in paleoclimatic studies does not fully represent probability distribution of alluvial geomorphic variability. Infrequent but recurring depositional or erosional events of a specific magnitude or potentially periods of nondeposition (*34*) may induce the structure into the stratigraphy and artificially create regularity in the time series. This hypothesis is supported by the observed cycles in bed thickness in some sections (Fig. 4E). These bed "cycles" are known to be generated by purely stochastic processes (*27*, *28*). Presumably, the red noise function within the time series analysis does not fully capture this component of the stochastic variability. Furthermore, we posit that this unaccounted variability, combined with the regularity imposed by the compensation time scale, is the likely origin of spurious oscillations identified in the randomized climate simulations (Fig. 4, B and C). The structure and periodicity must be artificially generated, and the two logical options are either a misrepresentation of the true stochasticity and/or the predictable behavior of alluvial systems to fill topographic lows. From our results, we conclude that the climate change events on time scales faster than twice the T_{comp} for a given depositional system are susceptible to (i) shredding and signal loss, (ii) signal aliasing, and in some cases, (iii) producing false patterns of climate fluctuations from noise.

Couching the statistical analysis in a process-based geomorphic framework, such as T_{comp}, can prevent false positives and negatives. Statistical rigor alone (95 or 99% confidence limits) appears insufficient (Fig. 3, A and B). On time scales longer than twice the compensation time scale, the stochastic component of the system has been accounted for by the geomorphic system itself, and the climate signal is accurately preserved. This threshold appears to capture the geomorphic equivalent of the Nyquist-Shannon sampling theorem, which states that any continuous analog signal must be sampled or discretized at a resolution of at least twice its frequency to faithfully be represented by a digital signal. We recommend future proxy-based paleoclimate studies to place their time series within this T_{comp} framework.

An initial assessment of the modern fluvio-deltaic systems suggests that the shortest compensation time scales in terrestrial settings may be close to 5000 years and the longest may be more than 150,000 years (Fig. 5) (*23*). Thus, most terrestrial strata should easily preserve long-term paleoclimatic shifts associated with tectonics (for example, ocean gateways and topographic barriers) and volcanism (for example, large igneous provinces and volcanic arcs generated by subduction). In contrast, "mesoscale" climatic shifts, such as those associated with Milankovitch cyclicity, will only be recognizable in basins with short compensation time scales. Short-term climate fluctuations will be difficult, and potentially impossible, to separate from stochastic variability.

Effects of sediment flux

The impact of climate and climate change on landscape morphology and sediment routing is a long-standing interest in the field of geomorphology and is growing as researchers seek to understand the

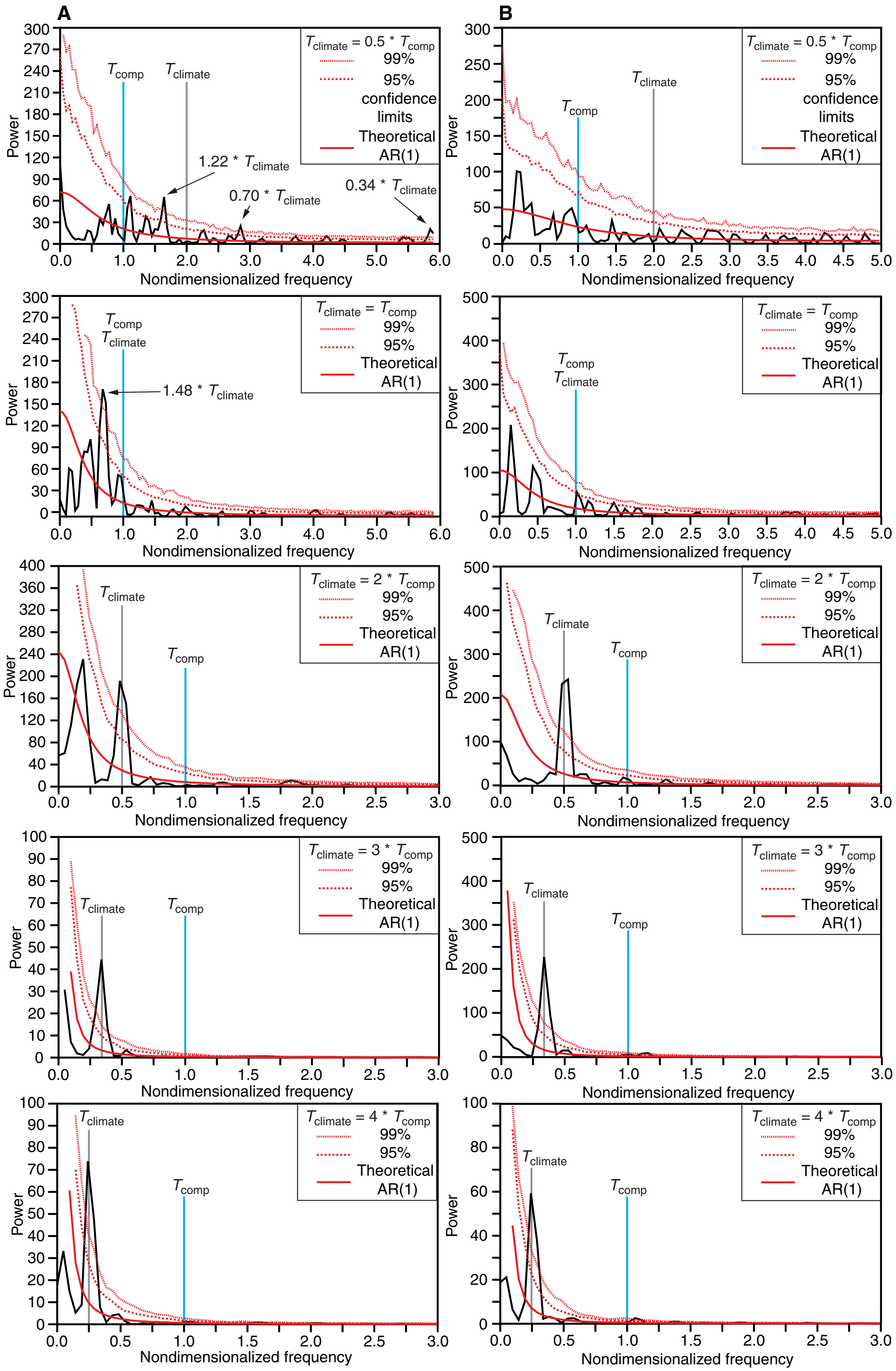

Fig. 3. REDFIT power spectra of proxy-derived paleoclimate data. (**A**) Spurious and inaccurate climate oscillations identified until the period of climate oscillation is twice the compensation time scale. (**B**) "Shredding" and signal loss until the period of climate oscillation is twice the compensation time scale. Frequency is scaled by the compensation time scale shown as a blue vertical line, and the true paleoclimate frequency of oscillation is shown as a gray vertical line.

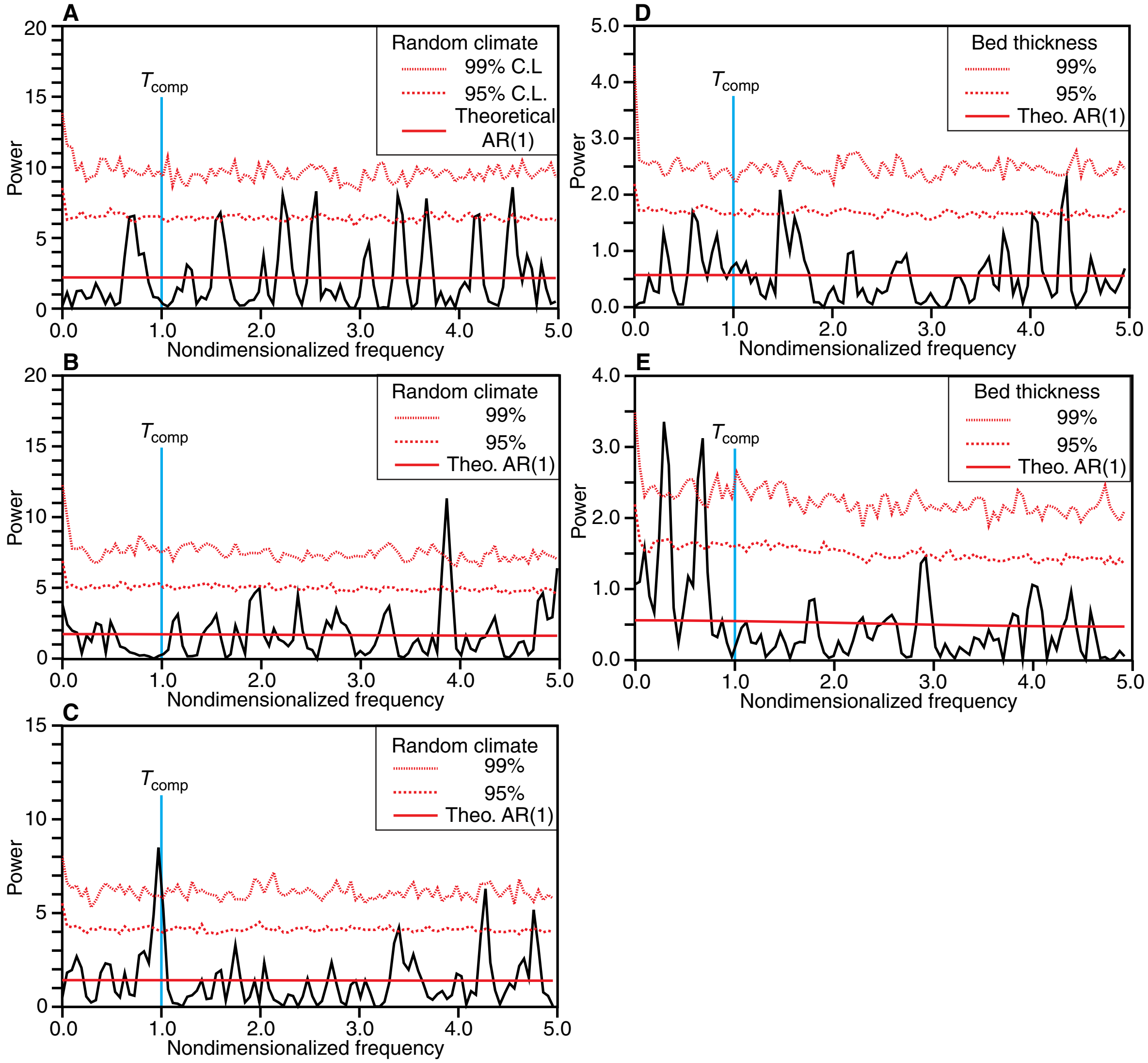

Fig. 4. REDFIT power spectra of randomly fluctuating paleoclimate and bed thicknesses. (**A**) Example power spectra of random climate time series showing no significant periodicities. C.L., confidence limit. (**B**) Example power spectra of random climate time series identifying spurious oscillations shorter and longer than T_{comp}. (**C**) Spurious oscillation at the time scale of T_{comp}. (**D** and **E**) Example power spectra from bed thickness variations showing no repetitive cycles (D) and a spurious oscillation (E). Frequency is scaled by the compensation time scale shown as a blue vertical line.

consequences of anthropogenic climate change. The most recent findings pertinent to our study focus on (i) sediment flux produced by climate change in the hinterlands and transported into depositional basins (*35*–*38*), (ii) adjustments in slope and sediment partitioning within basin alluvial systems in response to shifts in discharge and sediment flux (*33*, *35*, *39*, *40*), and (iii) the buffering or shredding capability of alluvial systems on different spatial and temporal scales (*30*, *31*, *41*–*43*). Many of these studies are based on experimental and numerical models so that researchers can isolate specific variables of interest. Applying and testing these ideas in the field will require explicit integration of geochemical proxies with stratigraphic and geomorphic data sets. Crucial for this integration will be a scaling framework that allows comparison between experimental, modeling, and field results. We view that T_{comp} offers one such avenue to accomplish these comparisons.

However, T_{comp} may be modified by the climate change events themselves in some instances, which, in turn, could alter the quality of proxy preservation and resolution of the recovered climate time series. We begin our discussion noting two important observations regarding the compensation time scale: (i) Topographic roughness and T_{comp} can be quantified from surprisingly small outcrop exposures (*23*), meaning that secular variations in T_{comp} can be constrained, and (ii) existing experiments suggest that T_{comp} is only modified when the ratio of water discharge to sediment flux (Q_w/Q_s) changes as long as basin size, geometry, and subsidence remain constant (*27*). Increasing water discharge relative to sediment flux produces a longer T_{comp}, whereas increasing sediment flux produces a shorter T_{comp} (*27*). The discussion below proceeds under the postulation that this behavior is robust and linear, which is supported by theoretical experiments and numerical studies (*27*, *44*–*46*). Although we restrict our discussion to Q_w/Q_s variations, the insights should apply equally to any geomorphic response that increases or decreases topographic roughness regardless of underlying cause (for example, discharge, grain size, and vegetation). These effects do not need to be

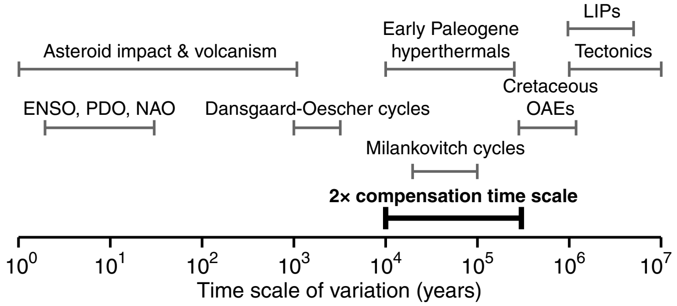

Fig. 5. A comparison of representative time scales of major climatic variations known operating in the modern system and past geologic events with an estimated range of compensation time scales in alluvial systems (*27*). ENSO, El Niño–Southern Oscillation; PDO, Pacific Decadal Oscillation; NAO, North Atlantic Oscillation; OAEs, ocean anoxia events; LIPs, large igneous provinces.

assumed but can be quantified independently from the stratigraphic record (*23*). Furthermore, climatic changes on time scales slower than T_{comp} should be well preserved in the stratigraphy, and the resolution of the proxy records can be determined by incrementally assessing T_{comp} (*30*).

Most alluvial systems contain a suite of autogenic sediment flux and water discharge variations related to a variety of sediment erosion, transport, and depositional processes. The existing literature suggests that these processes effectively shred and mask sediment flux variability due to any allogenic forcings when it occurs on smaller spatial and shorter temporal scales (*30*, *31*, *41*–*43*). Within the T_{comp} framework, this would imply minimal differences in stratigraphic completeness and proxy resolution for any climate-related forcing that did not cause a change in the maximum topographic roughness of the system. Allogenically forced changes that are encompassed by the probability density distribution of the stochastic and autogenic processes will likely not be recognized. For example, the volume of an allogenic sediment pulse must be greater than that typical of autogenic floodplain storage and release volumes within a basin (*31*), or alternatively, the climate forcing would need to exceed the typical autogenic scour depths in river systems, which can exceed five times the mean flow depth (*47*, *48*). In terms of a geomorphic landform, this implies that climate-driven alluvial terraces and incised valleys would need to exceed five times the mean flow depth to be recognized as different from the inherent, autogenic variability of the alluvial system. By extension, the T_{comp} and resolution of the proxy records would also be unaffected until that threshold. Any changes in sediment flux would need to build alluvial terraces at minimum five times a typical flow depth to substantially alter the T_{comp} that is already in existence. Similarly, any change in sediment flux on time scales shorter than T_{comp} would dissipate within the autogenic noise (*30*, *31*).

These inferences can be expanded to basin-scale stratigraphic patterns in that sediment flux signals must transit the spatial scales of the basin. Numerical models and field studies indicate that basins exhibit an "equilibrium time scale" that represents the efficiency with which adjustments can occur due to secular changes in grain size, sediment flux, subsidence, and discharge (*39*). For intermediate and large basins (length scales of 100 km and greater), this equilibrium time scale will likely be on the order of 10^5 to 10^6 years (*39*, *42*, *49*). This basin equilibrium time scale relates linearly to the diffusion (transport) coefficient of the alluvial system but by the square of the basin length scale (*39*, *42*, *49*). This means that basin size will play a greater role than any changes in diffusivity brought on by discharge variation; basins are predisposed to buffering flux signals. Furthermore, the compensation time scale of a given system will likely be equal to or shorter than the basin equilibrium time scale (*27*, *39*, *42*, *49*). Thus, any climate forcing that is "rapid" relative to T_{comp} will also be rapid relative to the basin equilibrium time scale, and there will be insufficient opportunity to propagate the sediment flux signal across the basin. Locally, this may adversely affect the resolution of the proxy records if Q_w/Q_s increases, or conversely, it could improve the proxy resolution if Q_w/Q_s decreases. On a basin scale, the obtainable climate record resolution from proxies will remain largely constant because the alluvial system in other areas was never able to respond to the perturbation before the stochastic geomorphic processes shred it.

Even if we hypothesize an extreme case of an abnormally large increase in sediment flux by 50% into an alluvial basin, the linear relationship between Q_w/Q_s and T_{comp} implies a concomitant decrease in T_{comp} by 50% (*27*, *28*, *44*–*46*). If, for example, the T_{comp} was previously 25,000 years in this example basin and now has transiently improved to 12,500 years, then this is an improvement for potential proxy records, but in most natural basins, this may only be marginally useful. This is because our statistical analysis presented above indicates that the finest resolvable proxy climate record is still twice the T_{comp} (that is, 25,000 years). Moreover, it will only improve the resolution at isolated, most likely proximal locations within the basin where the "excess" sediment was deposited.

In addition, two recent studies provide different arguments for a strong buffering of environmental flux signals in transport systems (*41*, *43*). First, many coarse-grained rivers appear to preferentially change their shape to maintain a universal critical shear velocity for a given flood regime, irrespective of climatic, tectonic, and lithologic controls (*43*). This phenomenon implies the maintenance of a characteristic flow depth and T_{comp} as long as that is the dominant determinant of topographic roughness (*23*, *25*, *27*, *28*). This view is bolstered by select field and physical experimental examples in finer-grained rivers, wherein the maximum vertical scales of channel topography remained unchanged before and after rare, large magnitude flood events (*50*, *51*). This is likely due to bed shear stress asymptotically approaching a maximum value during larger and larger floods, as progressively more water spills out of the channel and inundates floodplain, preventing channel deepening (*50*). However, the effects of the frequency and magnitude of floods on channel morphology and avulsion behavior are far from settled, and recent experimental work suggests that they may play a major role in determining deltaic depositional patterns through nonnormal hydraulics in the backwater reach (*52*). Specifically, floods impart an influence on the size and shape of depositional lobes, which could affect T_{comp} (*52*). This behavior is a kind of autogenic feedback that could operate within alluvial systems, but there is a distinct lack of research on this at the present time.

Second, in terms of buffering, the advection length scale for sediment in depositional systems sets the minimal scale on which morphodynamics occur and results in landforms that produce the topographic variability involved in the compensation time scale formulation (*41*). Within the length scales influenced by morphodynamics, both autogenic and allogenic processes are convolved and may be difficult to reconcile (*31*, *41*). It appears that floodplains are not susceptible to these effects because their length scale is typically smaller than the advection length for the associated sediment carried in overbank floods (*41*).

Although we view the buffering and shredding of climate-driven sediment flux and water discharge variations as common systems, there may be scenarios wherein the T_{comp} could be modified by short-term climate change. For example, certain catchments may exhibit a resonance frequency with a climatic oscillation that leads to massive sediment flux signals on time scales of 10^4 to 10^5 years exiting the basin depending on the erodibility of the exposed lithologies (*36*). If these sediment flux signals are sufficient to deposit strata of a greater thickness than the subsequent climate regime's topographic roughness, then an improvement in proxy resolution may be possible. Feasibly, compaction and sediment loading of the lithosphere in the basin could aid in this preservation by "artificially" enhancing subsidence rates. However, in most cases, erosive catchments themselves probably mute and shred pulses of the sediment before introducing to the depositional basin (*36*, *53*, *54*).

Unfortunately, a unified, predictive theory that links the entirety of the source-to-sink system remains elusive (*6*). Several experiments, numerical models, and targeted field studies are needed. However, it is also clear that to be successful in developing a process-based understanding of these geomorphic systems and their response to perturbations of variation duration and scales, we need the explicit integration of proxy records. The T_{comp} offers a robust avenue to frame this problem and address paleoclimate issues.

Early Paleogene case study

As a case example, we use early Paleogene hyperthermals that are well documented globally within marine strata but thus far identified at only a few isolated terrestrial locations (*13*–*15*, *55*, *56*). Greenhouse climatic conditions dominated the Paleocene and Eocene epochs, but these conditions were punctuated with extreme global warming events linked to massive releases of exogenic carbon into Earth's atmosphere and oceans (*2*, *56*). In addition to increased temperatures, the events had substantial effects on atmospheric carbon dioxide levels, ocean acidification, the hydrologic cycle, and biologic systems (*56*–*61*). The most notable hyperthermal events are the Paleocene-Eocene Thermal Maximum (PETM) that occurred ca. 56 million years ago (Ma) and the paired Eocene Thermal Maximum 2 and H2 events that occurred ca. 53 Ma (*13*–*15*, *62*). On the basis of marine geochronometers, the PETM was ca. 200,000 years in duration, whereas the other two events were each ca. 50,000 years in duration (*13*–*15*, *56*, *62*). Subsequent, smaller magnitude events are preserved in several marine records, and there is evidence that these warming events occur on Milankovitch periodicities (*62*). The magnitude and duration of the hyperthermal events are constrained by stable isotope records (predominantly δ^{13}C and δ^{18}O values from inorganic and organic proxies) and are used to evaluate potential carbon sources, rates of carbon release, and CO_2 sensitivity of the climate system (*63*–*65*). The isotopic records are also important for understanding mesoscale carbon cycle feedbacks and sequestration processes, specifically in regard to those involving methane (*63*, *64*). Although comparatively sparse, the existing record of terrestrial climate change during these events has yielded important information on hydrologic cycle changes, vegetation shifts, mammal responses, and local modulations of the carbon isotope excursion magnitudes (*55*, *56*, *58*–*61*, *66*, *67*). Perhaps the most significant findings based on terrestrial records are related to nonlinear CO_2 sensitivity among the hyperthermal events (*68*), challenges to hypotheses that high atmospheric CO_2 levels cause equable conditions (*69*), precessional-scale astronomical influences on soil development (*14*, *70*, *71*), and pulsed releases of carbon and warming (*15*). Many of these conclusions depend on a temporal completeness of the alluvial stratigraphic record on time scales finer than 10^3 to 10^5 years, which the T_{comp} framework can explicitly evaluate.

The most extensive terrestrial record of early Paleogene hyperthermals is in the Bighorn Basin of northwest Wyoming. The hyperthermals are identified by negative carbon isotope excursions in pedogenic carbonates, bulk soil organic matter, and plant biomarkers hosted within floodplain strata (*13*–*15*, *69*, *72*–*74*). We estimated the T_{comp} for the Bighorn Basin at ca. 10,000 years using the long-term sedimentation rates and estimates of maximum river flow depths (see Materials and Methods) (*22*, *67*). This suggests that the Bighorn Basin paleoenvironmental time series is approaching the completeness of marine records and provides independent support for recent arguments that floodplains, deltaic, and shallow marine display similar stratigraphic completeness on the 10^3-year time scale (*4*). Overall, this analysis provides additional confidence when estimating the rates and assessing the mechanisms of carbon release and sequestration (*13*–*15*) because the observed time series is less likely to be affected by stochastic geomorphic behavior. The hyperthermals show disparate temperature and hydrologic responses to elevated atmospheric CO_2 levels in the Bighorn Basin, hinting at nonlinearities or significant local modulation of the climate signal (*14*, *68*). Our analysis suggests that these are not sampling artifacts or noise but true variability. The estimated T_{comp} is also sufficiently short to garner support for recent proposals that floodplain soil development varied on precessional (ca. 20,000 year) time scales in the Bighorn Basin (*14*, *70*, *71*). However, these studies also found higher-frequency cycles that are faster than T_{comp} (*71*). On the basis of our results herein, a climatic driver for these high-frequency cycles should be viewed with suspicion and is either spurious or generated by intrinsic geomorphic variability unaccounted for by the time series analysis.

The estimated T_{comp} allows a lower limit to be placed on our ability to detect the rates of biologic response by mammals and plants to the hyperthermals, for example, the rate of radiation of primates, artiodactyls, and perissodactyls during the onset of PETM from Asia to the Bighorn Basin in North America (*75*), rates of mammal dwarfing in relation to temperature increases (*26*, *58*, *76*), and transient northward range shifts in dry tropical floras to the Bighorn Basin from the Gulf Coast region (*56*, *61*). On the basis of the Bighorn Basin, these changes occurred in less than 10,000 years or faster according to the T_{comp} framework. Feasibly, another basin with a shorter T_{comp} could resolve these rates even finer. Finally, some studies have proposed that terrestrial records may contain a higher-resolution record of the hyperthermals, specifically the PETM, than marine records because the latter is subject to dissolution during associated ocean acidification (*56*). Our formulation here suggests that this could be the case in some basins and is consistent with the recent identification of the pulsed carbon release previously unrecognized in marine strata (*15*). Moving forward, the T_{comp} framework provides researchers an opportunity to quantitatively assess the completeness of a given basin before extensive geochemical studies.

However, as explored above, the compensation time scale is not necessarily a static feature of a depositional basin but is potentially influenced by climate. In the Bighorn Basin, the long-term sedimentation rates do not vary substantially from the sedimentation rates observed during the ca. 200,000 years of the PETM (*15*, *22*, *70*), which suggests that any changes in T_{comp} will primarily be driven by altered topographic roughness. These alterations in landscape heterogeneity might be expected given the estimated decreases in mean annual precipitation (*59*, *66*) and a shift to a more open vegetated landscape during the PETM (*56*, *61*). Furthermore, coeval with the PETM, an anomalously thick and widespread fluvial sandbody was generated in the northern, distal portions of the basin (*67*), and several cut-and-fill fluvial structures occur in the southern, proximal portions (*61*, *77*). The cut-and-fill structures are 3 to 5 m thick, which match the maximum flow depth estimates from fluvial sandbodies (*61*, *67*, *77*). Surprisingly, flow depth estimates do not change substantially across the PETM (*67*). This observation is consistent with recent propositions that geomorphic systems efficiently shred climatically induced changes in sediment flux and discharge via storage and release processes (*31*, *43*) or could alternatively mean that elevated temperatures and atmospheric CO_2 levels had relatively little change in the channel-forming discharge in the basin (*67*). Instead, the major geomorphic repercussion of the PETM may have been mediated through altered partitioning of the sediment within the basin due to changes in sediment supply (*66*) or channel-floodplain dynamics (*67*). This behavior is comparable to the muted aggradation and erosional phases produced in some numerical models by catchment-derived sediment flux oscillations (*33*). This hypothesis finds further support in the southern, proximal portion of the Bighorn Basin where researchers observed increases in the abundance of allochthonous, recalcitrant organic debris, pollen, and marine vertebrate fossils (for example, shark teeth) that were reworked into the PETM strata from Cretaceous shales exposed in the surrounding uplifts (*77*, *78*). The southern portion of the basin also contains a thick sequence of particularly well-developed soils near the top of the PETM, informally named the Big Red sequence (*77*, *78*), which could represent a transient reduction in sediment supply or a subdued alluvial terrace, although an associated incised valley has not been recognized and the Big Red soils postdate the observed cut-and-fill structures (*59*, *77*).

Overall, these observations indicate that although the PETM affected the behavior of geomorphic systems in the Bighorn Basin, there appears to be no evidence for any major changes in topographic roughness of the depositional system. To be sure, the changes in sediment partitioning affected the abundance and distribution of certain lithofacies within the basin with the consequence of affecting the availability of certain lithofacies-dependent proxies (*61*, *72*, *74*, *77*, *78*). However, the temporal completeness of the stratigraphy does not appear to have been negatively affected. This contrasts with the records in other Laramide basins, such as the Piceance Creek Basin in northwest Colorado, wherein river flow depths increased by 50% during the PETM, whereas the long-term sedimentation rates remained roughly constant (*55*). This would cause T_{comp} to increase and reduce the resolution possible for proxy records. Unfortunately, existing proxy records are insufficient to evaluate and compare the two basins in detail.

At the present time, it is unclear how prevalent shredding and maintenance of landscape heterogeneity are compared to transient shifts in T_{comp} in response to climatic forcings. If the compensation time scale is predominantly buffered, then this would be a boon for proxy-based paleoclimatic studies because it would provide a uniform sampling of the time series. However, this buffering capacity of geomorphic systems still needs extensive evaluation on laboratory and field scales (*6*, *23*, *31*, *67*). These can only be performed by explicitly integrating process-based geomorphic behavior with environmental proxy records such as those proposed herein.

Quantifying the completeness and resolution of these types of records is particularly important because they are increasingly used as geologic analogs and comparisons to anthropogenic global warming (*13*–*15*, *61*). Overall, our analysis should spur work in other sedimentary basins spanning the early Paleogene time interval and embolden research into terrestrial climate change associated with oceanic anoxic events, which occur several times during Earth's history (for example, Permian, Jurassic, and Cretaceous) and are being used as case studies for the expansion of marine oxygen minimum zones due to modern global warming (*79*). The T_{comp} framework will provide more accurate reconstructions of local time series of environmental change, yielding more accurate comparisons with regional and global climate patterns. These improvements will aid in the identification of causality, feedbacks, and response times among the atmosphere, hydrosphere, and biosphere in deep geologic time.

MATERIALS AND METHODS

Run parameters for the experiment TDB-10-1 (*27*) performed at the Sediment Dynamics Laboratory at Tulane University had a water discharge of 0.451 liters/s and sediment discharge of 0.011 liters/s into a basin that is 2.8 m wide, 4.2 m long, and 0.65 m deep. Base-level rise (equivalent to subsidence rate) was constant at 5 mm/hour, creating a long-term aggradational fluvio-deltaic system. Base-level rise was maintained with submillimeter-scale precision using a computer-controlled weir system (*27*). The sediment was a mixture of 70% quartz sand with a median grain diameter (D_{50}) of 110 μm and 30% coal sand with a D_{50} of 440 μm. Quartz sand and anthracite coal had a specific gravity of 2.65 and 1.3, respectively. These two sediment types represented the coarse and fine components of natural systems, respectively. This overall experimental setup and methodology are similar to many previous experiments evaluating a variety of scale-independent phenomena in sedimentary basins (*25*–*28*, *32*). A laser scanner obtained surface topography every 2 min, generating a high-resolution evolution of the surface as aggradation proceeded. Total experimental duration was 78.2 hours. The topographic roughness of the experimental surface scaled with the maximum flow depth of channels on the experimental surface (18.5 mm). This yielded a T_{comp} of 222 min for the system.

The climate model takes the form of a simple sinusoid: $P(t) = A \sin(2\pi t/T_{\mathrm{climate}})$, where P is a hypothetical climate parameter captured by a proxy (for example, mean annual temperature), t is the time, A is the amplitude of the climate variation, and T_{climate} is the period of the climate variation. The climate model was run for the entirety of the experiment (78.2 hours) for five scenarios. These scenarios vary T_{climate} relative to T_{comp} at $T_{\mathrm{climate}} = 0.5 * T_{\mathrm{comp}}$, $T_{\mathrm{climate}} = T_{\mathrm{comp}}$, $T_{\mathrm{climate}} = 2 * T_{\mathrm{comp}}$, $T_{\mathrm{climate}} = 3 * T_{\mathrm{comp}}$, and $T_{\mathrm{climate}} = 4 * T_{\mathrm{comp}}$. For 100 random vertical columns in the basin transect (Fig. 1D), these climate sinusoids were then sampled by the coeval depositional events. The climatic conditions that corresponded to periods of nondeposition and depositional events that were eroded were not represented. Subsequently, the time intervals represented by sediment deposition were reassigned to an age using a linear interpolation based on the proxy's position in the accumulated sediment column and the known start and end time of the experiment. This was an identical approach to that applied in the field to proxy records, for example, interpolating between two dated ashes or magnetochrons within a stratigraphic section (*5*, *10*, *17*). However, in the experiment, we know that the long-term sedimentation rates are constant and the precise start and end times with certainty, whereas in natural basins, it is unknown whether long-term sedimentation remained constant between dated horizons. Moreover, any dated horizon will be associated with analytical uncertainties that will propagate to uncertainties in the age model and rates of paleoclimate change. This is not the case for the experiment. Time series analysis was performed using the software Past3 version 3.14 (*80*) using the REDFIT protocol with $n = 1000$ Monte Carlo simulations of the autoregressive (AR1) process, oversampling and segmentation were set to 1, and a Blackman-Harris window was used. This is a standard methodology for time series analysis of unevenly sampled signals, specifically designed for paleoclimatic records (*24*, *80*).

Rigorous field quantification of the compensation time scale required detailed mapping and lithofacies analyses (*23*, *26*, *29*). However, a reasonably conservative approximation can be derived from age models of long-term sedimentation and maximum estimates of river flow depths as a gauge of topographic roughness (*25*, *26*). The compensation time scale for the early Paleogene strata in the Bighorn Basin of northwest Wyoming was derived from the long-term sedimentation rates of the Willwood Formation (~0.4 m/thousand years) (*15*, *22*) and estimates of river flow depths (maximum of ca. 4 m) obtained from the relief on bar clinoforms and fining upward sequences within fluvial sandbodies from the same area (*67*). Proxy records were sampled at a vertical resolution that was finer than the topographic roughness estimate (that is, finer than 4-m increments) (*13*–*15*).

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