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Autogenic Sedimentation in Clastic Stratigraphy

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Abstract

Internally generated, or autogenic, terrestrial and marine sediment-transport dynamics can produce depositional patterns similar to those associated with climatic, tectonic, or sea level changes. A central challenge in accurately interpreting the sedimentary archive is determining what scales and types of deposits reflect autogenic controls on sedimentation in different environments. Autogenic sediment-transport dynamics commonly result from intermittent sediment storage in transient landforms, which produces episodic, spatially discontinuous sedimentation across a basin. The transition from localized, variable sedimentation to even, basin-wide sedimentation marks the shift from stochastic landscape dynamics to deterministic deposition responding to the long-term balance between sediment supply and the creation of space to accommodate sediment. This threshold can be measured in a wide variety of stratigraphic successions and has important bearing on whether climatic, tectonic, or sea level signals can be recognized in physical sedimentary deposits.

1. INTRODUCTION

Autogenic: processes, patterns, or dynamics that arise solely as a consequence of the interaction of the components within a system

One of the main goals of stratigraphy is to use the sedimentary archive to reconstruct Earth's climatic, geodynamic, and biological history. To accomplish this, stratigraphers look at the packaging and character of sedimentary rock successions to understand how environmental conditions changed through time. Terrestrial and marine environments are not spatially uniform or static, so we typically expect some intra-environmental variability in the stratigraphic record—for example, conformable shifts between channel sandstone and floodplain mudstone deposits. In turn, we generally posit that large-scale changes in environmental conditions will produce pronounced stratigraphic signatures. For example, abrupt changes between terrestrial and marine deposits might reflect significant changes in sea level.

An important challenge, however, is determining what constitutes a major change. What scale and type of stratal patterns reflect internal dynamics of terrestrial and marine environments? What magnitude of climatic, tectonic, or eustatic changes leave distinct marks in the sedimentary record? Recent studies have shown that internally generated, autogenic dynamics in terrestrial and marine sedimentary systems can occur on temporal and spatial scales much larger than previously thought—scales that rival important changes in global climatic, tectonic, or eustatic conditions. This challenges long-standing assumptions about what types of stratigraphic successions reflect large-scale global change versus local environmental dynamics. But the realization that landscape and seascape dynamics may comprise a larger fraction of the sedimentary archive also presents an important opportunity to understand more about the dynamic nature of Earth's surface environments. How did landscapes behave before human modification of Earth's surface? What determines the sensitivity or resilience of a given environment in the face of climatic, tectonic, or eustatic change?

Our ability to identify sedimentary patterns of landscape and seascape dynamics and to disentangle them from stratigraphic signals of climatic, tectonic, and sea level change is essential for accurately reconstructing Earth's history; for sustainably managing our habitat, water, and energy resources; and for mitigating hazards. Understanding how Earth's surface responded to past global warming events is critical for developing effective and economical management plans for agricultural landscapes, coastal regions, and marine ecosystems. Sedimentary deposits house important records of the frequency and size of events like floods, earthquakes, tsunamis, and landslides that can inform statistical models for predicting and planning for natural hazards. Furthermore, understanding the scales and nature of heterogeneity in buried sedimentary deposits is necessary for finding and producing hydrocarbon, water, and mineral resources. Our ability to reconstruct historical landscape conditions and hazards and to predict subsurface stratigraphy hinges on how well we understand and can model internal sedimentary dynamics and the response of sedimentary systems to climatic, tectonic, and eustatic change.

1.1. Connecting Landscape Dynamics and Stratigraphy

To discuss the relationship between autogenic landscape dynamics and the stratigraphic record, we find it useful to outline a conceptual framework. Consider a representative swath of Earth's surface extending from a high mountain range, down through alluvial plains, to a coastal region and a shallow marine shelf, and eventually into a deep ocean basin (**Figure 1**). The pronounced topographic gradient that arose from geodynamic and tectonic processes that control where uplift and subsidence occur on Earth drives the first-order dynamics across this scene. As a consequence of this topographic gradient, material is moved from high elevation to low elevation. The rate of material transport depends on climate, which determines how rock weathers and breaks down

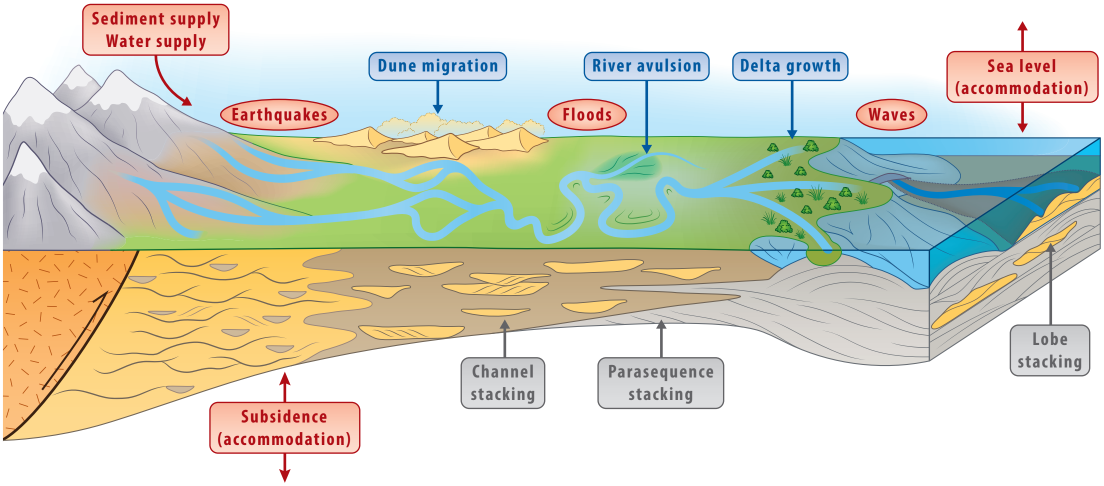

Figure 1

Conceptual overview of Earth's surface (∼10^1–10^3 km in length and kilometers thick) showing the interaction of allogenic and autogenic processes and example sedimentary deposits. Large-scale external factors like climate, tectonics, and eustatic sea level (*red boxes*) ultimately control the amount of space created to store sediment (i.e., accommodation) and the amount of sediment available to fill it. External environmental variability (*red ellipses*), characterized by the frequency–magnitude distributions of, for example, earthquakes, floods, or waves from storms or tsunamis, also impacts sediment storage and transport on Earth's surface. Example autogenic dynamics (*blue boxes*) arise spontaneously in sediment-transport systems and create distinctive spatial and temporal heterogeneity in how sediment and water are distributed across a landscape. These internal and external factors convolve to produce stratigraphic patterns—observable as the arrangement (stacking) of deposits such as channels, marine parasequences, or deepwater lobes (*gray boxes*)—at some scales reflect primarily autogenic processes and other scales record changes in allogenic controls on deposition. **Supplemental Video 1** presents a physical experiment showing fast-acting autogenic surface dynamics (mobile channel network) filling a basin experiencing large-scale sea level changes (Hajek et al. 2014).

Supplemental Material

and also how much water, ice, or wind is available to transport sediment and solutes (e.g., Riebe et al. 2004, Dixon et al. 2009, Perron 2017); climate also mediates vegetation and land cover that significantly influence weathering (e.g., Drever 1994, Chen et al. 2000) and sediment transport on Earth's surface (e.g., Tal & Paola 2007, Davies & Gibling 2010, Nardin & Edmonds 2014). Under these boundary conditions, Earth's surface is spontaneously configured to convey available material from mountainous source areas into deep-sea basins via terrestrial and marine sediment-transport networks.

Even when boundary conditions are steady and constant, sediment-transport systems do not smoothly advect material downslope. Rather, the power to transport sediment is distributed unevenly in most sedimentary environments, and transport systems frequently move and reconfigure themselves without any external provocation. For example, in alluvial river landscapes, water and sediment are funneled through a network of self-formed channels. Because sediment is largely confined to these conduits, sedimentation rates within and near channels can be much higher than on adjacent floodplains. This results in an inherent instability; as river channels aggrade, they can become topographically perched. This condition eventually leads to a reorganization of the channel–floodplain system, where the channel relocates, or avulses, to a lower, more stable position in the basin (e.g., Mohrig et al. 2000, Tornqvist & Bridge 2002, Slingerland & Smith 2004). As soon as a new channel is established, the cycle begins anew. Channel avulsion is a quintessential example of an autogenic process that arises spontaneously within a sediment-transport network.

Allogenic: driven by factors outside the landscape or sedimentary system

Environmental variability: variability from conditions external to the sediment-transport system and unaffected by sediment-transport dynamics (e.g., storms or earthquakes)

Allogenic forcing: change in external boundary conditions acting on a system (e.g., an event, step change, periodic change, or change in environmental variability)

At the largest scales in **Figure 1**, the ensemble of sediment-transport processes acting on Earth's surface is an autogenic response to external (allogenic) climatic, tectonic, and eustatic forcing. However, we can also consider sediment-transport dynamics within a specific region or depositional environment. For example, if we are interested in understanding autogenic behavior within a delta, regional- and global-scale allogenic boundary conditions influence the amount of sediment and water delivered to and deposited by the deltaic system. However, the delta may also be affected by dynamics in environments upstream in the source-to-sink network (e.g., Berger et al. 1992, Allen 2008, Romans et al. 2015). In this context, variable sediment supply imposed by the upstream sediment delivery system could be considered an allogenic control on the delta. Additionally, the characteristic frequency and magnitude of events like earthquakes, storms, and floods are extrinsic to sediment-transport systems on Earth's surface. This type of stochastic environmental variability can cause significant regional variations in sediment supply, sediment-transport energy, or the space available to preserve sediments (Ashton et al. 2001, Goldfinger et al. 2012, Peters & Loss 2012, Perron 2017). These more nuanced types of allogenic controls underscore why it is useful to clearly define the scope of the system of interest and to carefully consider what external factors might influence its dynamics.

In this review we focus on the ways in which Earth surface process dynamics can be preserved in the sedimentary archive. Consequently, we primarily discuss net-depositional environments (e.g., regions of geodynamic subsidence or marine settings). Internally or externally driven sediment-transport dynamics are manifest in the stratigraphic record as vertical or lateral variations in sedimentary rock properties observable as packages of sediment (e.g., lithofacies with different sediment size, composition, or attributes like sedimentary structures) or surfaces (e.g., erosional unconformities or hiatal surfaces). These aspects of stratigraphic architecture can be observed across scales ranging from centimeters to kilometers, but it remains unclear what scales of deposits reflect autogenic versus allogenic processes.

1.2. Approaches to Studying Autogenic Dynamics

Fast-acting autogenic dynamics can be observed and measured on Earth's surface (**Table 1**). However, understanding autogenic dynamics that act over longer timescales (centuries and longer) requires other approaches like reduced-scale physical and numerical experiments—which allow us to effectively speed up time (Paola et al. 2009)—along with studies of ancient sedimentary deposits that record real-world case studies of landscape and seascape dynamics. Insights from physical and numerical experiments have produced hypotheses about the nature of and controls on sedimentary autogenics (e.g., Muto & Steel 2004; Kleinhans 2005; Kim et al. 2006, 2014; Jerolmack & Paola 2007; Clarke et al. 2010; Reitz et al. 2010; Straub & Esposito 2013; Straub & Wang 2013; Karamitopoulos et al. 2014; Postma 2014; Li et al. 2016), which have more recently begun to be tested in field settings (Hajek et al. 2010, 2012; Hofmann et al. 2011; Straub & Pyles 2012; Flood & Hampson 2014; Reitz et al. 2015; Hampson 2016). Physical controls on autogenic dynamics in fluvial–deltaic systems have been particularly well studied, and scaling approaches have helped overcome limitations associated with often poor absolute age dating in deep time stratigraphy.

Conventional wisdom suggests that relatively large-scale changes, particularly if they are regular or periodic, are the result of allogenic forcing, whereas smaller scale, chaotic, uncorrelatable changes are the result of autogenic dynamics. This assumption is directly challenged by results from physical and numerical experiments that demonstrate autogenic dynamics can be both large scale and organized (**Figure 2**). Fortunately, recent progress toward understanding

Table 1 Links to videos of autogenic landscape dynamics from natural systems, physical experiments, and numerical models

Autogenic process	Link
Dune migration (experiment)	**https://www.youtube.com/watch?v=iq8-H3Hkodg**
Dune migration (numerical model)	**https://www.youtube.com/watch?v=pL02a1l6edY**
Wave ripple formation (experiment)	**https://www.youtube.com/watch?v=zRGuMddjRGg**
Channel meandering (numerical model)	**https://www.youtube.com/watch?v=VXuMWVnEJNw**
Channel meandering and braiding (physical experiment)	**https://www.youtube.com/watch?v=fv_oCOvsnLA**
Channel meandering (Bolivia, 1984–2012)	**https://earthengine.google.com/timelapse/#v=-16.76174,-64.84472,9.65,latLng&t=2.86**
Coastal sand spit evolution (numerical model)	**https://www.youtube.com/watch?v=N_LBeJPWqFM**
Channel meandering (experiment with vegetation)	**http://phys.org/news/2009-10-alfalfa-line-meandering-streams-video.html**
Channel braiding in subaqueous density flow (experiment)	**http://www.nature.com/ngeo/journal/v8/n9/abs/ngeo2505.html#/supplementary-information**
Cyclic steps (experiment)	**https://youtu.be/TJYaDapFD9s?list=PLj9y4F08zw6qd_vlbHAgfD9QSk6fWcMrT**

controls on autogenic dynamics and their manifestation in the stratigraphic record has positioned the sedimentary geology and surface process communities to answer significant outstanding questions related to autogenic dynamics: (*a*) What controls autogenic dynamics in marine and terrestrial sedimentary environments? What are the characteristic temporal and spatial scales associated with autogenic processes in different environments? (*b*) How can autogenic processes be modeled and predicted, and what consequences do they have for managing modern systems and understanding subsurface stratigraphic architecture? (*c*) How do autogenic processes interact with allogenic boundary conditions? What scale of allogenic change or environmental variability will be preserved in a given depositional environment?

Here we review advances in understanding autogenic sedimentary dynamics in the stratigraphic record. We provide an overview of state-of-the-art understanding of autogenic dynamics in sedimentary systems, focusing on approaches that can be used to identify and predict the spatial and temporal scales of autogenic processes. Then we discuss current understanding of how autogenic processes interact with allogenic drivers and their potential impact on the sedimentary archive. We highlight promising approaches to measuring autogenic scales and organization from stratigraphy, and we discuss the potential implications of autogenic dynamics on cyclostratigraphy and the completeness of the stratigraphic record.

2. SELF-FORMED AND SELF-ORGANIZED SEDIMENTARY DYNAMICS

Beerbower (1964) formally presented the concept of self-formed stratigraphic packages, or autocyclicity, and evaluated origins for cyclic coal (cyclothem) packages, including intrinsic variability in fluvial environments. Recently, Olszewski (2016), Paola (2016), Purkis et al. (2016), and Wang & Budd (2016) reviewed overarching concepts of autogenic behavior and self-organization in geophysical, geobiological, and geochemical sedimentary systems. These reviews demonstrate the commonalities of self-formed dynamics across different types of Earth systems. Here we

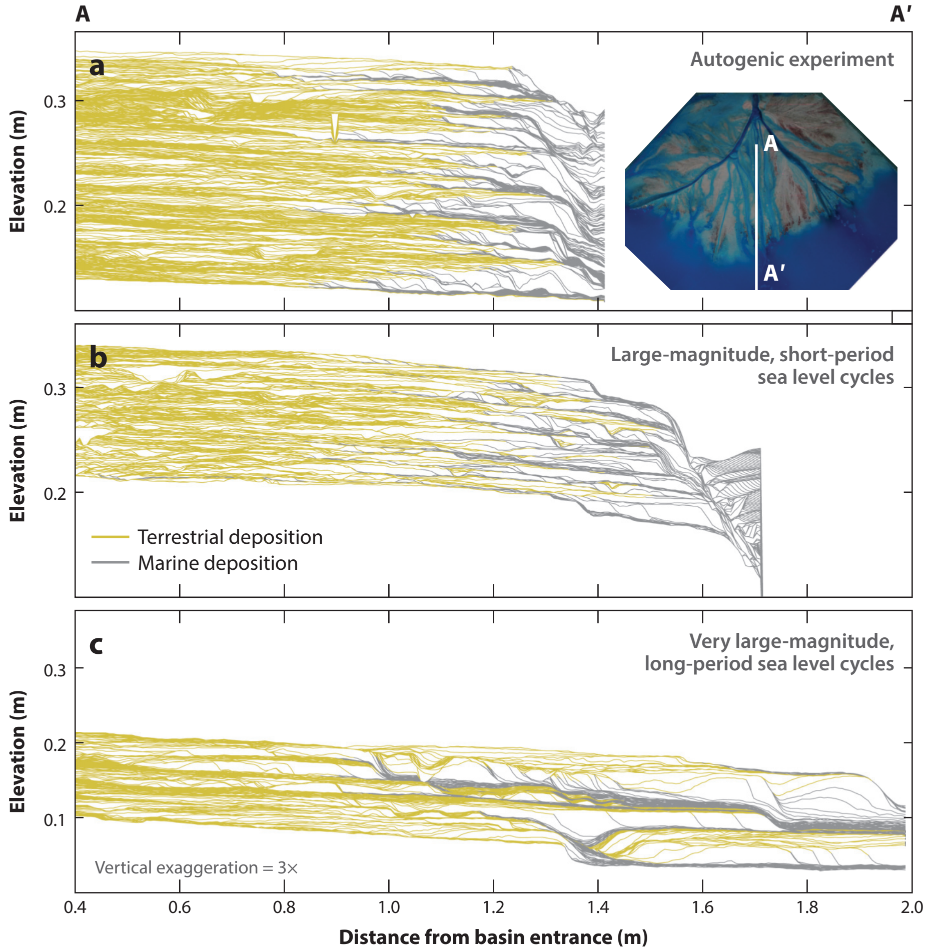

Figure 2

Example dip sections from experimental deltas that experienced (*a*) constant boundary conditions, (*b*) large-magnitude, short-period sea level fluctuations, and (*c*) very large-magnitude, long-period sea level fluctuations (Li et al. 2016), depicting subaerial (terrestrial) deposition (*yellow*) and subaqueous (marine) deposition (*gray*). Synthetic stratigraphy is generated from stacked maps of topography that have been clipped for erosion. (*Inset*) Location of dip panels. Typically allogenic drivers are thought to be responsible for the largest and most prominent patterns in the sedimentary archive; however, the entirely autogenic experimental deposit (*a*) shows fairly regular packaging with a few large transgression–regression cycles, each comprising several smaller-order cycles. In contrast, deposits of the sea level–forced experiments, especially those in panel *b*, produced stratigraphy that appears less organized, with discontinuous flooding surfaces and less regular stratigraphic packaging. **Supplemental Videos 2–4** present overhead images of the experiments in panels *a*, *b*, and *c*, and **Supplemental Video 5** shows an animation of the buildup of the stratigraphic successions (Li et al. 2016).

Supplemental Material

focus on examples of how physical sediment-transport dynamics are manifest in clastic sedimentary deposits and emphasize landscape dynamics that are most directly observable in the stratigraphic record. However, we note that autogenic dynamics are also important in upland and erosional landscapes (e.g., Perron et al. 2009, Finnegan et al. 2014).

2.1. Definitions

Autogenic behavior refers to patterns, variability, or dynamics that arise solely as a consequence of interacting components within a particular system. Many sediment-transport systems are characterized by local episodes of sediment storage (i.e., bed aggradation) and release (bed lowering or degradation), as exemplified by the passage of dunes across a riverbed (**Table 1**). Dunes form spontaneously and produce variable bed elevations even when the amount of sediment and water being supplied from upstream remains constant. In this example, variability in bed elevations through time is entirely a consequence of how a morphodynamic system configures itself. Autogenic variability is sometimes ordered or patterned, which is referred to as self-organized behavior. Examples of self-organized autogenic behavior include the regular spacing of bars in meandering rivers (Stølum 1996, Hooke 2007), consistent scaling of braided channel networks (Murray & Paola 1994), or spatial patterns in aeolian dune fields (Kocurek & Ewing 2005, 2016).

Self-organized: ordered or patterned autogenic behavior

Self-organization has been studied across a wide range of natural systems and can sometimes be characterized by well-defined models. For example, Turing (1952) described how scale-dependent reactions can lead to self-organized patterns in reaction–diffusion systems where a short-range, fast-acting reaction that creates a product competes with a long-range, slowly acting inhibitor that destroys the same product (Reitkerk & van de Koppel 2008). The interaction of these reactions can produce ordered, regular patterns, and these kinds of models have been used to describe processes as diverse as the development of animal stripes and large-scale vegetation patterns (e.g., Reitkerk & van de Koppel 2008, Kondo & Miura 2010). Self-organized criticality is another specific type of autogenic relationship between agents in an autogenic system, where fractal patterns arise from interdependencies within the system that extend over a large range of scales (Bak et al. 1988). This type of complex, scale-invariant behavior (i.e., power law frequency–magnitude relationships) can be modeled with simple, rule-based cellular automata models (Turcotte 1999). These specific types of self-organized relationships have been identified in some clastic depositional systems and can be useful for understanding the underlying process dynamics that drive autogenic organization (e.g., Plotnick 2016). However, not all autogenic sediment-transport systems exhibit these specific types of self-organization.

2.2. Controls on Scales and Complexity of Autogenic Sedimentation

Complex sedimentation patterns arise from morphodynamic feedbacks in Earth surface systems. Nonlinear interactions among components of a sediment-transport network lead to variations in sediment-transport capacity across a landscape, which generate episodes of sediment storage (deposition and aggradation) and release (bypass or erosion) that have the potential to be recorded in stratigraphy. Transient landforms serve as temporary and dynamic sediment accommodation and provide a basis for understanding controls on and scales of autogenic processes in different environments (Hajek & Wolinsky 2012, Straub & Wang 2013). For example, in river networks the dynamics of bars, levees, and alluvial ridges can be approximated with mass-balance relationships equating the growth rate of each landform to its characteristic volume and system-averaged sedimentation rates (e.g., Hajek & Wolinsky 2012). This same principle applies to larger-scale autogenic dynamics, for example, the long-term slope adjustment of sediment-transport networks (Paola et al. 1992, Castelltort & van den Driessche 2003, Kim et al. 2006, Dalman & Weltje 2008, Kim & Jerolmack 2008, Hamilton et al. 2013, Dalman et al. 2015), delta growth and shoreline progradation (Muto & Steel 2004, Leva Lopez et al. 2014), and the development of alluvial megafans (Hartley et al. 2010, Weissmann et al. 2010) (**Table 2**).

In general, depositional systems with bigger landforms will be associated with larger spatial variability in sediment-transport dynamics. However, the effective spatial and temporal

Table 2 Example scaling relationships for autogenic landform storage and release dynamics in terrestrial and deepwater clastic sediment-transport systems

Autogenic process	Associated landform or deposit	Scaling equation or important variables	Vertical scale of relief	Lateral scale of landform	Timescale of operation	Example reference
Dune migration	Dunes (subaqueous or aeolian)	$T_D = \frac{\lambda H_D \varepsilon_{bed}}{2q_s}$	10^{-2}–10^2 m	10^{-2}–10^2 m	10^0 min–10^1 years	Exner 1925
Upstream migrating cyclic steps	Bedforms (e.g., antidunes) that form shallow, supercritical flow conditions	Celerity set by H_s, U, S_e	10^{-1}–10^2 m	10^1 m–10^1 km	10^0 h–10^1 years	Sun & Parker 2005
Channel migration/ meandering	Channel belt and point bars	$T_{ChST} = \frac{BH_c\varepsilon_{bed}}{q_s}$	10^0–10^2 m	10^1 m–10^1 km	10^0–10^1 years	Cazanacli et al. 2002, Jerolmack & Mohrig 2007
Channel bifurcation	Mouth bars	Time to generate mouth bar set by H_c, D_{50}, U, S_e	10^0–10^2 m	10^0 m–10^0 km	10^0–10^1 years	Edmonds & Slingerland 2007
Avulsion	Channel belt and alluvial ridge	$T_A = \frac{H_c}{\bar{r}_{IC}}$	10^0–10^2 m	10^2 m–10^3 km	10^0–10^3 years	Jerolmack & Mohrig 2007
Regrading of depositional surface	Longitudinal transport slope changes (e.g., river planform changes)	$T_{ChLT} = \frac{(B_t - \sum B)H_c}{q_s}$	10^0–10^2 m	10^1–10^3 km	10^3–10^6 years	Kim et al. 2010

Abbreviations: λ, dune wavelength; H_D, dune height; ε_{bed}, bed concentration; q_s, width averaged sediment flux; H_s, step height; U, velocity; S_e, equilibrium slope; B, channel width; H_c, channel depth; D_{50}, median grain diameter; $\bar{r}_{IC}$, in-channel deposition rate; B_t, basin width.

variability manifest in the stratigraphic record will depend on the rates of autogenic processes relative to long-term sediment accumulation rates (Straub & Wang 2013). Systems that tend to move quickly—either because sedimentation rates are very high or because they can easily reorganize—will generally exhibit a smaller range of autogenic dynamics, all else being equal. Cohesion is one of the most important factors that influence the mobility of a sediment-transport network (i.e., the speed with which sediment-transport fields reorganize). Stickiness—whether it comes from clay minerals, chemical weathering, or biological factors—increases the shear stress necessary to entrain sediment, thereby increasing the stability of a landscape (Tal & Paola 2007, Braudrick et al. 2009, Edmonds & Slingerland 2010, Malarkey et al. 2015, Baas et al. 2016). Cohesion has the effect of increasing the steepness and maximum topographic relief that can be sustained across a given landscape, which effectively increases the potential magnitude of dynamic sediment storage and bypass events within a system (Caldwell & Edmonds 2014, Straub et al. 2015). Consequently, a cohesive landscape may exhibit autogenic dynamics that extend over much longer spatial and temporal scales than a less cohesive landscape experiencing the same boundary conditions. An example of the effects of cohesion can be seen in a comparison of stratigraphy built in experiments conducted with cohesive and noncohesive sediments (**Figure 3**)

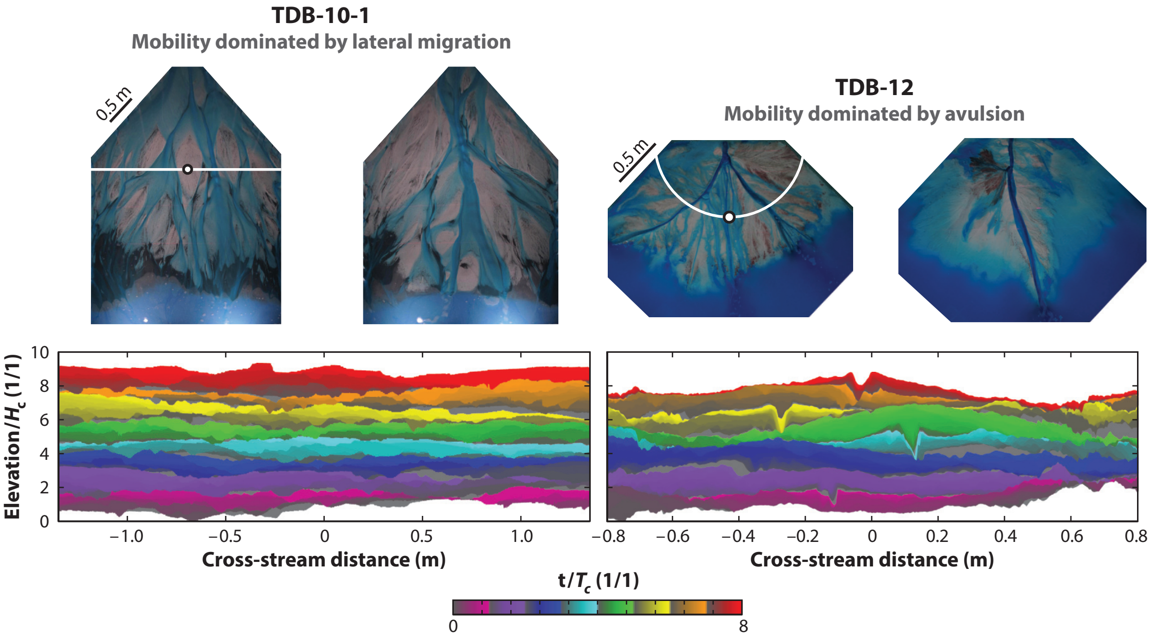

Figure 3

Comparison of surface morphology and stratigraphic stacking patterns of two experiments, TDB-10-1 (Wang et al. 2011, Straub & Wang 2013) and TDB-12 (Straub et al. 2015). Overhead photos show that the TDB-10-1 experiment had a laterally mobile, braided channel network due to noncohesive sediment introduced to the experimental basin with a high ratio of sediment to water flux (1:40). The TDB-12 had a more stable, single-thread channel network caused by cohesive sediment introduced with a low ratio of sediment to water flux (1:1,000). White lines mark the locations of cross-stream transects (also for **Figures 5** and **6**) and white dots show the location of the 1D time series used in **Figure 8**. Transects are colored to show chronostratigraphic packages deposited during one compensation scale (T_c) and are normalized in thickness (elevation) to the maximum channel depth in each experiment (H_c). **Supplemental Video 6** shows overhead images from TDB-10-1. Overhead images from TDB-12 are shown in **Supplemental Video 2. Supplemental Video 7** shows an animation of the stratigraphic buildup of the cross sections.

Supplemental Material

(Straub et al. 2015). In one experiment (TDB-10), noncohesive sediment was introduced to the basin under conditions that led to channels with a high degree of lateral mobility; in contrast, an experiment that used strongly cohesive sediment (TDB-12) developed relatively stable, deep channels that avulsed more than they migrated laterally. The impact of cohesion is striking: Topographic relief across the experimental surface of the noncohesive experiment is significantly lower than in the cohesive experiment, and chronostratigraphic packages from the noncohesive experiment generally extend across the entire basin and have relatively uniform thickness, in contrast to the irregular, lobe-shaped packages formed in the cohesive experiment.

3. THE HANDOFF BETWEEN AUTOGENIC AND ALLOGENIC SEDIMENTATION

Although experiments and models can fully isolate autogenic processes, boundary conditions on Earth are always changing. Consequently, a critical aspect of interpreting the sedimentary record involves considering how autogenic and allogenic processes interact and how their influence is preserved stratigraphically. We now know that autogenic processes can act over large temporal and spatial scales, but at the largest scales, sedimentation is controlled by tectonic, climatic, and eustatic boundary conditions that, on global scales, dictate where sediment is generated and accumulates (e.g., **Figure 1**). Consequently, there are critical questions about the transition or handoff between sedimentation that is largely controlled by autogenic processes and stratigraphy that predominantly reflects allogenic controls. At what scale does this handoff occur? Is the transition from autogenic to allogenic control on sedimentation abrupt or gradual? What kinds of allogenic and autogenic signals are preserved in the stratigraphic archive? The concepts of compensational sedimentation and signal shredding are helpful for answering these questions.

Signal shredding: modification or obliteration of an allogenic signal by sediment-transport dynamics in a landscape and/or by dynamics of stratigraphic preservation

Compensation: the tendency of a system to compensate for landscape topography that arises from uneven sedimentation through preferential deposition in topographic lows

3.1. Compensational Sedimentation

The underlying basis of sequence stratigraphy is the idea that the packaging of sedimentary rocks reflects changes in the balance of the amount of sediment delivered to a region relative to the amount of space being created to store it (e.g., Jervey 1988, Muto & Steel 1997). In this mass-balance perspective, the main drivers of sediment supply (climate and tectonic uplift) and accommodation for sediment storage (tectonic subsidence and eustacy) are allogenic. At this level, stratigraphic patterns are deterministic in that they can be predicted directly by knowing the sediment delivery to a basin and the rate of accommodation creation throughout the basin.

Sedimentation patterns driven by these types of mass-balance changes are unequivocally allogenic. One way of identifying the type of sedimentary filling that responds to mass-balance changes is to find the scale at which successive packages of sediment can be observed to fill a basin evenly. Variable autogenic sedimentation arises from the fact that most sediment-transport networks—particularly strongly cohesive ones—do not efficiently distribute sediment uniformly. The time it takes the sediment-transport system to catch up to subsidence and distribute sediment evenly across a basin defines the upper limit of autogenic sediment-transport influence in a given setting and the handoff to deterministic (mass-balance) allogenic sedimentation.

We can exploit this shift from variable to predictable sedimentation patterns as a means of identifying autogenic versus allogenic scales in sedimentary deposits. The compensation scale defines the scale at which a basin is filled evenly and marks the handoff between fully autogenic and fully allogenic controls on sedimentation. Experimental and field examples have shown that this transition is related to key topographic-relief scales in different environments (**Figure 4**) (Wang et al. 2011, Chamberlin et al. 2016, Trampush et al. 2017). Recall that the characteristic topographic relief that develops on a landscape is related to the efficiency with which deposition and erosion are partitioned in a given environment. Strongly cohesive settings may generate more relief than more mobile landscapes (**Figure 3**).

The compensation statistic (*CV*) provides a formal way of detecting the transition from variable (autogenic) sedimentation to deterministic (uniform, mass-balance) sedimentation in stratigraphic deposits. It has proven useful in both experimental and natural deposits (Sheets et al. 2002, Lyons 2004, Straub et al. 2009, Wang et al. 2011, Straub & Pyles 2012, Trampush et al. 2017). Using the variability in sediment-package thickness across a basin, *CV* compares stratigraphic packaging across a range of scales to what would be expected from uncorrelated, random sedimentation. *CV* is the standard deviation of the thickness of a given sediment package ($\Delta\eta_{A,B}$) across a basin of width L relative to the average thickness of the sediment package observed in the basin ($\Delta\bar{\eta}_{A,B}$) (Wang et al. 2011, Straub & Pyles 2012, Trampush et al. 2017):

$$CV = \left(\int_L \left[\frac{\Delta\eta(x)_{A,B}}{\overline{\Delta\eta}_{A,B}} - 1 \right]^2 dL \right)^{1/2}. \tag{1}$$

If absolute dates are available for a deposit, average bed thickness can be related to long-term sedimentation rates (Straub et al. 2009, Wang et al. 2011). When sediment packages have highly variable thickness (i.e., they reflect strongly localized deposition, such as in a channel or discrete

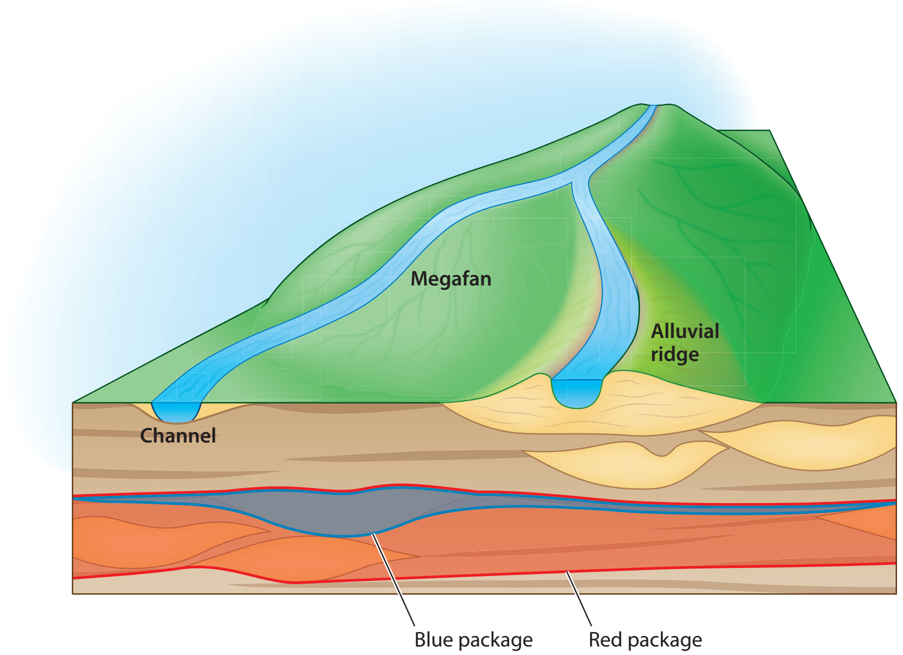

Figure 4

Conceptual diagram of compensational basin filling in a fluvial landscape characterized by a range of morphodynamic processes that produce different scales of topographic relief, including channel incision (*left*), alluvial ridge growth (*right*), and the development of large-scale alluvial megafans. Over relatively short timescales, sedimentation is uneven across a basin because of autogenic sediment-transport dynamics (e.g., erosion or aggradation can be locally restricted to active channel locations). Eventually, over long enough timescales, sedimentation evens out to match long-term accommodation creation and becomes compensational. The blue package represents avulsion-related deposition of a channel-belt and alluvial-ridge deposit; it has a high standard deviation of thickness across the basin. In contrast, the red package, which comprises multiple channel-belt deposits, is thicker (i.e., it represents a longer timespan) and has relatively uniform thickness across the basin.

lobe), they will have a high CV value, and sediment packages with relatively constant thicknesses have low CV values, indicating evenly distributed sedimentation, such as floodplain sedimentation (**Figures 4** and **5**) (Trampush et al. 2017). In this way, comparing sediment packages with similar average thicknesses (and consequently similar durations) reveals information about the range of morphodynamic processes active on a landscape; a large range of thickness variations among packages deposited over approximately the same amount of time suggests the landscape experienced phases of both strongly localized and broadly distributed sedimentation (**Figure 5**) (Trampush et al. 2017).

When successively larger sediment packages are compared—i.e., when we average more and more small-scale variations in sedimentation—the overall variability of chronostratigraphic packages of sediment within a basin decreases as a power law:

$$CV = a\Delta\bar{\eta}^{-\kappa}. \quad (2)$$

If sedimentation occurs randomly across a basin, CV decays with a power law exponent $\kappa = 0.5$. When sedimentation is evenly distributed across a basin (i.e., compensational), the thickness of chronostratigraphic packages observed over any given time period reflects the long-term

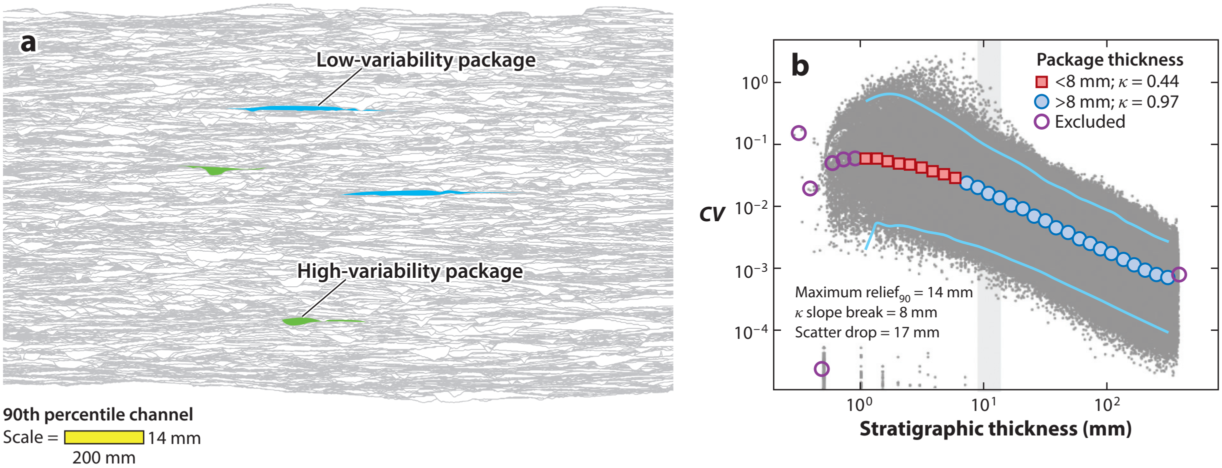

Figure 5

Example compensation-statistic analysis from autogenic experiment TDB-10-1 (Wang et al. 2011, Trampush et al. 2017). Synthetic stratigraphy data from the experiment (*a*) are constructed from topography scans collected every 2 min that were clipped for erosion at the cross section location shown in **Figure 3**. The deposit is 2.3 m wide and 0.65 m thick. An approximation of the 90th percentile channel is shown below the stratigraphic panel (*a*). In order to calculate the compensation index, each preserved surface is compared to every other surface in the data set and the averages and standard deviations (*CV*) of the thickness of each sedimentary package are calculated. Highlighted packages show example chronostratigraphic deposits with the same mean thickness (∼4 mm) but with high (*green*) or low (*cyan*) variability in thickness across the packages. These differences reflect variability in the configuration of the sediment-transport network (e.g., photos in **Figure 3**) that produces strongly channelized deposits (*green*) sometimes and broad, sheet-like deposition (*cyan*) at other times. *CV* values are shown for each chronostratigraphic package (*gray dots*) in panel *b*. The 95% envelope for all *CV* data is shown with cyan lines. Median values (of *CV* groups binned by thickness) are shown in red and blue, and purple circles are bin medians that were excluded from analysis (i.e., any bins with average thicknesses below the topographic resolution of the data set, as well as the largest bin). Sedimentary packages thicker than 8 mm (*blue*) show a compensation index κ value of ∼1, indicating regular, even basin filling at these scales. Packages thinner than 8 mm (*red*) show significantly more variability and an average trend of $\kappa = \sim 0.4$, indicating random or persistent sedimentation patterns. This transition coincides with the envelope of maximum relief observed on the delta surface (thickness range highlighted in *gray*).

basin-averaged sedimentation rate fairly well and *CV* shows a $\kappa > 0.5$, with $\kappa = 1.0$ reflecting even sedimentation.

The exponent κ—the compensation index—describes the degree to which sedimentary packages compensate for relief generated within the basin. If the allogenic mass-balance scale is characterized by spatially uniform sedimentation, we can use *CV* to measure where κ equals 1.0 as an estimate of the transition from autogenically to allogenically controlled stratigraphy (Wang et al. 2011). In an experimental example with constant boundary conditions, *CV* values show both a distinct reduction in scatter and a change in trend around 14 mm (**Figure 5**) (Trampush et al. 2017). This means that stratigraphic packages that are, on average, thinner than 14 mm range from very flat to highly channelized, and chronostratigraphic packages larger than 14 mm have relatively uniform thicknesses. This distinct drop in variability and the shift from relatively random sedimentation ($\kappa \sim 0.5$) to evenly distributed sediment packages ($\kappa \sim 1.0$) coincide directly with the maximum relief observed on the experimental delta surface (**Figure 5**). This demonstrates that stratigraphy can reflect characteristic landscape relief generated by autogenic landform-driven deposition and erosion. We note, however, that the degree to which allogenic controls, including high-frequency climatic, tectonic, or eustatic variation and environmental variability, may also contribute to creating characteristic relief across a landscape remains unexplored. For example, landscapes in climates with high-magnitude, low-frequency flooding may have different maximum roughness scales than those in climates with the same mean annual discharge but more moderate flood events.

3.2. Signal Shredding

Autogenic sediment-transport processes not only add variability (noise) to the stratigraphic record but also can destroy (shred) environmental signals before they can be transferred into the sedimentary archive (Jerolmack & Paola 2010). Jerolmack & Paola propose that sediment-transport dynamics can act as a nonlinear filter on allogenic signals. Autogenic storage and release serves as a sort of morphodynamic turbulence in a landscape. Processes like bar migration, channel avulsion, or delta-lobe switching can smear an incoming signal (e.g., a spike in sediment supply associated with a tectonic uplift event) and distribute it over a range of scales to the degree that the input signal is no longer detectable at the outlet of a system. This type of sediment-transport shredding can affect allogenic signals that overlap with the maximum autogenic scale in a given landscape. The timescale of autogenic shredding T_x is defined as

$$T_x = \frac{L^2}{q_0}, \tag{3}$$

where q_0 is the input sediment flux to a system and L is the length of the system, which defines the maximum possible autogenic storage scale on the landscape (Jerolmack & Paola 2010). Allogenic sediment-flux cycles with periodicities greater than T_x are expected to pass through a transport system and have an opportunity to be stored in the stratigraphic record, but signals with periodicities less than T_x are expected to be shredded. Similarly, the magnitude of signals subject to autogenic transport shredding (M) is related to the amount of sediment that would be liberated as a result of a system-clearing event that would relax a transport slope from a self-organized upper to lower limit:

$$M = L^2 S_c, \tag{4}$$

where S_c is a critical slope for a transport system. Jerolmack & Paola (2010) successfully tested this theory in a 1D numerical rice pile and a 2D numerical delta avulsion model.

Li et al. (2016) extended this concept to evaluate how allogenic signals are not just transmitted through a sediment-transport network, but can be incorporated into the sedimentary archive. They proposed a theory to define "stratigraphic signal shredding" and hypothesized that preservation of allogenic signals in stratigraphy requires (*a*) that the magnitude and/or periodicity of the signal must generate stratigraphic products that exceed the maximum scales of deposits generated autogenically within a sediment-transport network, and (*b*) that those stratigraphic products must get transferred below the characteristic autogenic reworking depth (i.e., the deepest autogenic erosion events) in a landscape. This means that a detectable signal not only needs to be big enough to be preserved, but also needs to be differentiable from background autogenic variability present in a stratigraphic succession.

Li et al. (2016) tested their stratigraphic shredding theory with a series of physical delta experiments that subjected an aggrading cohesive delta system to relative sea level (RSL) changes with a range of magnitudes and periodicities. Leveraging the insight that the maximum topographic relief on a landscape provides a good estimate of the largest autogenic dynamics in a system, they scaled the range of imposed RSL changes R_{RSL} to the depth H_c of the largest channels observed in an experiment with constant boundary conditions:

$$H^* = \frac{R_{\mathrm{RSL}}}{H_c}. \tag{5}$$

Morphodynamics: coevolving fluid and sediment-transport fields

They compare the period of an RSL cycle T_{RSL} to the maximum timescale of autogenics in deltaic systems, i.e., the compensation timescale T_c. The compensation timescale reflects the time necessary to deposit, on average, one channel depth of stratigraphy everywhere in a basin, which also estimates the time required to bury a particle deposited at Earth's surface to a depth that is no longer susceptible to erosion from autogenic incision events (Straub & Esposito 2013). This produces a nondimensional time that scales as

$$T^* = \frac{T_{\mathrm{RSL}}}{T_c}. \tag{6}$$

Together, H^* and T^* provide a method to scale the magnitude and period of RSL cycles to the autogenic morphodynamics of individual systems. Li et al. (2016) showed that stratigraphy from deltas that experienced RSL cycles where H^* and/or $T^* \gg 1$ stored RSL cycle information as periodic changes in the sedimentation rate; however, RSL signals were undetectable when H^* and $T^* \ll 1$ (**Figure 6**).

To estimate stratigraphic shredding scales in natural systems, Li et al. (2016) compiled a database of channel depths and compensation timescales for a suite of medium to large modern river deltas. They showed that Quaternary-scale eccentricity-driven eustatic sea level changes (M_{RSL} ~100 m, T_{RSL} ~100,000 ky) would be preserved in the stratigraphic record of even the biggest rivers on Earth because the magnitude of the eustatic change is so large. However, obliquity-driven sea level cycles like those of the Late Miocene (M_{RSL} ~15–35 m, T_{RSL} ~40 ky) would only be preserved in the stratigraphic records of deltas similar to or smaller than the Rhine or Rio Grande deltas and not in larger systems like the Ganges-Brahmaputra or Mississippi deltas, due to their large autogenic spatial and temporal scales. Interestingly, many of the systems included in Li and colleagues' comparison lie close to the predicted storage thresholds, suggesting that the stratigraphic records of deltas the size of the Nile could preserve signatures of Late Miocene–scale sea level cycles, but they may be difficult to identify.

Combined, results from Jerolmack & Paola (2010) and Li et al. (2016) provide null hypotheses for stratigraphic interpretation. If the maximum autogenic scale on a particular landscape is large, only big or long-period signals should be detectable in the stratigraphic record. Climate-driven sediment-supply signals—for example, those driven by hydrologic and weathering changes during hyperthermal events—might be easily identified if they are associated with large-magnitude events, like the Paleocene–Eocene Thermal Maximum (e.g., McInerney & Wing 2011, Foreman et al. 2012, Foreman 2014), but uniquely identifying the signatures of rapid hyperthermal events, such as those of the Eocene, might be difficult. Furthermore, allogenic signals shredded by morphodynamic turbulence are not merely difficult to detect; they may be impossible to reconstruct. Because they have been smeared throughout a sediment-transport system chaotically, even advanced signal-processing tools would not be able to recover shredded allogenic signals. The conditions under which autogenic dynamics preserve, modify, or destroy allogenic signals are poorly constrained; this is an important concept needing further study.

4. DETECTING AND MEASURING AUTOGENIC SEDIMENTATION IN STRATIGRAPHY

The idea of compensational sedimentation being the product of truly allogenic, mass-balance sedimentation provides a useful approach for identifying scales of stratigraphy that represent autogenic

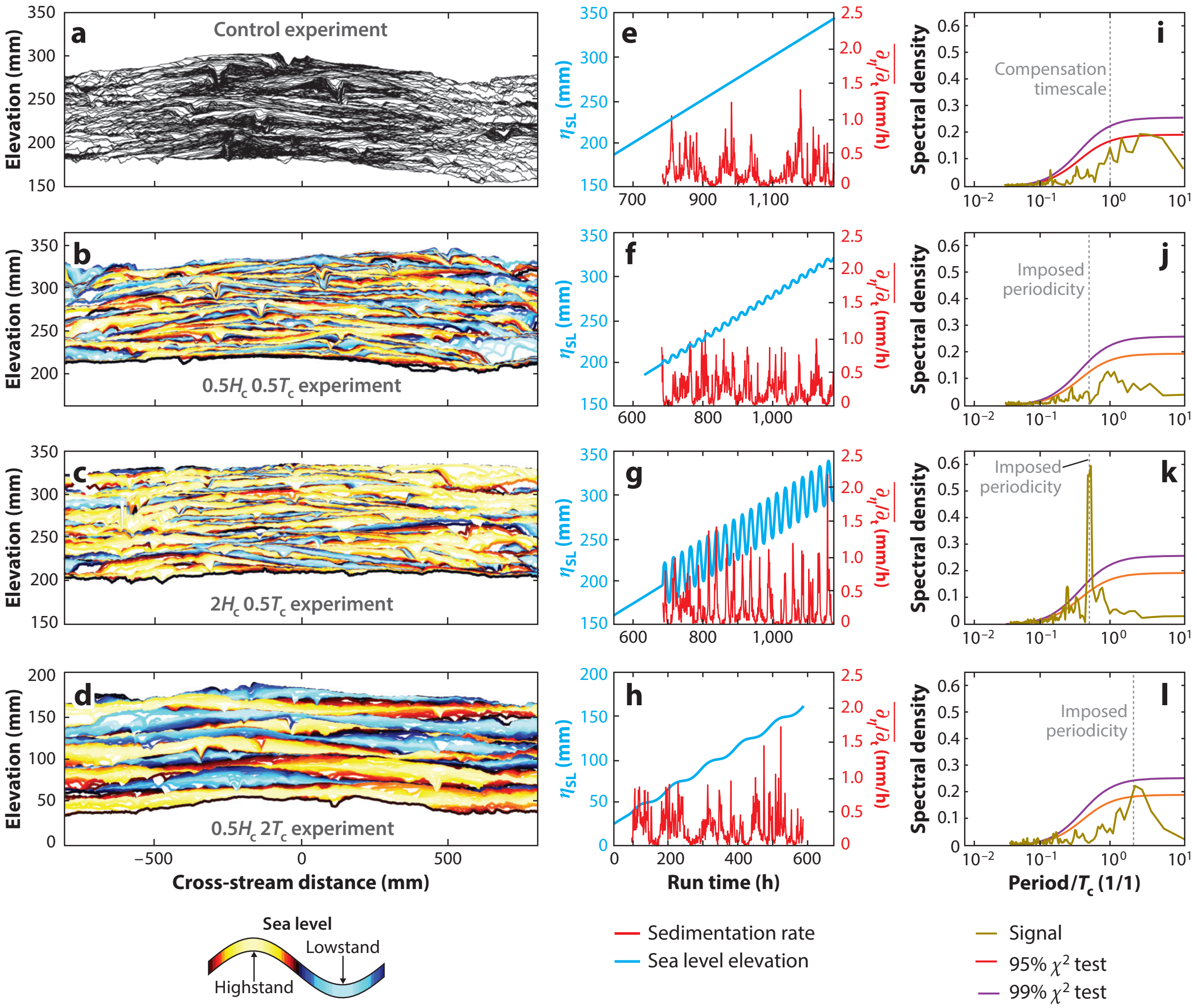

Figure 6

Results illustrating stratigraphic storage/shredding thresholds for relative sea level (RSL) cycles from Li et al. (2016). Analysis centers on time series of mean deposition rates measured from preserved experimental stratigraphy along a strike transect located approximately halfway between the basin entrance and mean shoreline (see **Figure 3** for location). Data from four experiments are presented that share identical forcing conditions, with the exception of the period and magnitude of RSL cycles. The experiments include (*a*) a control experiment with no RSL cycles, (*b*) an experiment with cycles defined by ranges that are half of the largest channel H_c and periods that are half of the compensation timescale T_c, (*c*) an experiment with cycles defined by ranges that are twice H_c and periods that are half T_c, and (*d*) an experiment with cycles defined by ranges that are half H_c and periods that are twice T_c. (*a–d*) Synthetic stratigraphy colored by time of deposition relative to location in RSL cycle. (*e–h*) Sea level (η_{SL}) and mean deposition rate (δ_η/δ_t) time series. (*i–l*) Power spectra of mean deposition rate time series and χ^2 confidence limits.

versus allogenic processes. The size and distribution of smaller sedimentary packages tell us about the scale and distribution of sediment storage and release events on ancient landscapes; measuring the scales and patterns associated with these packages provides an avenue for reconstructing ancient autogenic dynamics.

4.1. Detecting the Maximum Autogenic Sedimentation Scale

Although *CV* and other quantitative tools can be very effective in high-resolution experimental and numerical data sets, it is less clear how sensitive these approaches are to sparse or low-resolution data sets from natural systems, including outcrop, well log, core, or seismic data. In practice, relative chronostratigraphic packages of sediment can be identified in any of these data sets using truncation surfaces, onlap or downlap surfaces, bed-set boundaries, biozones, facies boundaries, marker beds, or any other relative timelines that can be mapped in a data set (e.g., Van Wagoner et al. 1990, Catuneanu 2006). To evaluate whether *CV* can be reliably applied to outcrop-scale data sets, Trampush et al. (2017) subsampled experimental data to evaluate how *CV* computed on outcrop-sized data sets reflected the overall behavior measured throughout the experiment from high-resolution data (e.g., **Figure 5**). Their results show that as long as a stratigraphic data set is at least three times as thick as the maximum paleotopographic relief observed in a system (i.e., the maximum channel depth in the autogenic experiments) compensation-scale estimates were reliable within a factor of two. This result demonstrates the potential power of *CV* to reveal important information about autogenic sedimentation from many stratigraphic data sets.

Trampush et al. (2017) used this insight to evaluate two deltaic and two fluvial outcrop data sets. Their results show that, as in autogenic experiments, channel depth can provide an appropriate estimate of the compensation scale for some natural systems; however, for other systems it significantly underestimates the compensation scale. For example, in the Upper Cretaceous deltaic Ferron Sandstone and fluvial lower Williams Fork and Ferris formations (**Figure 7**), measured compensation scales were 4–10 times the maximum paleoflow depths observed within each system. This indicates that, in contrast to many experimental data sets, the maximum relief that characterized these ancient landscapes significantly exceeded the maximum channel scale. Sedimentologically, the Ferris Formation shows no evidence of allogenic forcing (Hajek et al. 2012), suggesting that these fluvial landscapes may have been capable of generating relief significantly larger than the scale of an individual channel. It remains unclear what processes are most important for generating large compensation scales on fluvial landscapes. It is possible that the development of large-scale landforms linked to avulsion, such as significant alluvial ridges (Edmonds et al. 2016) or megafan features, might influence the temporal and spatial scales of sedimentation in highly aggradational basins (e.g., **Figure 4**). In deltaic systems, basin water depth may play a role in setting the compensation scale (Trampush et al. 2017).

4.2. Characterizing Autogenic Sedimentation Patterns

If sedimentation controlled by autogenic processes can be separated from allogenic sedimentation, the spatiotemporal organization of sediment packages at autogenic scales can be evaluated in order to reconstruct autogenic paleolandscape dynamics. Approaches to characterizing autogenic sedimentation have largely leveraged some type of statistical test to determine if sediment packages are organized randomly, if sedimentation events cluster, or if they are spread out evenly (Hajek et al. 2010, Hajek & Wolinsky 2012).

Statistics that are useful for this type of analysis characterize the type, and perhaps strength, of spatiotemporal organization over a range of scales. Because basin-filling sedimentation varies in both space and time, but often only spatial aspects of stratigraphy can be precisely measured, many stratigraphic analyses are inherently underconstrained in time. However, metrics that emphasize either spatial or temporal patterns can still be useful for characterizing autogenic sedimentation—provided that they can detect different types of organization over a wide range of scales—and can be especially informative when they are connected to a known or hypothesized autogenic scale (e.g., **Table 2**).

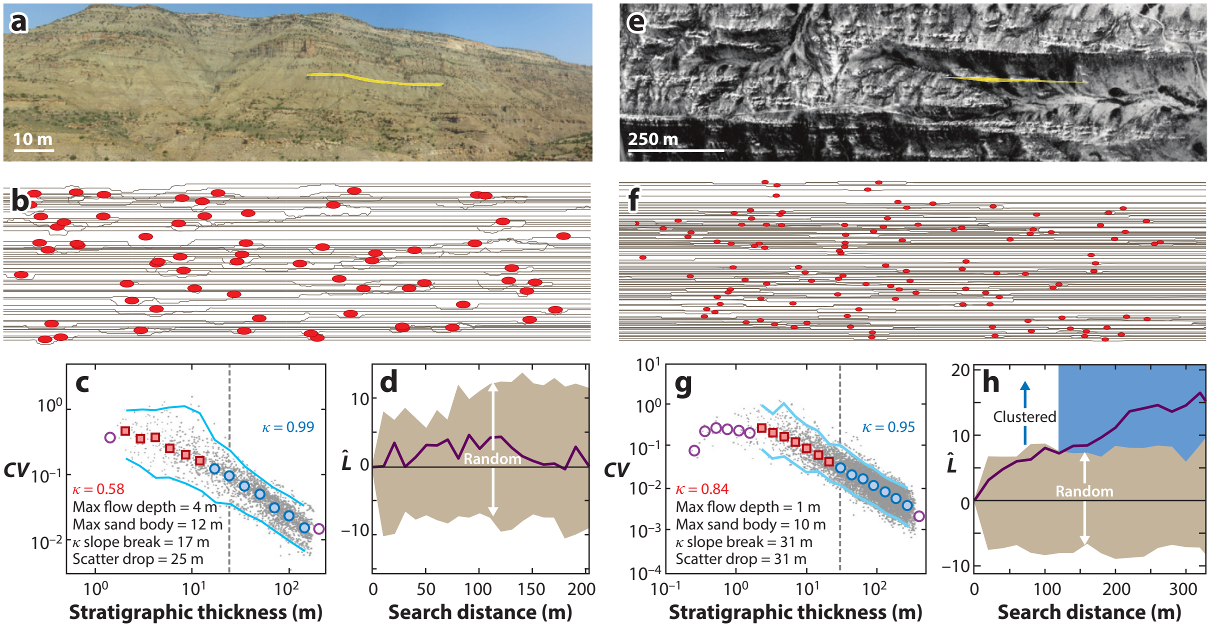

Figure 7

Comparison of compensation and spatial point process (SPP) statistical analyses of two ancient fluvial deposits in the western United States, (*a–d*) the Upper Cretaceous lower Williams Fork Formation in Colorado (Chamberlin et al. 2016, Trampush et al. 2017) and (*e–h*) the Cretaceous–Paleogene Ferris Formation in Wyoming (Hajek et al. 2010, Wang et al. 2011, Trampush et al. 2017). In extensive field exposures (*a*,*e*), channel and floodplain deposits were mapped and used to locate avulsion channels (examples in *yellow* in *a* and *e* and mapped channel centroids are *red dots* in panels *b* and *f*) and create pseudochronostratigraphic surfaces (*brown horizons* in panels *b* and *f*). These pseudochronostratigraphic surfaces were used to calculate the compensation statistic (*CV*) over a range of stratigraphic thicknesses (*c*,*g*) (see **Figure 5** for more details of *CV* plots). The Williams Fork Formation shows a transition from variable to even sedimentation that occurs between 17 and 23 m, marked by the rage of scales for which $\kappa = 1$ (*blue*) and the major drop in *CV* scatter (*gray dashed line*). This scale is significantly larger than maximum paleoflow depth (4 m) observed in the system or even the maximum channel-deposit thickness (12 m). The Ferris Formation also shows a transition to even sedimentation that occurs at a stratigraphic thickness (31 m) significantly larger than the maximum observed paleoflow depth (1 m) or channel-deposit thickness (10 m). (*d*,*h*) SPP analysis of channel-deposit locations in each cross section using Ripley's K function ($\hat{L}$) (see Hajek et al. 2010 and Chamberlin et al. 2016 for details). In this metric, $\hat{L} = 0$ represents the normalized expected distribution of channels in the study area (channels per unit area) and the range of $\hat{L}$ values considered as randomly distributed are constrained with Monte Carlo simulations (*brown area*). Channels in the lower Williams Fork Formation are randomly distributed at all search distances (*d*), whereas Ferris Formation channels are clustered at scales of 120–300 m (*h*). Panel *h* modified from Hajek & Wolinsky (2012) with permission from Elsevier.

Several measures that have proven particularly useful include *CV*, spatial point process (SPP) statistics (e.g., Hajek et al. 2010, Flood & Hampson 2014), and lacunarity analysis (Plotnick et al. 1993, Flood & Hampson 2014). SPP statistics are a family of spatial statistical approaches used to characterize the distribution of objects. Unlike nearest-neighbor statistics, SPP metrics like Ripley's K function and pair correlation functions compare the number of objects found within a specified search area to the background distribution of objects that would be expected under complete spatial randomness (Cressie 1993, Diggle 2003). By looking over a range of search areas, spatial organization can be determined across a variety of scales. When applied to stratigraphy, SPP approaches reveal aspects of the underlying stochastic behavior controlling the origin and positioning of sedimentation events (**Figure 7**). Similarly, lacunarity analysis measures the distribution of gaps that occur in a spatially distributed pattern and tests whether they match what would be expected for translation-independent spatial patterns. Lacunarity analysis has been used to characterize and discriminate spatial patterns among systems that have the same fractal dimension (Plotnick et al. 1993, Flood & Hampson 2014). Still other approaches, including geostatistical methods, can be used to detect organization in the chronostratigraphic arrangement of sediment packages (e.g., Hu & Chugunova 2008).

Many of these methods have been applied to ancient deposits in an effort to reconstruct spatiotemporal sedimentation patterns. In fluvial deposits, SPP (Hajek et al. 2010, Flood & Hampson 2014, Chamberlin et al. 2016) and lacunarity analyses (Flood & Hampson 2014) have been used to characterize the distribution of channel deposits in an effort to understand paleo-avulsion patterns (**Figure 7**). Although these statistical approaches are helpful for description and comparison, none fully characterizes the spatiotemporal history of sedimentation in ancient deposits. Issues like spatial anisotropy (sedimentation packages tend to be very wide relative to their thickness) and temporal dependence (e.g., sedimentation events may not be truly independent and identically distributed) mean that the specific scales and magnitudes of spatial patterns cannot always be directly interpreted and need to be scaled or compared carefully (e.g., Flood & Hampson 2014, Hajek & Wolinsky 2012). Nonetheless, these approaches provide a basis for more quantitatively describing stratigraphic patterns over a range of scales and, particularly when used in combination, can provide important insight into the structure and organization of autogenic sedimentation. For example, a combination of SPP and *CV* analysis on the Williams Fork and Ferris formations shows that, although both units have maximum characteristic landscape relief well in excess of channel scales, avulsion patterns of Ferris channels resulted in clustered channel deposits, whereas Williams Fork channels avulsed randomly across the basin (**Figure 7**).

Statistical information is useful for revealing patterns in autogenic sedimentation; however, even highly refined statistical approaches will not by themselves reveal the underlying processes driving autogenic dynamics. Furthermore, most natural stratigraphic data sets are insufficiently constrained to fully characterize autogenic sedimentation patterns because they are limited in spatial extent, temporal resolution, or both. Forward modeling and experimental approaches can be used to overcome these limitations. Chamberlin and colleagues (2016) employ a forward modeling strategy to gauge whether an SPP analysis of a fluvial outcrop that yielded evidence of random autogenic stratigraphy was a consequence of truly random paleo-avulsion patterns, or whether the extent and resolution of the outcrop were insufficient to detect different degrees and geometries of clustering. Likewise, with geostatistical, Bayesian, sparse sampling, or adaptive sampling approaches (e.g., Cressie 1993, Diggle & Lophaven 2006, Dobbie & Henderson 2008), it may be possible to use a series of limited data sets from the same basin (e.g., well logs or multiple outcrops representing independent samples of the same basin fill) to ascertain characteristic organization in a particular system. These types of approaches, whereby a range of process-focused synthetic or experimental scenarios are tested against field data from natural systems, offer tremendous promise for improving our understanding of what kinds of autogenic dynamics and mechanisms are active in different landscapes and seascapes. Ultimately, this type of process-based understanding is required for developing a comprehensive picture of how autogenic processes in different sediment-transport networks integrate to fill basins evenly over long timescales.

5. AUTOGENIC SEDIMENTATION AND CYCLOSTRATIGRAPHY

Cyclostratigraphy is an important tool for developing chronologies and correlations in sedimentary deposits that lack high-resolution age control (Hinnov 2013). It is also a useful approach to understanding how Earth systems respond to climate forcing (Berger et al. 1992, Hilgen et al. 2015). Because most astrophysical climate forcing is periodic, a central tool for cyclostratigraphers is frequency analysis of stratigraphic time series, sometimes conducted on spatial data like bed thicknesses (e.g., Abels et al. 2010, Husson et al. 2014). An underlying assumption of these analyses is that autogenic variability is relatively small scale and uncorrelated. In light of current understanding that autogenic dynamics can comprise a significant fraction of the sedimentary archive, are these assumptions reasonable?

Theory demonstrates that autogenic processes could destroy Milankovitch-scale signals in some depositional environments before they have a chance to be preserved in stratigraphy (Jerolmack & Paola 2010, Li et al. 2016). This means that astrophysical signals may be absent from stratigraphic records in systems with large autogenic dynamics. Such cases may be recognizable as records that lack strong statistical periodicity. But could autogenic variability in some environments produce periodicity that might be confused with orbital forcing? We have thus far used the term autogenic to describe self-formed behavior irrespective of its spatiotemporal structure, but some stratigraphers—including Beerbower's initial discussion of autocycles—suggest that autogenic processes like meander cutoff, avulsion, or delta-lobe progradation could be cyclical. For example, several physical and numerical experimental studies have identified spikes in the power spectra of deposition rates at predicted avulsion frequencies (Kim & Jerolmack 2008, Reitz et al. 2010, Karamitopoulos et al. 2014), whereas others have not (Straub & Wang 2013, Li et al. 2016). There has even been the suggestion of periodic autogenic dynamics occurring over very long timescales. For example, Kim & Paola (2007) observed autogenic cycles of lake formation and infilling in the zone of maximum subsidence in an experiment with offset normal faults. The durations of these cycles would be 10^4–10^5 years in field-scale systems. It is reasonable to expect that, due to the natural variability and stochasticity associated with many sediment-transport processes, pseudocyclicity resulting from autogenic dynamics would not produce strong enough power spectra to be statistically detectable. This largely depends on how statistical tests are constructed: If tests are too rigid, they may miss weak orbital signals, but if they are too permissive, false positives may arise.

Advances in understanding autogenic dynamics offer an opportunity to better constrain the potential for autocyclic signals in stratigraphy and to improve statistical approaches to detecting astronomical climate cycles. To demonstrate the potential for advances in this area, we generated power spectra of deposition rates measured from the synthetic stratigraphy of two autogenic experiments (**Figure 8**). The first experiment, TDB-10-1, is dominated by lateral migration (Wang et al. 2011) and, due to its forcing conditions, has faster autogenic dynamics and a shorter compensation scale than the second experiment, TDB-12, which is dominated by channel avulsion (Straub et al. 2015). Each experiment was run with constant forcing conditions, including constant feed rates of water and sediment and a constant base-level rise rate. Consequently, any depositional variability expressed in these experiments arises solely from autogenic behavior.

We evaluate pseudocores of the synthetic stratigraphy (1D time series of deposition from point locations located near the center of each fan delta) and ensemble-averaged time series representing data that might be obtained by mapping an outcrop panel or seismic volume (**Figure 8**). These data sets have extremely high temporal precision, eliminating uncertainty associated with age models necessary for cyclostratigraphic analysis of natural data. Power spectra presented here are generated with methods commonly used in cyclostratigraphy studies (Thomson 1982, Meyers 2012, Husson et al. 2014, Hilgen et al. 2015). We produce confidence bands for the identification of statistically significant frequencies by performing a χ^2 test on the power spectra of our control experiment with an underlying autoregressive-1 red noise model. This is consistent with other studies that document correlation in morphodynamic (Jerolmack & Paola 2010) and stratigraphic time series (Meyers 2012). Confidence bands are constructed for each spectrum using 1,000 Monte Carlo realizations of a theoretical best-fit red noise model. For comparison, deposition rate (D_m)

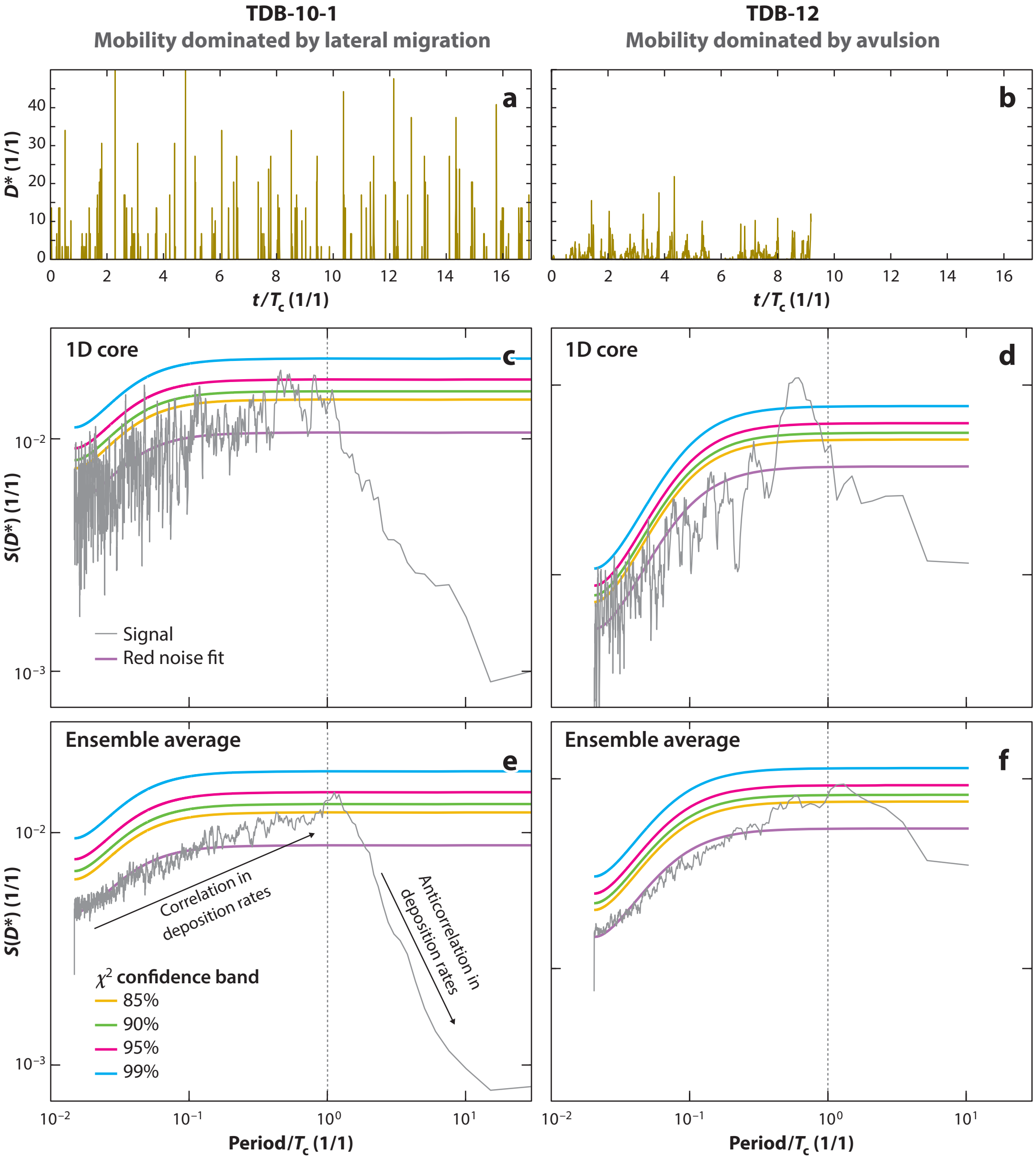

Figure 8

Time series analysis of preserved deposition rates from two experiments: TDB-10-1 (Wang et al. 2011) and TDB-12 (Straub et al. 2015). (*a*,*b*) The time series of preserved deposition rates from a single point location (identified in **Figure 3**) in each basin. Preserved deposition rates are measured from synthetic stratigraphy and normalized by the long-term rate of accommodation production in each experiment (5 mm/h for TDB-10-1 and 0.25 mm/h for TDB-12). Time is normalized by the compensation timescale T_c of each experiment (3.7 h for TDB-10-1 and 49 h for TDB-12). (*c*,*d*) Power spectra of these time series, as generated with a multitaper method with four 2π prolate tapers using scripts designed for and implemented in cyclostratigraphic analysis. Confidence bands are generated with 1,000 Monte Carlo realizations of best-fit red noise model. Similar power spectra were constructed for all 1D locations that define the strike transects in the two experiments ($n = 2{,}007$ for TDB-10-1 and $n = 324$ for TDB-12). (*e*,*f*) Ensemble-averaged spectra from both experiments.

time series for each experiment are normalized by the long-term base-level rise rate ($\bar{r}$):

$$D^* = \frac{D_m}{\bar{r}}, \tag{7}$$

and absolute time is normalized by the compensation timescale (**Figure 8**).

1D cores from both experiments exhibit a suite of peaks that breach the 85%, 90%, and 95% χ^2 confidence bands, with one peak exceeding the 99% confidence band (**Figure 8**). Ensemble-averaged spectra for both experiments are smoother than the 1D data and show a dominant frequency that breaks the 95% confidence threshold at a scale just larger than the compensation scale (T_c) in each system.

This suggests that purely autogenic dynamics may be capable of generating pseudosignals at relatively large scales, potentially complicating work to develop orbital chronologies in sedimentary deposits. For example, cyclostratigraphic analyses of sedimentation in the fluvial Willwood Formation have documented peak periodicities in floodplain and channel deposits at thickness scales of ∼7 m. Based on available age control, this extrapolates to timescales of ∼21 ky, which Aziz and colleagues and Abels and colleagues interpret as indicating precession controls on sedimentation (Aziz et al. 2008, Abels et al. 2013). We know from the Williams Fork and Ferris formations that field-scale fluvial systems like the Willwood may have compensation scales commensurate with a channel deposit thickness or greater (i.e., much larger than the maximum observed paleoflow depths; Wang et al. 2011, Chamberlin et al. 2016, Trampush et al. 2017). Median channel deposit thickness in the Willwood Formation is ∼6 m (Foreman 2014), suggesting that the same scale of packaging found in spectral analyses might be possible with autogenic dynamics alone.

In natural systems, differentiating an autogenic peak imposed by compensational packaging from true signals of Milankovitch cyclicity may be difficult, particularly if uncertainties associated with imprecise age models are fully acknowledged and propagated. But improved understanding of the character and structure of autogenic sedimentation could help build improved statistical tests, particularly in light of recent discussions that p-tests and confidence bands are only as good as the statistical model used to describe a system (Hilgen et al. 2015, Wasserstein & Lazar 2016). **Figure 8** highlights two attributes of autogenic sedimentation that may be helpful for constructing more appropriate null statistical models and confidence bands for discriminating orbital cycles from autogenic cyclicity: the shape of autogenic power spectra and the variability associated with local versus spatially averaged trends.

All spectra presented in **Figure 8** share a similar background shape with growth in power for periodicities up to T_c followed by decrease in power for higher periodicities. This indicates temporal correlation in deposition rates up to T_c followed by anticorrelation. The physical justification for this is intuitive: Over short timescales, a sediment-transport system is statistically likely to continue doing what it was doing previously, and at allogenic, mass-balance scales (i.e., T_c), sedimentation patterns eventually match accommodation everywhere in the basin. In order to accomplish this even basin filling, at timescales greater than T_c, sedimentation patterns may need to be anticorrelated such that if a large package of sediment is deposited, it is likely to be succeeded by a small package. This phenomenon has been observed in models of deltaic sedimentation (Wolinsky 2009). Depending on the model used to generate confidence bands, this switch from correlation to anticorrelation in power spectra could be confused with a statistically significant periodicity, particularly under common assumptions used in cyclostratigraphy models that use red noise models for short timescales and uncorrelated, white noise over longer timescales (Husson et al. 2014). Fitting spectra with this type of model could result in an underestimation of power associated with the spectral turnaround from correlated to anticorrelated sedimentation, making an apparent signal. χ^2 tests generated with this model would then underestimate possible random variability in spectrum power at periodicities equal to or greater than T_c.

The observation that many spectral peaks from 1D data exceed high confidence bands suggests that the variability in our Monte Carlo realizations of the assumed red noise model is likely too low relative to the actual autogenic variability in the experimental transport systems. Recently, researchers have shown that the deposition and sediment-transport rates in many landscapes have heavy-tailed distributions (e.g., Ganti et al. 2011) in which large-magnitude events are overrepresented relative to non-heavy-tailed distributions like normal or exponential distributions. The weight of this tail (i.e., the preponderance of large events) is linked to the style and strength of autogenic dynamics in sediment-transport systems, but at present we lack theory to fully predict what a characteristic distribution shape should be for a given landscape under different boundary conditions. Fortunately, this problem may be mitigated by measuring and averaging over multiple stratigraphic sections, as shown in the ensemble-averaged power spectra, which have a smoother distribution and only one pronounced peak.

6. COMPLETENESS OF THE STRATIGRAPHIC RECORD

Inversion of the stratigraphic record for paleo-environmental signals is complicated for all the reasons highlighted above but is impossible unless there is sediment to interpret. This brings us to the concept of stratigraphic completeness. Following the definition of Ager (1973), a stratigraphic record is complete if at least one grain of sediment is preserved that records a time interval of interest. Of course, the more sediment that records a time of interest, the easier it will be to invert for information about paleo-environmental conditions and landscape dynamics. Importantly, Ager (1973) noted that completeness of any stratigraphic record is intimately and proportionally tied to the timescale at which a record is discretized. The greater the discretization interval, the more complete a record is, a point made quantitatively by Sadler & Strauss (1990) and Straub & Esposito (2013). For example, the likelihood of generating a perfectly complete record of environmental changes associated with every hour of the Mississippi delta is less than the likelihood of generating a complete record of environmental changes every thousand years.

Incompleteness of a stratigraphic record is directly related to self-organization and autogenic temporal and spatial scales for channelized systems. Autogenic organization results in large patches of transport systems being inactive at any given time. Tipper (2015) highlighted the "importance of doing nothing" and suggested that it is the primary challenge to constructing complete stratigraphic records. Thus, autogenic processes that reduce channel mobility and keep a system stuck along one transport path for long periods of time will result in strong incompleteness in other inactive regions of a basin. Strong storage and release in channelized systems also result in cut and fill sequences. Removal of sediment during episodes of erosion erases information from the final record. These two processes—stasis on geomorphic surfaces and erosion—are influenced by autogenic dynamics and control the completeness of a stratigraphic record.

In addition to the timescale of discretization, Straub & Esposito (2013) hypothesized that the completeness of autogenically forced channelized deposits is linked to T_c and the channel timescale, T_{ch}. For a suite of channelized experiments, Straub &Esposito show that normalization of the discretization timescale by T_c successfully predicts the discretization level necessary to generate complete stratigraphic records and much of the shape of the completeness as a function of the discretization interval trend. Accounting for T_{ch} further improves the prediction of this trend. Additional analysis of the experiments highlights that stasis is the dominant cause for incompleteness over short discretization internals, whereas erosion controls this incompleteness for records discretized at coarser intervals (**Figure 9**). This handoff is controlled by the mobility of a transport system, and the timescale at which the fraction of the record associated with stasis goes

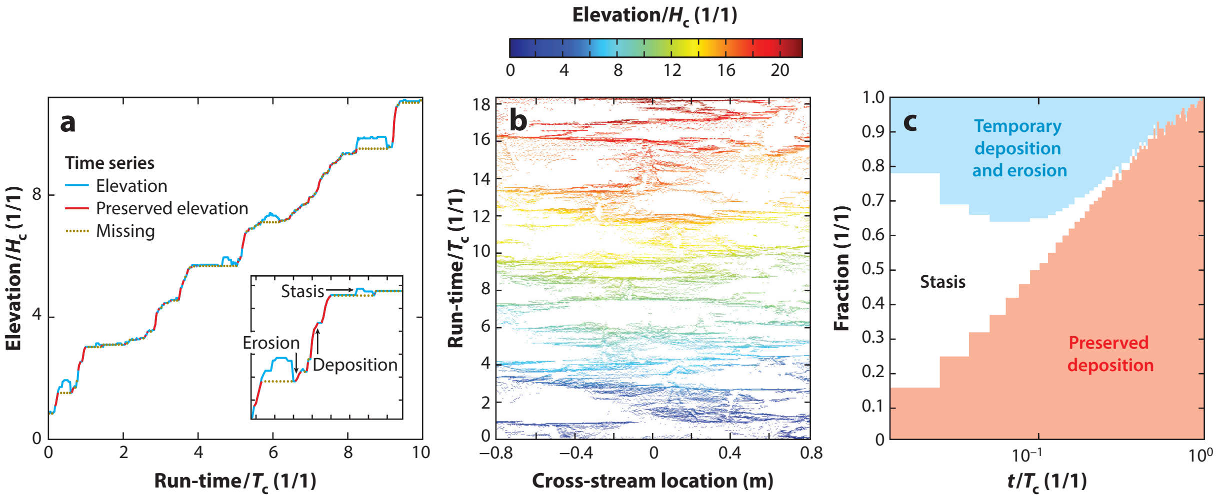

Figure 9

Data defining the evolution of topography and how this relates to stratigraphic completeness for the strike-oriented transect of TDB-12 identified in **Figure 3**. (*a*) An example of time series of topography measured at a single location on a strike transect and the resulting preserved record of elevation in the stratigraphy at this location. Periods of stasis, deposition, and erosion are all highlighted. (*b*) Time-space-elevation maps of preserved elevation for the experimental transect. These maps are equivalent to Wheeler diagrams and are discretized at the timescale at which the data were collected (1 h). Time is normalized by the compensation timescale T_c and elevation is normalized by the depth H_c of the largest channels in this autogenic experiment. White regions in maps represent time–space pairs where either stasis or erosion resulted in lack of preserved time. (*c*) Stratigraphic completeness versus timescale of discretization and associated causes for incompleteness for each discretization level. Incompleteness is associated with stasis if a cell has experienced no erosion or temporary deposition during a given time interval. If a cell has experienced some activity over a time window of interest but leaves no preserved sediment, it is labeled as temporary deposition and/or erosion.

to zero is set by T_{ch}. This further highlights the importance of T_c and T_{ch} not just for stratigraphic architecture but also for the completeness of a record.

Outside of channelized settings, the controls on stratigraphic completeness are less well understood and require far more study. For example, in quiescent lake bottoms or in unchannelized deep marine settings, sedimentation is controlled by a mixture of hemipelagic fallout and suspension fallout from gravity currents. The limited reworking of these deposits presents the potential for more complete records, but with the trade-off of generally lower accumulation rates and therefore less sediment to interpret. In other settings (e.g., shelf environments), sediment transport, reworking, and deposition are strongly related to the storm activity that expands the wave base. Resulting tempestites have the capacity to then record climate variability, assuming they can quickly get transferred below a reworking depth through further deposition and generation of accommodation.

7. FUTURE DIRECTIONS

Over the last 15 years, developments in understanding sediment-transport dynamics and connecting insights about morphodynamic processes to the stratigraphic record have significantly enhanced our ability to explicitly and quantitatively identify autogenic sedimentation patterns in ancient deposits. These important advances have brought us closer to addressing the following motivating questions: (*a*) How can the deposits of autogenic sedimentary processes be identified and differentiated from deposits that reflect changes in tectonic, climatic, or eustatic conditions?

(*b*) Can we leverage the realization that landscape and seascape dynamics are a prevalent part of the sedimentary archive to better understand the sensitivity and resilience of different environments? (*c*) How can autogenic dynamics be incorporated into models and predictions of buried sedimentary deposits?

Significant progress has been made toward answering the first question, and the concept of compensational deposition—the handoff between stochastic, autogenic sedimentation and deterministic, mass-balance-controlled basin filling—holds promise as an accessible and effective test in a variety of data sets and deposit types. However, major questions remain unanswered, such as "What controls autogenic sedimentation in different environments?" and "How do autogenic processes interact with a range of allogenic forcings?" Experimental work continues to yield insight into these issues, and expanded efforts to test hypotheses generated in experiments with observations from natural systems will help refine our mechanistic understanding of autogenic landscape dynamics. Additionally, forward modeling approaches provide an avenue for exploring a range of hypothetical responses and testing them against natural data sets. Presently, studies that leverage the concept of compensation have largely considered the spatiotemporal stacking of sedimentation events within a basin generically. Significant insight will come from detailed evaluations of the covariation of sedimentation patterns and other paleomorphodynamic observations from ancient deposits. Documenting changes in variables like paleoslope, sediment flux, paleohydrology, land cover, and environmental stability (i.e., cohesion) will provide more comprehensive understanding of the interrelationship between landscape processes and sedimentary products.

We have emphasized how physical aspects of the sedimentary archive reflect physical sediment-transport conditions on Earth's surface. Interdisciplinary efforts that blend geochemistry, paleobiology, and paleoclimate approaches will be essential for comprehensively studying the nature of autogenic dynamics in different environments. This is particularly critical as our community works to leverage the stratigraphic record to understand Earth's surface responses to past climate changes. Understanding how the physical stratigraphic archive is assembled can serve as a unifying framework for evaluating similarities and discrepancies among sedimentary, geochemical, and paleontological records, which are often collected or available over a variety of spatial and temporal scales.

Presently our understanding of autogenic dynamics in river and delta systems outpaces what we know of other environments, but the successes comparing theory, experiments, and natural fluvial-deltaic deposits can serve as a template for studying other terrestrial and marine environments. A broader inventory of sediment-transport dynamics in a variety of settings will be valuable not only for enhancing our scientific understanding of autogenic dynamics on Earth's surface, but also for modeling and predicting stratigraphic heterogeneity in different environments, as well as for understanding what types of records may best preserve information about paleoenvironmental variability like earthquake, flood, storm, or tsunami occurrences. Additional quantitative descriptions will be useful for modeling, but solid theory connecting physical autogenic process to sedimentary records in different settings is ideal.

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