ANNUAL REVIEWS

Annual Review of Earth and Planetary Sciences

Time Not Our Time: Physical Controls on the Preservation and Measurement of Geologic Time

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Annu. Rev. Earth Planet. Sci. 2018. 46:409–38

First published as a Review in Advance on March 16, 2018

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

https://doi.org/10.1146/annurev-earth-082517-010129

Keywords

stratigraphy, time, physical, process, completeness

Abstract

Sadler's (1981) analysis of how measured sedimentation rate decreases with timescale of measurement quantified the vanishingly small fractional time preservation—completeness—of the stratigraphic record. Generalized numerical models have shown that the Sadler effect can be recovered, through the action of erosional clipping and time removal (the "stratigraphic filter"), from even fairly simple topographic sequences. However, several lines of evidence suggest that most of the missing time has not been eroded out but rather represents periods of inactivity or stasis. Low temporal completeness could also imply that the stratigraphic record is dominated by rare, extreme events, but paleotransport estimates suggest that this is not generally the case: The stratigraphic record is strangely ordinary. It appears that the organization of the topography into a hierarchy of forms also organizes the deposition into concentrated events that tend to preserve relatively ordinary

conditions, albeit for very short intervals. Our understanding of time preservation would benefit from insight about how inactivity is recorded in strata; better ways to constrain localized, short-term rates of deposition; and a new focus on integrated time–space dynamics of deposition and preservation.

1. INTRODUCTION

The remarkable capacity of Earth to record time in strata is the basis for essentially all our knowledge of past surface environments and life. Yet the fraction of time actually represented in the strata is so vanishingly small that recorded time is best thought of as a kind of dust (Plotnick 1986, Sadler 1999). Our purpose here is to review and synthesize what is known about the physical processes that control how, and how much, time is recorded. We review quantitative models for time preservation and then consider case examples of time preservations in the field and in experiments, estimating key parameters and recording metrics as quantitatively as possible. We focus mainly on rivers and deltas, though a brief comparison with their submarine counterparts in Section 5 helps illuminate controls on time preservation. We believe that many of the basic principles apply across environments.

A field example may help frame the discussion. **Figure 1** shows a section of Torridonian sandstones of the Applecross Formation that exemplifies two major aspects of physical time preservation: First, the individual beds making up the section, typified by those shown in the foreground, were deposited on timescales of minutes to a few hours. There are at most a few thousand such beds in the section, so the sum of active depositional time represented by all of them is orders of magnitude less than the bulk stratigraphic time spanned by the section, measured in tens of millions of years. Second, the transport conditions the beds represent are notable for both their consistency and their banality—and this is generally true for the whole Applecross, spanning as much as 11% of Earth history. The quantity of missing time is all the more dramatic for the absence of any obvious signature of the cause of its absence.

These two issues are a central focus of recent work and of this review. Our point of departure is the landmark Geological Society of London Special Volume *Strata and Time* (Smith et al. 2015). We seek to build on, synthesize, and complement the ideas presented there, and we recommend it heartily. We make particularly extensive use of the articles by Miall (2015), Sadler & Jerolmack (2015), and Tipper (2015).

Modern thinking about the physical nature of time recording begins with Barrell (1917), who established the conceptual framework for connecting erosion and sedimentation with the fractional preservation of time (**Figure 2**). His focus on rhythms, which we generalize to variability with no implication of periodic repetition, applies across space and timescales. The fractional preservation of time leads naturally to the idea of completeness, which we define more precisely in Section 2 but is essentially the fraction of all elapsed time recorded in a specified set of strata.

Here we make a somewhat arbitrary but useful distinction: At large (basin) scales, the construction of strata and the associated preservation of time are largely deterministic, controlled by allogenic factors like subsidence and sea level. At smaller (outcrop) scales, stratal construction and time recording are governed by autogenic dynamics associated with self-organized structures like channels, bars, and bedforms (Paola 2016), along with high-frequency allogenic forcing. These processes typically appear more stochastic.

Figure 1

Sandstones of the Applecross Formation, Torridonian Supergroup, Liatach, Scotland. The scale on the notebook is 0.15 m long. The whole visible section is about 300 m thick, representing about 6% of the total thickness of the Applecross and thus, interpolating from the time spanned by the whole formation, some 25 Myr of total stratigraphic time. The section comprises bedding similar to that visible in the foreground: a monotony of decimeter-scale cross-beds. Moreover, this section is generally representative of the whole ~5 km thickness of the Applecross, which is thought to span up to 0.5 Gyr, i.e., ~11% of Earth's history. Across this large window of time, all that remains are commonplace events. Photo courtesy of Alex Whittaker, Imperial College London.

1.1. Time at Stratigraphic Scales

In the study of large scales, the main line of research over the past few decades has been sequence stratigraphy (Catuneanu 2006, Catuneanu et al. 2009, Emery & Myers 2009, Neal & Abreu 2009, Van Wagoner et al. 1990). At the scales where sequence stratigraphy is usually applied, the connection between physical strata and time is generally made via Wheeler diagrams (Wheeler 1958, 1959, 1964), space–time sections in which the vertical axis indicates depositional time span (**Figure 3**). These are straightforward, largely deterministic maps of preserved time in which time gaps are generally associated with externally forced erosional events like relative sea-level falls. The question of completeness is less commonly asked at stratigraphic scales, but the answer to this question can be easily estimated by comparing lithostratigraphic sections with Wheeler's time representation (**Figure 3**).

An important question regarding time preservation that arises mainly at larger scales is the chronostratigraphic significance of stratal surfaces that can be imaged seismically. Much has been written about the chronostratigraphy of key sequence stratigraphic surfaces (Embry 2010, Miall

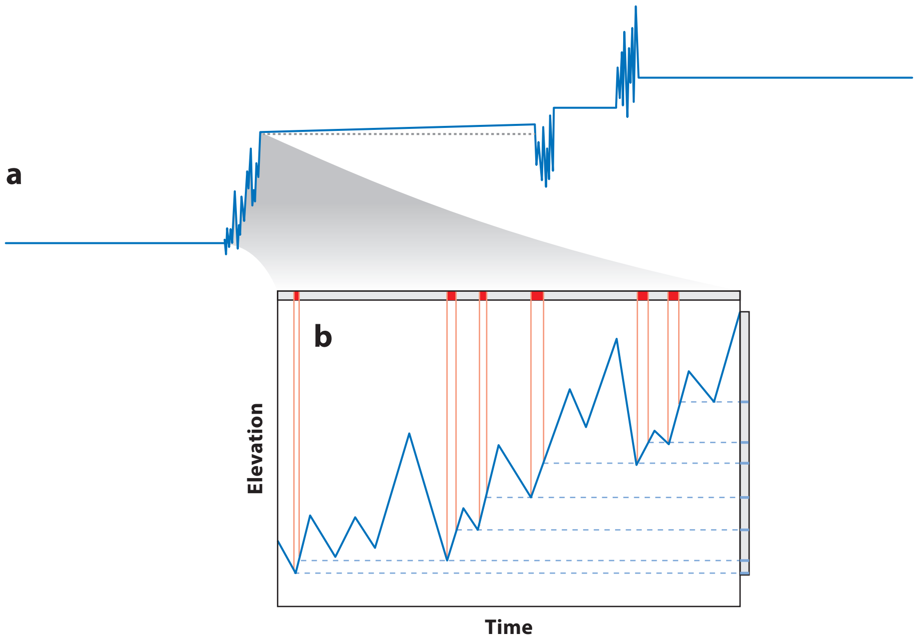

Figure 2

(*a*) A temporal record of bed elevation. (*b*) An enlarged detail illustrates Barrell's (1917) analysis of how bed boundaries are defined by the vertical distance between successive erosion events (*blue dashed lines*), which also delimit intervals of preserved time (*red intervals*). The main temporal record indicates bursts of activity separated by periods of stasis, as proposed by Tipper (2015), along with the possibility of extremely slow sedimentation during the stasis periods.

1991). For our purposes, the most important point is that any true chronostratigraphic surface must be a preserved geomorphic surface, i.e., a surface that, however briefly, constituted the synoptic topography of the sedimentary system. Imaging of apparently intact geomorphic features, their general form readily apparent in seismic time slices, has given rise to the subdiscipline of seismic geomorphology (Posamentier 2004, Prather et al. 2012). What matters here is that the intact preservation of large-scale morphologic features provides important information as to the nature of the preservation process and, thus, the preservation of time. We return to this point in Section 5.2.

1.2. Time at Smaller Scales and Across Scales

At smaller scales, i.e., those of outcrops and cores, physical strata are dominated by autogenic variability associated with features like bedforms, channels, and bars (Kim et al. 2014, Paola 2016, Postma 2014). It is at these scales that most of the work on time preservation has been done over the past few decades, building on the enormously influential approach to analyzing stratal completeness developed by Peter M. Sadler (Anders et al. 1987; Sadler 1981, 1999; Sadler & Strauss 1990; Strauss & Sadler 1989). We use this work extensively throughout this review. Sadler's core idea was to measure the dependence of sedimentation rate on the timescale over which it is measured, from contemporary (years or less) to planetary. The observed sedimentation rate typically shows a power-law decrease with timescale (**Figure 4**). The exponent $-\gamma$ of the observed power law measures the extent to which erosional and/or nondepositional events are increasingly incorporated in stratal columns as one integrates over longer time spans: $\gamma = 0$

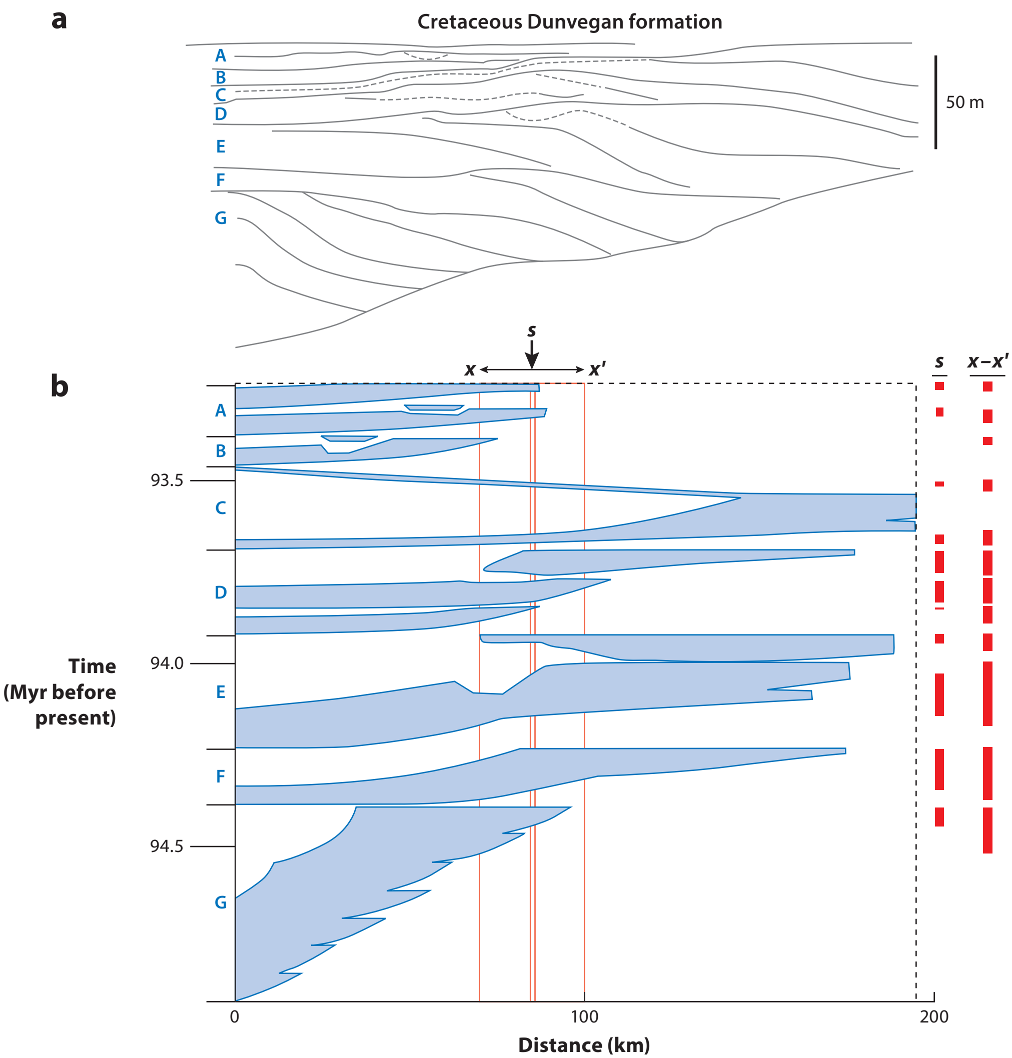

Figure 3

(*a*) Allostratigraphic units for the Cretaceous Dunvegan formation, labeled A–G, and (*b*) the equivalent distance–time (Wheeler) diagram. The overall time preservation in this section is 31.4%. The red bars on the right show the effect of expanding the spatial window for time preservation: Compare the bar for a single section (*s*) with that for the expanded section (*x*–*x*′). Figure adapted from Bhattacharya & Posamentier (1994) with permission from the Canadian Society of Petroleum Geologists, whose permission is required for further use.

would indicate a constant sedimentation rate across timescales and thus steady sedimentation and perfect completeness; larger values of γ indicate increasing incorporation of erosion and/or nondeposition into the record and thus decreasing completeness (Sadler & Strauss 1990). This idea, as well as the definition of completeness that follows from it, forms the basis of current thinking about time preservation.

Analyses of preservation at sub-basinal scales can be broadly divided into two classes, representing two complementary views of surface processes. In one class, exemplified by Miall (2015) and

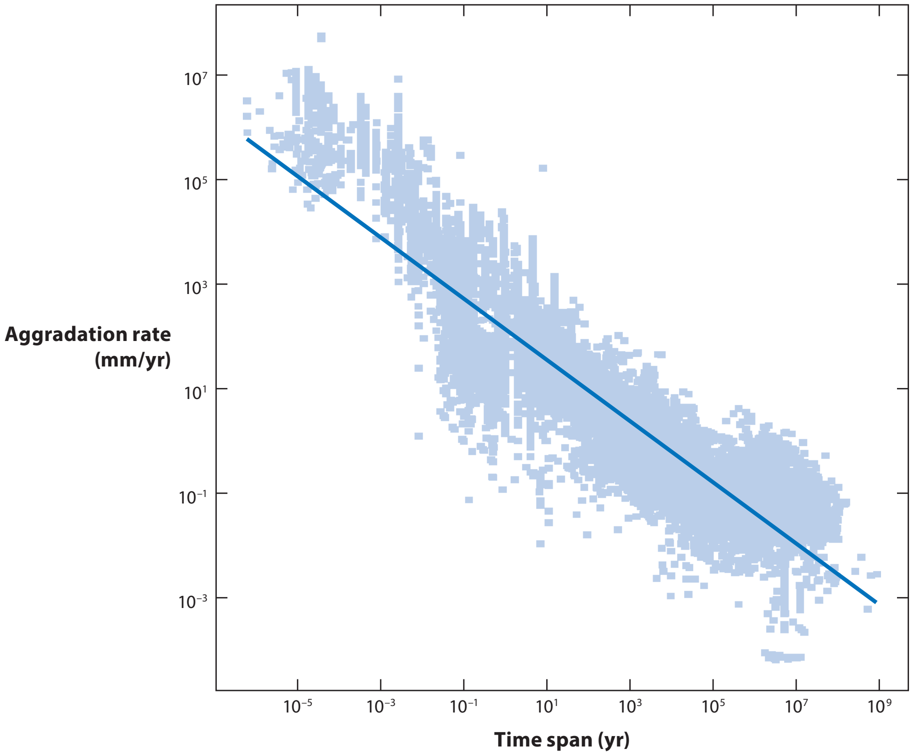

Figure 4

Example Sadler plot showing vertical sedimentation (aggradation) rate versus time span, using data for alluvial deposits from Sadler & Jerolmack (2015). The power-law fit shown by the heavy blue line has an exponent $-\gamma$ of -0.585.

in earlier work (Miall 1985, 1993, 1994; Miall & Tyler 1991), the broad spectrum of morphologic variation is explicitly divided into the named categories familiar to sedimentologists: bedforms like ripples and dunes, bars, channels, channel networks, etc. Although, in total, these features span many orders of magnitude in space and time, and although their scales overlap, this view explicitly recognizes the distinctive dynamics of each category. The other class, exemplified by the models discussed in Section 3, uses generalized equations for morphologic evolution that do not distinguish morphologic subclasses but rather try to capture essential features of self-organized morphology generally. This approach offers simplicity and the chance to study general phenomena in their most uncluttered form, and can reveal underlying similarities among apparently disparate processes. Before reviewing such models, we first review the standard framework for analyzing time recording.

2. WHAT IS RECORDED TIME?

A given instant in time is generally considered preserved if a deposit spanning that instant is preserved, i.e., there is deposition during that instant, and the deposit is not subsequently eroded. Building on the work of Strauss & Sadler (1989), we formalize this definition of preservation by considering a time interval $\delta t = t_1 - t_0$ to be preserved at a later reference time t_r (by default, the present) if, at t_r, a layer of thickness $h > 0$ representing any time from the interval δt remains in the stratigraphic column at the location of interest. (We defer for now an important question: Should the definition be $h > 0$ or $h \geq 0$?) We define an indicator function I as $I(\delta t) = 1$ if δt is preserved and as $I(\delta t) = 0$ if not.

This definition is unambiguous in the context of a specific time interval δt. Questions of completeness and fragmentary preservation of time come into play upon consideration of more than one interval scale. Consider a longer interval $\Delta t = N\delta t$. Completeness f_c is the fraction of preserved time, i.e.,

$$f_{c,\delta t} = \left[\sum_i \delta t_i I(\delta t_i)\right] / \Delta t, \qquad 1.$$

where the subscript δt on f indicates that the completeness of any interval is a function of how finely we subdivide it. The important point is that f_c is a function of two time-interval parameters, Δt and δt.

The above definitions of preservation and completeness generalize to spatial-temporal completeness (Mahon et al. 2015, Runkel et al. 2007) via a simple modification:

$$f_{c,\delta t,A} = \left[\sum_i \delta t_i I(A, \delta t_i)\right] / \Delta t, \qquad 2.$$

where everything remains the same as in Equation 1 except that the indicator function $I(A, \delta t)$ is equal to 1 if time is preserved (as defined above) in any sediment column within the area A. Evidently, as long as sediment supply is maintained, $f_{c,\delta t,A} \rightarrow 1$ as $A \rightarrow$ basin area A_b.

We return now to the question deferred above, namely, what to do in the case where there is neither deposition nor erosion, represented in stratigraphy as surfaces of nondeposition. The importance of this state has been argued by Tipper (2015), who refers to it as "stasis." Tipper presents a compelling argument, adding to ideas proposed by Dott (1983), that surfaces of nondeposition, as opposed to erosion, are the predominant cause of missing time in the stratigraphic record. Should we consider the time spanned by such surfaces as preserved or not? Clearly, if a surface is not eroded, then it has a chance of recording evidence of events occurring during the interval it spans; equally clearly, the likelihood and/or quality of preservation is low without burial, and the temporal sequence of any recorded events is lost. Here we adopt the conventional view that stasis time is not preserved, but we stress that this is a point that deserves further investigation—stasis is a singularity in the realm of preservation and completeness, and a more sophisticated analysis could dramatically change both computation and conception of time preservation. **Figure 2** illustrates a composite view of time preservation, including bursts of activity in which the temporal record is alternately created and destroyed by deposition and erosion, interspersed with highly variable periods of stasis and/or very slow deposition. We return to this point after reviewing models of time preservation.

3. GENERALIZED MATHEMATICAL MODELS OF TIME RECORDING

Recent years have seen major advances in one-dimensional mathematical models that focus on time recording and completeness. These are typically not intended as detailed models of specific physical processes; rather, they aim to capture general quantitative properties of time and/or surface evolution.

3.1. The Cantor Dust

The Cantor dust is a one-dimensional fractal created by successive deletion (**Figure 5**). Plotnick (1986) suggested that the way superimposed processes of erosion clip time successively from the stratigraphic record leads to vertical temporal records that resemble such a dust. The process can be iterated indefinitely, in which case the fraction remaining in the bar tends to zero, i.e., referring

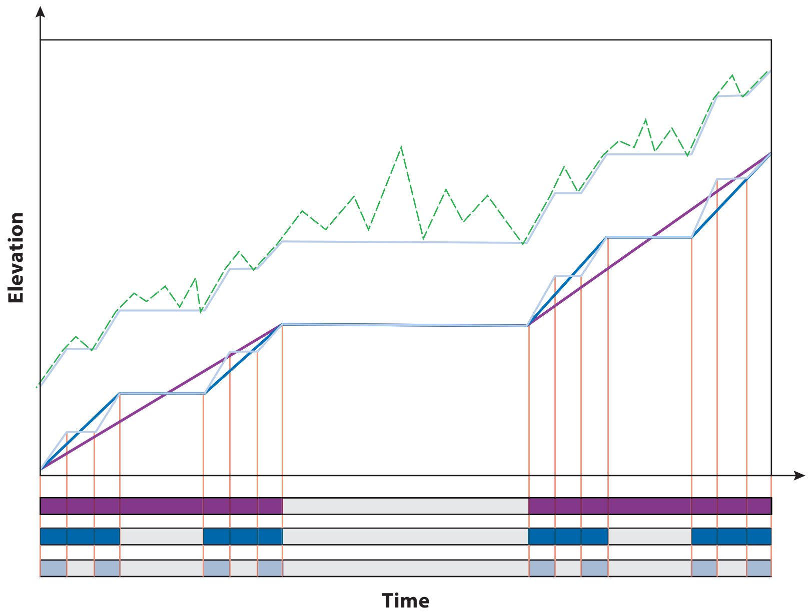

Figure 5

A sequence of bed elevations illustrating the Cantor dust model of preserved time (Plotnick 1986). The three bars below the lower sequence show three stages of the Cantor iteration by which the fractal dust is produced; each stage involves removal of the middle third of each bar from the stage before. Above this is a plot of bed elevation at three levels of temporal resolution δt in which the depositional events match the corresponding preserved time intervals in the bars below. Stasis times (horizontal sections) are considered not to be preserved. The upper elevation sequence is a copy of the light blue sequence below with a sequence (*green dashed line*) superimposed that has no stasis time but in which the sequence of depositional and erosional events produces the same hiatus and time-preservation distribution as in the original bed-elevation sequence. Figure adapted from Miall (2015) with permission.

to Equation 1, $f_{c,\delta t} \to 0$ as $\delta t/\Delta t \to 0$. The integral of the Cantor process is called the Devil's staircase, also shown in **Figure 5**. In terms of sedimentation, the risers in the staircase represent net depositional events, and the treads either intervals of inactivity [stasis in the sense described by Tipper (2015)] or erosional hiatuses, as we discuss in the next section.

3.2. Conventional and Fractional Brownian Motions

The modern probabilistic treatment of erosional and depositional events and how these events are recorded in strata dates back to Kolmogorov (1951), who developed the first quantitative relationship between preserved bed thicknesses and the governing distributions of erosional and depositional events. More recently, a new generation of probabilistic models has been developed, aimed at understanding stratigraphic incompleteness as quantified by the Sadler effect, discussed above. The two key parameters that quantify the Sadler effect are the scaling exponent γ and the timescale at which this power-law decay ceases, called the saturation timescale.

Schumer & Jerolmack (2009) showed that the Sadler effect can arise from power-law-distributed hiatus lengths, where the tail index of the hiatus lengths is greater than 1 (i.e., they have a divergent mean). In this framework, the saturation timescale corresponds to the truncation timescale of hiatus lengths (Ganti et al. 2011, Schumer & Jerolmack 2009), i.e., the power-law

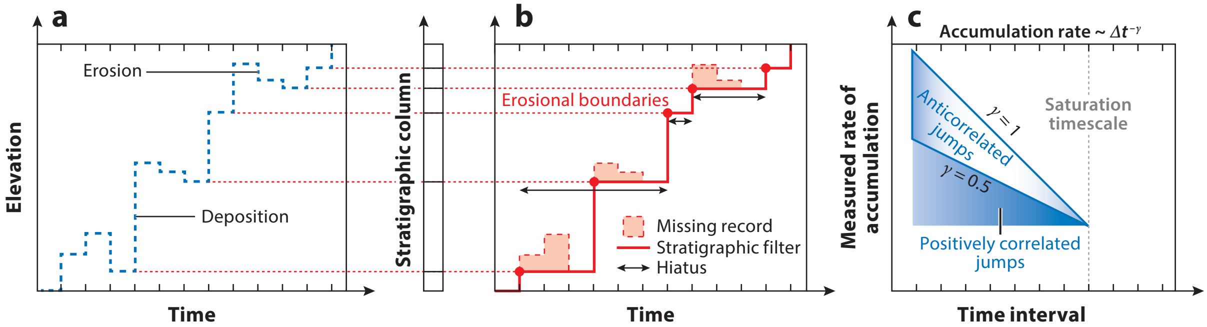

Figure 6

Schematic of how random-walk models for surface evolution generate one-dimensional stratigraphy. (*a*) Time series of surface evolution represented as a discrete random walk where depositional and erosional events are positive and negative jumps over a constant time interval. The long-time limit of such discrete random walks is governed by fractional Brownian motion with a given Hurst exponent (H), as shown in **Figure 7**. (*b*) Conversion of surface evolution into the record of strata and time. The column between panels *a* and *b* represents a schematic stratigraphic column with the erosional boundaries indicated as horizontal dashed red lines. The solid red line in panel *b* denotes the stratigraphic filter, which Schumer et al. (2011) modeled as a reversed ascending ladder process. Note how hiatuses, indicated as double-headed arrows after stratigraphic filtering, are produced by erosion of previous deposits rather than by stasis. (*c*) Schematic of a log-log plot of measured accumulation rate versus the averaging time interval (Sadler plot). The Sadler effect is quantified by the scaling exponent (γ) of the negative power-law relationship shown here and the saturation timescale that corresponds to the timescale at which this power-law relationship ceases. Panels *a* and *b* adapted from Schumer et al. (2011) with permission.

decay ceases at the largest hiatus length that a given sedimentary system can produce. While power-law-distributed hiatus lengths can be a direct result of power-law-distributed periods of stasis (Ganti et al. 2011), Schumer et al. (2011) showed that the Sadler effect is equally likely to result simply from randomness in surface fluctuations, with no need for stasis intervals.

A common aspect of both conventional and fractional Brownian motion models is that surface evolution at a given location is modeled as a random walk where depositional and erosional events with a given time step are treated as positive and negative jumps, respectively (**Figure 6**). The long-time limit of these random walks depends on the distribution of the jumps and, importantly, on their correlation structure. The tails of the distribution play a special role: Exponential-type tails decay quickly, and extreme jumps are extremely unlikely, whereas power-law tails decay slowly so that extreme jumps become merely rare as opposed to almost impossible. If the jump distribution has exponentially decaying tails, then the summed jumps (the model for surface elevation in time at a given location) acts as a classical Brownian motion (**Figure 7*b***). If the jump distribution has power-law-decaying tails, then the sum is governed by Levy motion (Samorodnitsky & Taqqu 1994), and if the jumps are correlated, then the sum is governed by fractional Brownian (or fractional Levy) motion (**Figure 7*a*,*c***) (Bouchaud & Georges 1990). Noisy diffusion models for Earth surface evolution (Jerolmack & Sadler 2007, Pelletier 2007, Pelletier & Turcotte 1997, Schumer et al. 2017) can be viewed as a particular case of random-walk models where correlated (or anticorrelated) jumps result from topographically controlled erosion or deposition. The key insight of Schumer et al. (2011) was to realize that in these random-walk models for surface evolution, one can treat the stratigraphic filter, i.e., the conversion of Earth surface evolution into strata by erosional clipping (**Figures 2** and **6*b***), as a stochastic process called the reversed ascending ladder (Stam 1977) (**Figure 6**).

Schumer et al. (2011) found that when the Earth surface evolution follows a Brownian or Levy motion with a small drift, the resulting stratigraphic hiatus lengths have a power-law distribution

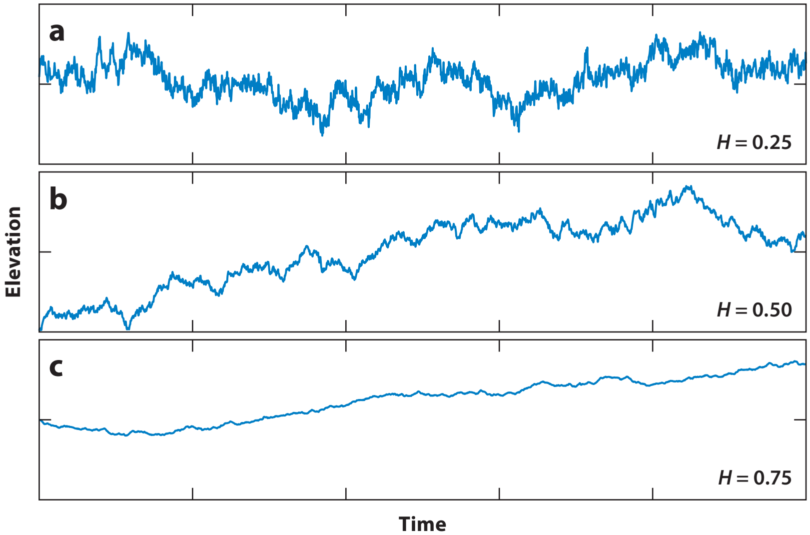

Figure 7

Three different realizations of the fractional Brownian motion model with varying Hurst exponents: (*a*) $H = 0.25$, (*b*) $H = 0.50$, and (*c*) $H = 0.75$. The classical Brownian motion model in panel *b* has uncorrelated jumps, while the fractional Brownian motion models in panels *a* and *c* have jumps that are negatively and positively correlated in time, respectively. All models shown have zero drift.

with a tail index of 0.5, which results in the Sadler scaling exponent $\gamma = 0.5$. When the surface evolution is governed by a Brownian motion with significant drift (i.e., high subsidence), the resulting scaling exponent on the Sadler plot is still 0.5; however, this scaling exists only until the overall average accumulation exceeds the variability in elevation fluctuations. This indicates that the saturation timescale is controlled by the ratio of topographic roughness to long-term sedimentation rate. In Section 6 we define this as the stratigraphic integral scale and summarize experimental observations that support this finding.

The assumption of uncorrelated jumps in the random-walk model can be relaxed by describing the surface evolution as a fractional Brownian motion with a Hurst exponent, H (**Figure 7**). $H = 0.5$ corresponds to the case of uncorrelated jumps, while $0.5 < H < 1$ and $0 < H < 0.5$ correspond to positively and negatively correlated jumps, respectively. Schumer et al. (2011) showed that when the surface evolution follows a fractional Brownian motion, the resulting scaling exponent on the Sadler plot is $\gamma = 1 - H$, i.e., the degree of incompleteness of the stratigraphic record is a function of the nature of elevation fluctuations that produce a given stratigraphic section. Available depositional data suggest that the sedimentary system evolution may be well characterized by Brownian motion or fractional Brownian motion with negative correlation up to saturation timescales of 10^6 yr (Schumer et al. 2011). Negative correlation in elevation jumps is consistent with the idea of compensational stacking of sedimentary basins, where the tendency of sedimentary basins is to preferentially fill topographic lows (Straub et al. 2009).

Two key features of these general mathematical models are important for our review. The first is that their generality, in which a single mathematical description represents dynamics across the full range of scales, precludes identification of specific elements of the morphodynamic hierarchy (e.g., as discussed in Miall 2015) and their specific idiosyncrasies. These hierarchical elements, though, represent the worldview by which most field workers measure and interpret what they see. The two views are not at all incompatible. The scale ranges of elements in the hierarchy, summarized by Miall (2015), clearly show a good deal of overlap between classes. Viewed over a whole basin, the hierarchy of forms and associated processes described by Miall (2015) occupies the full scale range available. Although, locally, morphologies like bars and bedforms clearly have preferred scales linked to channel width and depth (e.g., Hundey & Ashmore 2009), a whole river network provides a sufficiently wide range of channel sizes and environmental patchiness that, overall, the topography has variance at all scales up to the size of the system, often without strong peaks at any particular scale. Absence of a preferred scale is a fundamental characteristic of the mathematical models summarized above and is part of their generality and power. Nonetheless, when it comes to interpretation of specific stratal sections, there are important distinctions among elements of the hierarchy. Specifically, the high-frequency end of the topographic spectrum includes forms like ripples and dunes that act in effect as paleocurrent meters, recording information about flow conditions. The characteristics of their preservation are central to the paradox that we refer to as *strange ordinariness* (Section 4.2).

The second key feature of the models we discuss above is that they do not explicitly or implicitly include stasis periods—they are busy in the sense discussed by Tipper (2015). In fact, as Schumer et al. (2011) show, random-walk models render stasis unnecessary, since the stratigraphic filter effectively converts sequences of random elevation fluctuations into power-law-distributed hiatuses. Periods of inactivity (stasis) are clearly not necessary to explain the Sadler effect and the general distribution of missing time in stratigraphy. However, that does not mean that these periods are not present, and in terms of the nature of time preservation, we join Tipper (2015) in arguing that such periods are of crucial importance. A hiatus produced by erosional clipping is one in which topography, as well as the time it represents, is definitively gone from the record. However, a period of stasis is usefully ambiguous in that it could record at least traces of environmental events and, in particular, of biota (Genise 2017). Stratigraphic evidence for stasis is strong. In terrestrial settings, paleosols (Driese & Nordt 2015, Kraus 1999, Retallack 2008) are primary indicators of stasis and slow sedimentation, and evidence for the extreme age of some modern geomorphic surfaces (Matmon et al. 2009, Widdowson 1997) supports the possibility of stasis over long time and space scales. Ganti et al. (2011) found that even in a tank experiment, in which the system is net depositional, continuously supplied, and artificially maintained in a highly active state, stasis is still the most common condition of the sedimentary surface. We know very little about time represented by ordinary bedding planes with no obvious signs of stasis (Dott 1983) or about how time is preserved in intervals of very slow but steady sedimentation—cases that, in the spirit of Tipper (2015), we might think of as doing almost nothing—that should have high temporal completeness. We do know, however, that erosion tends to create relief, at all scales. So, while time gaps in the cut-and-fill of bedforms and channel fills could be due to either erosion or stasis, whatever time gaps are hidden in conformable strata, at any scale, must mainly represent stasis.

4. PHYSICAL CONTROLS ON TIME RECORDING

We turn now to physical process controls on time preservation and completeness. For a single basin, as long as net sediment supply to the basin continues, deposition must be occurring somewhere, and so at the basin scale, time must be recorded somewhere as well (Sadler & Jerolmack 2015). That the completeness of time preservation in any one section is usually small indicates that the creation and removal of the record must be extremely variable across the basin.

The themes that structure the remainder of this review are:

1. Physical controls on time preservation include both processes internal to the basin, which influence sediment distribution and redistribution, and processes external to the basin, such as changes in base level and the supply of water and sediment.

2. At small scales, time preservation is controlled by the kinematics and characteristic geometries of the morphologies that mediate transport and deposition in the basin.
3. Completeness must be thought of in spatial as well as temporal terms, and these terms are linked: Temporal completeness increases as spatial scale increases.
4. Completeness has a qualitative dimension: not just how much time, but what kind of time. Specifically, to what extent are the tiny preserved slivers of recorded time typical of all the time that they represent? We term this "process completeness": the extent to which Miall's (2015) "frozen accidents" are typical of the broad spectrum of events from which they were somehow selected.

We turn first to external controls on sediment supply, since one might expect the bulk sediment supply, relative to the basin size, to set an important overall constraint on time preservation in the basin. It appears, however, that this is not the case and that temporal variation in external supply is not a major factor in time recording. We thus focus mainly on the second, third, and fourth points in the list above.

4.1. External Controls on Sediment Supply

Variability in supply arises from the following main sources: (*a*) variability in tectonic uplift rate, the ultimate driver of supply; (*b*) variability in sediment production due, for example, to variability in lithologies, in precipitation (amount, seasonality, ice versus water), and/or in biotic processes that mediate weathering; and (*c*) temporary storage and release of sediment within the erosional domain.

Variability in erosion rate has not received as much attention as variability in deposition rate, presumably because erosion rates are harder to measure. Some researchers (Ferrier et al. 2005, Kirchner et al. 2001) report an inverse Sadler effect: The apparent erosion rate increases with timescale, a finding that can be attributed to the increasing likelihood of including rare large transport events with increasing timescale. In principle, the same effect could apply to sedimentation rate if longer scales preferentially incorporated rare, large depositional events rather than hiatuses, but the observations discussed in Section 1.2 clearly do not support this. Similarly, the denudation rate data compiled by Sadler & Jerolmack (2015) indicate an overall trend of decreasing denudation rates with timescale. This seems to saturate on long timescales (10^6 yr and up), constrained by the rate of tectonic mass input into the erosional system (Willenbring & Jerolmack 2016).

Much of the work on sediment delivery from catchments focuses on short (submillennial) timescales (De Vente et al. 2007, Lu et al. 2005, Parsons et al. 2006) and on effects, such as spatial variability (Pelletier 2012, Stock et al. 2009) and human influences (Hooke 1994, Wilkinson 2005, Wilkinson & McElroy 2007), that are less relevant for sediment delivery to basins as it affects time preservation. Storage within erosional systems can reduce sediment output, but this effect appears to be limited to timescales shorter than 10^3 yr (Lu et al. 2005); if anything, the existence of an adjacent depositional sink (the basin) should reduce the efficacy of such storage. The fact that erosional (tributary) river systems are integrative (i.e., they sum their inputs) also acts to dampen the influence of spatial fluctuations within the supply system. The above evidence seems broadly consistent with the remarkable finding of Sadler & Jerolmack (2015) of a consistent mean unit sediment flux (volume of sediment per unit transverse distance and time) of roughly 1 m^2/yr across orders of magnitude in timescale and a broad range of clastic environments. Overall, we suggest that, while supply to basins certainly does vary, it is unlikely to be a first-order limitation for time preservation. Rather, time preservation in clastic strata is mainly influenced by topographic dynamics within the depositional system, to which we turn next.

4.2. Depositional Controls on Time Preservation

We noted above that, averaged over the whole area of the basin, completeness must tend to unity, i.e., $f_{c,\delta t,A_b} \rightarrow 1$, as long as net supply is maintained. There are two general factors causing the completeness to be typically much less than 1 for individual stratigraphic sections. The first is the self-organization (autogenics) of physical sediment transport systems into spatial forms, such as channels and bars, that concentrate sediment flow and localize deposition (Hajek & Straub 2017, Trampush & Hajek 2017). Basin filling involves movement of these forms such that over time each point in the basin is visited by sufficient deposition to compensate for subsidence and maintain the overall synoptic surface relief within whatever limits the transport system will tolerate. The second factor is variability in external forcing (allogenics), including relative sea-level changes; precipitation, wind, and other meteorological factors; and tectonic processes like differential uplift and subsidence and earthquakes. Although our discussion broadly includes the effects of both factors, the autogenic component seems to predominate in time preservation and is our main focus.

The primary evidence for the extreme incompleteness of most physical stratigraphy is the Sadler effect, defined above. As a simple example (see also **Figure 1**), consider a section 20 m thick composed of cross-bedded fluvial sandstone. If the long-term rate of deposition is 1 km/Myr, then on the Myr timescale, the section represents a total of 20,000 years, which is Δt in Equation 1. If the average cross-set thickness is 0.2 m, then there are 100 sets in the section. Of course, we cannot measure the deposition time for each set directly, but by assuming they were created by dunes and using known dune migration rates, we can constrain the time required for the passage of each dune. For the boundary shear stresses associated with fluvial sand dunes (Wilkerson & Parker 2011), sediment fluxes are in the range 10^{-5}–10^{-2} m^2/s. If we assume that the dunes were no more than twice the height of the preserved sets (Leclair 2002, Paola & Borgman 1991), then based on the low end of the transport rates, the passage time per dune face is under 4 h, which becomes δt in Equation 1. The total time represented by 100 sets is then under 400 h, and the temporal completeness is, at most, 2×10^{-6}. And, in keeping with the dust idea discussed above, the completeness would become still smaller if we looked into the passage of the dunes in more detail, i.e., if we reduced δt to account for effects like turbulence and grain avalanching. This would add a successive scale of deletion to the Cantor set suggested in **Figure 5**.

If only a tiny fraction of all the countless episodes of erosion and deposition that took place in a given location is preserved, then one would think that the events that are preserved must be extraordinary in some sense. The obvious candidates for preservation are rare, extreme events like enormous floods, and the idea that these events are disproportionately represented is the centerpiece of the neocatastrophist view of the stratigraphic record.

4.2.1. Neocatastrophism. The rejection of biblical catastrophism and its relation to uniformitarianism have been extensively discussed elsewhere (Berggren & Van Couvering 2014, Gould 1965). The catastrophism that we are concerned with here is simply the idea that the events that are recorded stratigraphically represent neither the usual transport conditions—for example, the average flow of a river—nor even the usual unusual conditions, e.g., annual floods, with above-average discharge but well within the compass of a human lifetime and readily accessible for study. Rather, the neocatastrophist argument is that stratigraphic preservation favors mega-events—obviously not supernatural, but rare and difficult to study. To quantify this in a simple way, for a record with temporal completeness of the order of ε, one might expect (using a year as a reference period) that preserved events would have recurrence intervals of the order of $1/\varepsilon$ yr. Given completeness values such as the hypothetical one discussed above, these are rare events indeed.

Scientific neocatastrophism received its greatest impetus from the discovery of the Cretaceous–Tertiary (KT) meteorite impact, but more relevant for our purposes are events like glacial megafloods (Bretz 1969, Gupta et al. 2007, Montgomery et al. 2004) or megafloods produced by landsliding and subsequent failure (Baker 2009, O'Connor & Costa 2004).

Far more, and more varied, examples of catastrophic events are presented in the enlightening and entertaining books by Ager (1993a,b). The impressive catalog of extreme events that have occurred over time and the extreme incompleteness of the stratal record seem to make a compelling case for a record dominated by such events. In terms of the idea of process completeness introduced above, one would conclude that the stratigraphic record is highly process incomplete: Out of the range of transport processes that have ever occurred, it would give us glimpses mostly of the extreme tails. In this view, the "frozen accidents" of Miall (2015) would be not just accidents but anomalies.

Over the past few decades, however, we have learned a good deal about inferring transport conditions from physical sedimentary structures (Ashley 1990, Boguchwal & Southard 1990, Southard & Boguchwal 1990), and it is quite clear that, at least in the cases of fluvial and deltaic strata, the transport conditions recorded are mostly quite ordinary. By this we mean flow speeds of a few m/s and shear stresses of the order of a few Pa. The evidence for this is so common that it is easy to overlook its significance until it is juxtaposed against the equally compelling evidence that preservation itself is exceedingly uncommon. For example, the formation conditions for dune cross strata, such as those discussed above and illustrated in **Figure 1**, are well known, and there is simply nothing extraordinary about them—a point also emphasized by Tipper (2015). We think of this paradox—the rarity of event preservation compared to the ordinariness of the preserved events themselves—as the *strange ordinariness* of the stratigraphic record.

The Devil's staircase model of deposition, which embodies Tipper's (2015) notion of stasis dominance and Plotnick's (1986) fractal model of preserved time, suggests that variability in the rate of deposition might explain this paradox. The rare events are not catastrophic transport events but short-lived intervals of rapid deposition, i.e., extraordinary preservation. This idea, which summarizes the arguments of Tipper (2015) and Dott (1983) and the observations of Reesink et al. (2015), is also an autogenic cousin of the notion of punctuated aggradation cycles (Goodwin & Anderson 1985). It suggests the following questions:

1. What does field evidence tell us about rates of deposition, especially in relation to transport conditions?
2. What physical processes modulate local rates of deposition so as to produce high rates of deposition without high transport rates, leading to extraordinary preservation of ordinary events?
3. What is the relationship between sedimentation rates over various timescales and preservation and completeness? For example, do basins with high long-term sedimentation rates preserve more and/or different kinds of transport events than basins with low rates?

4.2.2. Rate of deposition and preservation. Climbing ripples are among the humblest of primary structures, but the simple geometric relationships between climbing and migration rate, bedform length, and deposition rate (Allen 1970, Rubin & Hunter 1982) nevertheless provide a basis for developing a basic understanding of ordinariness, time preservation, and rate of deposition. The geometry is generalized in **Figure 8**, building on the analyses of Jerolmack & Mohrig (2005) and Reesink et al. (2015). The conceptual picture is clearest if we divide the topography into discrete classes (e.g., ripples, dunes, bars, bar complexes), as does Miall (2015). The scale breaks between the classes, as fuzzy as they may sometimes be, provide a natural way of estimating the

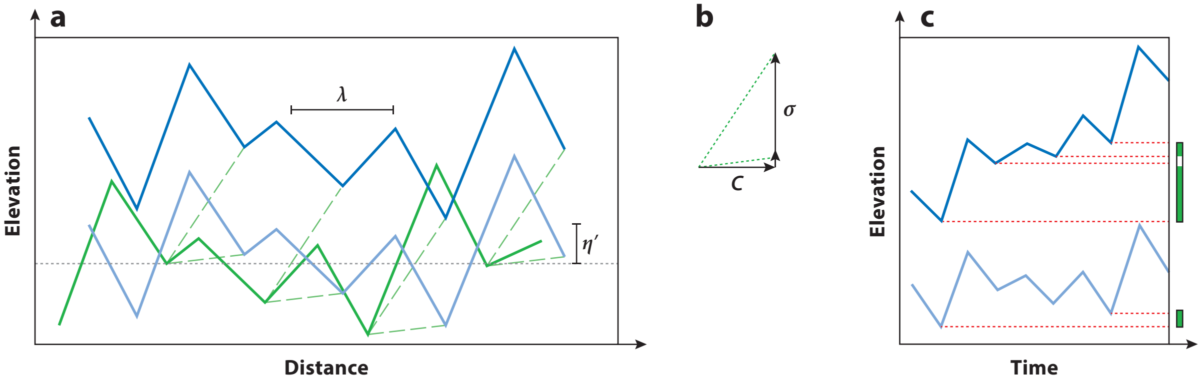

Figure 8

Definition of variables for considering the effect of aggradation versus progradation (climbing) on time and event preservation. (*a*) The topography in green migrates a fixed distance to the right, but in one instance (*light blue*) only a small amount of aggradation occurs, while in the other case (*dark blue*) much more aggradation occurs (i.e., the climb angle is steeper). The geometric terms in Equation 3 are defined in panel *a*, while the kinematic ones are defined in panel *b*. (*c*) A sketch of the time record associated with the two climbing conditions. The low-climb case is dominated by extreme scours [it is variability dominated, in the terminology of Reesink et al. (2015)]; the high-climb case preserves a greater overall thickness and more beds and samples elevations from the central part of the elevation distribution (i.e., more ordinary elevations).

relevant average rate of deposition; more importantly, they make clear that the rate of deposition at any scale is controlled by dynamics at the next scale up.

Given a rate of deposition $\sigma(\Delta t)$ averaged over timescale Δt and three properties of the topography, namely elevation variability η' (e.g., rms variation of height), characteristic migration speed c, and characteristic streamwise spacing λ, we can slightly recast the traditional climbing relation as a dimensionless index for preservation of time and stratal boundaries (**Figure 8**):

$$\theta = c\eta'/\lambda\sigma. \qquad 3.$$

In effect, θ measures the number of topographic elements of spacing λ that pass a given location in the time needed to deposit a thickness of sediment equal to η'. As suggested in **Figure 8**, if $\theta \sim 1$, most or all of the topographic elements are preserved, the topographic climb angle is high, and, over the interval Δt, $f_c \sim 1$ holds true. Reesink et al. (2015) provide nice examples of this condition, which they term the deposition-dominated case, for dunes. The extreme case of depositional dominance would be $\theta < 1$, i.e., supercritical climb, a case that is rare for bedforms larger than ripples, though not uncommon for features, such as channels, that may migrate slowly. In the regime $\theta \gg 1$, numerous topographic elements rework the point in question, $f_c \ll 1$, and stratal thickness is set by differences between extreme scour depths. Reesink et al. (2015) term this regime the variability-dominated case and make the important point that even for relatively large dunes, field evidence from both modern and ancient deposits shows that relatively high preservation fractions, indicating $\theta \sim 1$, are fairly common. Specifically, Reesink et al. report numerous examples of preserved form sets in dunes, which can happen only if θ is near or below unity. Such sets are distinctive in the field, though in some cases (e.g., the form being preserved by a mud drape), the preservation represents abandonment ($c = 0$) and burial of the dune rather than rapid deposition. But Reesink et al. (2015) show examples in which the form sets are clearly associated with high local rates of deposition, for example, on the lee sides of large bars. This is an important clue as to the explanation of strange ordinariness to which we will return shortly.

Recent research (Ganti et al. 2013, Jerolmack & Mohrig 2005) has shed light on the geometry of dune sets for varying climb angles. This work hints that it might be possible to identify cases in which θ approaches 1, but not quite to the level of preserving the entire dune form, through careful analysis of variability in set thicknesses and set boundary curvature. If we could identify such cases, it would help constrain local paleodeposition rates. This in turn would allow us to distinguish between two fundamentally different models of physical time preservation: one in which missing time is accounted for by repetitive scour and fill, leaving behind only a handful of beds from the deepest autogenic scours (the variability-dominated case), and the other in which missing time is represented by periods of stasis or very slow deposition, punctuated by episodes of rapid deposition under otherwise ordinary transport conditions (the deposition-dominated case, also embodied in the Devil's staircase model). The research summarized here suggests that such work will show that episodes of rapid deposition are common and that most alluvial stratigraphy is created under the second model.

This prediction is derived directly from the work of Miall (2015), Tipper (2015), Dott (1983), and Reesink et al. (2015), who have called attention to the idea that variability in preservation essentially concerns variability in sedimentation rate. What has been less clear is the origin of this variability; in this case, Reesink et al.'s (2015) important contribution is a set of field examples in which local high deposition rates are associated simply with the hierarchical internal organization of topography, rather than with some externally imposed depositional event. This finding in turn helps explain how extremes in local sedimentation rate can be decoupled from extremes in transport. How does topographic self-organization constrain the variables in Equation 3 and influence variability in rate of deposition?

Across the Sedimentation Rate Scale (SRS) hierarchy described by Miall (2015), his data summary indicates consistent relations among the variables on the right of Equation 3. The ratio of the two geometric parameters, η' and λ, represents a characteristic steepness of the topography; the self-organized topographic elements in Miall's hierarchy (SRS 1–8) commonly have characteristic steepnesses of the order 0.01–0.1. The other component of θ is c/σ, the ratio of horizontal to vertical surface-migration speed and also the inverse of the tangent of the climb angle. For freely migrating topography, we generally expect $c/\sigma \gg 1$, i.e., this ratio pushes θ toward larger values and less complete preservation. It is overall more variable than steepness is, but in general, Miall (2015) notes higher deposition rates for the smaller, faster-moving elements in the hierarchy, acting to moderate values of c/σ across the hierarchy. Overall, the key to maximizing local preservation and completeness is sufficiently high σ values to keep θ not far above 10. Interspersing periods of stasis helps accomplish this by focusing deposition in time; hierarchically ordered topography, by focusing deposition in space.

In summary, we suggest that the essential character of physical completeness in terms of both time and process is set by two things: stasis dominance, as proposed by Tipper (2015), and a strong morphodynamic hierarchy such as that described by Miall (2015). Both of these factors act to focus deposition and create high local completeness in terms of both time and process. The overall low completeness of stratigraphy results from spatial and temporal intermittency of transport and interaction among scales in the hierarchy. Although variable external forcing certainly plays a role and could in particular be dominant in creating stasis periods, including it explicitly does not appear necessary for understanding the basics of time preservation at sub-basin scales.

We close with a simple illustration. **Figure 9** shows two topographic sequences and their associated strata. The basis for each sequence is a succession of local maxima and minima chosen from a gamma distribution, alternating sign so that the average elevation is zero. The upper sequence (**Figure 9*a***) results from a hierarchy of three such sequences, each of which has a characteristic spacing 10 times greater than the next. Amplitude does not increase proportionally,

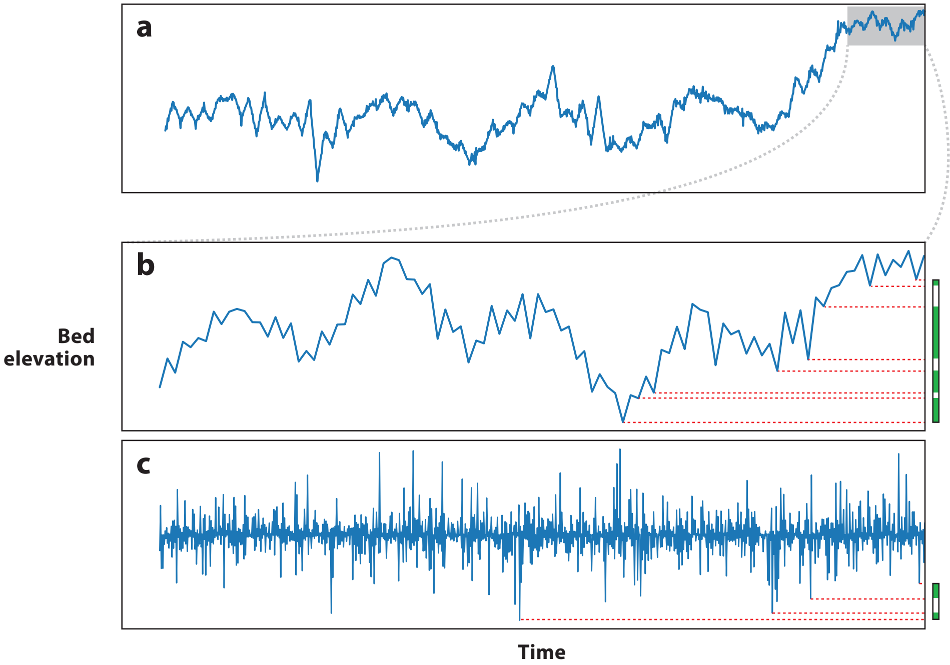

Figure 9

Results of a simple model of how stochastic topography organized into a hierarchy can produce local depositional events and help explain strange ordinariness. (*a*) Sequence of elevations produced by summing topographic sequences from a three-level hierarchy, each of which has a characteristic spacing 10 times greater than the next and reduced steepness. (*b*) The resulting strata shown with a detail of the last 10% of the sequence in panel *a* (*gray box*). The preserved elevations from the highest-frequency part of the hierarchy come, on average, from the 54th percentile of their probability distribution. (*c*) The topographic sequence of only the high-frequency part of the hierarchy and its resulting strata. The preserved elevations are much more dominated by the extremes of the distribution (97th percentile on average).

so that longer forms have lower steepness. We focus on the preservation of beds originating from the sequence with the shortest wavelength, which we can think of as dunes and which thus record information about local flow conditions. In **Figure 9*a***, the preserved short-wavelength stratal boundaries originate from brief intervals of rapid deposition brought about by the higher levels of the hierarchy, as in Reesink et al.'s (2015) deposition-dominated example of dunes interacting with bars. The preserved elevations (shown in detail in **Figure 9*b***) come from near the center of the probability density function (54th percentile) of the short-wavelength bed elevations: They are ordinary. The lower sequence (**Figure 9*c***) shows the short-wavelength sequence with the longer-period elements of the hierarchy removed, and the associated stratal boundaries. Without larger-scale ups and downs, the sequence reworks itself repeatedly, and the preserved beds come from bed elevations from the tail of the distribution (in this case, the 97th percentile). **Figure 9*c*** exemplifies Reesink et al.'s variability-dominated case and, in a simple way, a catastrophic (extreme-dominated) view of the stratigraphic record. The next step would be to intersperse periods of stasis, as suggested by Tipper (2015), which can be done probabilistically using observations like those of Ganti et al. (2011). The result would look like **Figure 2**. Adding stasis gaps does not change the bed-thickness statistics but strongly affects time preservation and the associated Sadler plot.

5. FIELD EXAMPLES

5.1. Low-Accommodation Cratonic Sequences

Stratal sequences developed under conditions of very low net sedimentation provide an informative end-member case study in preservation and completeness, especially when contrasted with sequences accumulated at much higher rates in tectonically active areas. In this section, we focus on the Lower Paleozoic cratonic interior strata of the Upper Mississippi Valley (UMV) region of North America, which accumulated at some of the lowest known long-term sedimentation rates (**Figure 10**). These strata have a long-standing reputation for being an exceptionally poor record of time (Holland 1995, Holland & Patzkowsky 2002, Sloss 1996). Sedimentation rates of 5 m/Myr or less for epoch- and period-length spans of time across vast areas of this and other cratonic platforms led Sloss (1996, p. 430) to suggest a history that "demands interrupted deposition, preservation as a relatively rare event, and long stretches of time on cratonic platforms unrepresented by a stratigraphic record"—entirely consistent with the stasis-dominated view we advocate here.

Sloss's (1996) characterization makes intuitive sense given exceptionally slow subsidence rates. However, more recently, Runkel et al. (2007, 2008) have shown that at a significantly large range of scales, and evaluated from a three-dimensional perspective, the UMV cratonic interior strata may rival in completeness records in deposited settings with markedly greater subsidence rates. The Cambrian and Lower Ordovician mixed siliciclastic and carbonate strata that they studied (**Figure 10*a***) accumulated at an average rate of about 7 m/Myr over a span of 15 Myr. Their high-resolution sequence stratigraphic framework revealed that, despite the exceptionally slow average sedimentation rate, at scales ranging from individual beds to parasequences and parasequence sets, the strata are physically similar to those preserved in settings that had orders of magnitude greater subsidence rates in more active tectonic settings. A more pronounced lateral shingling of parasequences appears to be the principal feature that distinguishes cratonic interior successions from those that accumulated in more rapidly subsiding areas, i.e., the preservation is lateral rather than vertical (**Figure 10*b***). Using these results as an example, Miall (2015) suggests that lateral accretion may be the key to long-term preservation in thin sedimentary successions in the slowly subsiding, low-gradient-ramp settings characteristic of cratonic interiors. This finding exemplifies both the importance of including the spatial dimension in measuring temporal completeness and the key point made by Sadler & Jerolmack (2015) that decreasing subsidence rate, rather than simply shutting off deposition, can instead shift the balance of sedimentation from vertical (aggradation) to horizontal (progradation). **Figure 10*b*** is a large-scale example of exactly this phenomenon.

The manner in which strata accumulate in low-subsidence settings has important implications for evaluating the fidelity of time preservation in those areas. At era timescales, the characterization of the record as exceptionally poor appears to be warranted by any measure. This is primarily because the major sequence boundaries that separate continental scale sequences (e.g., Sloss 1963) have hiatal magnitudes that, in general, inversely correlate to subsidence rate (Sloss 1988, 1996). But the correlation does not apply to deposits at scales ranging from laminae to features as large as parasequence stacks, which can accumulate in low-subsidence settings in a manner generally similar to any other basin regardless of subsidence rate. At those scales, the quality of recorded time is independent of subsidence rate: The sedimentation rates given by, for example, Sadler (1981) or Miall (2015) for comparable depositional features (e.g., laminae to nearshore depositional systems) are as applicable to the slowly subsiding cratonic interior as they are to basins with greater subsidence rates. In the cratonic interior strata studied by Runkel et al. (2007, 2008), one example of high sedimentation rates at the smallest physical and temporal scales is the preservation of regionally extensive facies containing thick cross-strata sets with rhythmic bundles recording

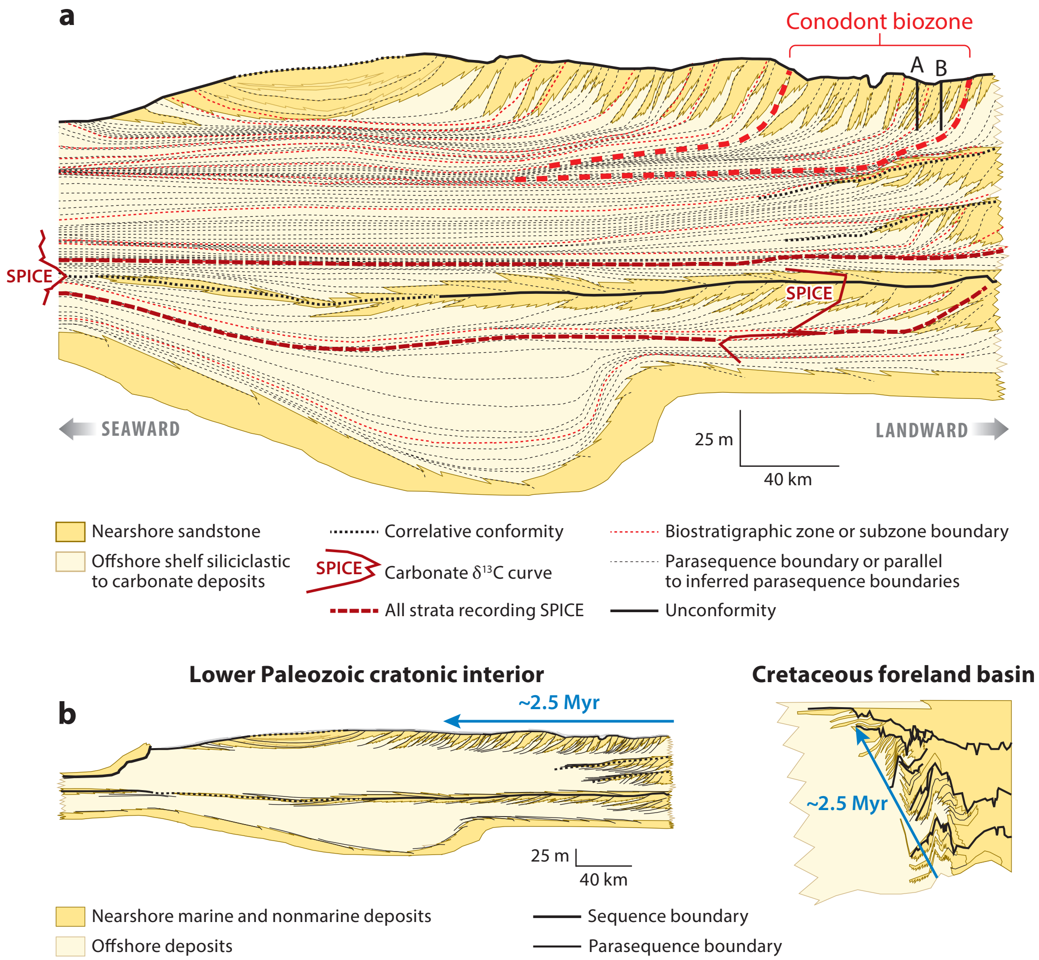

Figure 10

(*a*) Representative cross section of Cambrian and Lower Ordovician strata in the Upper Mississippi Valley (UMV) cratonic interior of North America, showing the pronounced lateral shingling of strata at parasequence scale. The record of a single conodont biozone of ~0.5 Myr duration is labeled and outlined by thick red dashes. The Steptoean positive carbon isotope excursion (SPICE) curve is shown where it has been documented in a relatively paleolandward position, as well as in a paleoseaward position. All strata deposited during the ~4 Myr duration of the SPICE are outlined by thick brown dashes. Note that lateral accretion is so pronounced that individual sections 10 km apart—indicated by the vertical black lines labeled A and B—within a single biozone may have no overlap in recorded time. The entire package was deposited over a span of about 15 Myr. (*b*) Comparison of the UMV strata shown in panel *a* to the Cretaceous Book Cliffs strata of Utah, USA. The blue arrows highlight how the record of time in low-subsidence settings (UMV) is shingled laterally compared to the more vertically stacked record characteristic of high-subsidence settings (Book Cliffs). Panel *a* adapted from Runkel et al. (2007, 2008), Saltzman et al. (2004), and Cowan et al. (2005). Panel *b* adapted from Runkel et al. (2007).

diurnal tidal events (Tape et al. 2003)—this lovely example of strange ordinariness being all the more striking for occurring in a setting with low overall time preservation at the scale of a single section. At larger scale, biozones averaging a duration of 0.5 Myr consist of stacked parasequences attaining thicknesses of tens of meters at individual vertical sections, comparable in thickness to the same biozones in sedimentary packages deposited elsewhere in North America, where longer-term subsidence rates are nearly an order of magnitude faster.

The record of time is even more complete, and is complete across even longer timescales, if it is measured using a three-dimensional perspective rather than via the conventional approach of evaluating individual vertical sections. For example, shingled parasequences composing individual biozones along a single transect perpendicular to depositional strike would attain cumulative thicknesses of over 250 m if they were stacked upon one another (**Figure 10**), significantly thicker than documented elsewhere in North America. A large positive carbon isotope excursion, referred to as the Steptoean positive carbon isotope excursion (SPICE), with an estimated duration of approximately 4 Myr, is recorded in the UMV cratonic interior along a similar transect by laterally extensive sets of parasequences (**Figure 10**) with a cumulative thickness of over 200 m, comparable to the thickest record of SPICE documented globally (e.g., Saltzman et al. 2004). It is noteworthy that these cumulative thickness estimates are minimum values because they are restricted to a single two-dimensional transect and thus do not include parasequences that may be located elsewhere in the basin.

Although lateral accretion appears to be more pronounced at parasequence and larger scales in slowly subsiding conditions, it is of course not unique to such settings. Miall (2015) emphasizes the relevance of this to the record of time, noting that many common sedimentary processes are dominated by lateral sedimentary accretion—a nice example of the effect of extending the horizontal scale that we discuss in Section 2. Miall (2015) also provides examples that suggest that this especially applies at intermediate timescales (10^1–10^5 yr) and notes that it has been demonstrated in experimental depositional basins (e.g., Sheets et al. 2002). Considered from this three-dimensional perspective and within this range of timescales, subsidence rate might have less impact on the completeness of the record of time than does sediment supply (Runkel et al. 2008). As we argue above, the available evidence—particularly the data compilation and analysis of Sadler & Jerolmack (2015)—supports consistency in supply to basins as a whole, across time and tectonic environments.

This raises the question of which is the most appropriate method to measure the completeness of the record of time. For example, the conventional method of quantifying an average sedimentation rate based on thickness of individual vertical sections deposited over era timescales works as a first approximation. But many geologic problems focus on events that occurred during smaller increments of time—for example, mechanisms triggering mass extinctions. The possible triggers (e.g., changing climate, oceanic anoxia, bolide impacts), as well as extinctions themselves, commonly occur over durations of only a million years or less. The most complete record of such events may very well be preserved in three dimensions in areas such as cratonic interiors, given adequate sediment supply.

While lateral accretion at large scales helps produce a high-quality record of time in three dimensions, it also exemplifies a limitation inherent in attempts to establish time equivalence in the stratigraphic record. Sections considered time equivalent on the basis of conventional correlation techniques may actually have no overlap in recorded time, even within individual basins. For example, vertical sections within a single lithostratigraphic formation in the UMV cratonic interior may correlate at the biozone level (~0.5 Myr) but have no overlap in age even over distances as short as 10 km (**Figure 10**, sections marked A and B) because of the pronounced lateral shingling of the strata. Similarly, individual sections recording the 4 Myr SPICE in the UMV (**Figure 10**) potentially have little or no overlap in recorded time from place to place, within the basin, or in comparison to sections elsewhere globally because of the same phenomenon. These types of standard correlations of vertical sections establish time equivalence only in that the correlated strata were deposited within a range of elapsed time, not in that there is overlap in recorded time within that range.

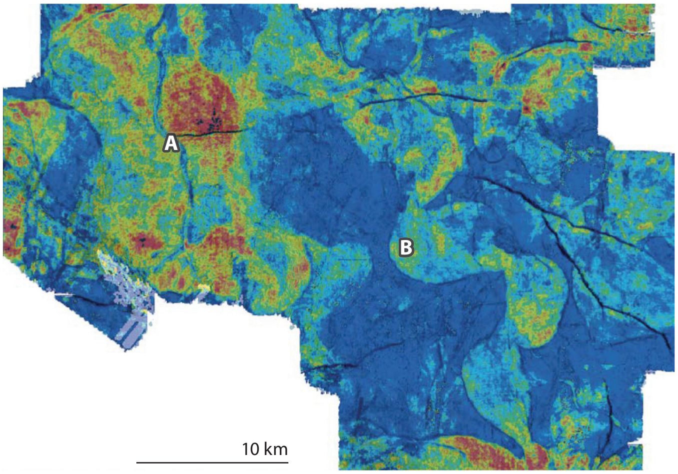

Figure 11

Seismic horizon slice imaging a 100-m-thick section of channelized, Late Miocene fluvial deposits (Armstrong et al. 2014). The map is a combined rendering of the similarity and sweetness seismic attributes, with similarity highlighting the discontinuities in acoustic reflectivity of the stratigraphy (*black*) and sweetness serving as a proxy for the sandiness (*warm colors*) versus muddiness (*cool colors*) of the preserved strata. Note that the map defines the preserved remnants of multiple, ordinary channel- and channel-belt-filling deposits. Sweetness indicates that the deposits of channel belt A are relatively muddy, while the deposits of channel belt B are relatively sandy. Both channel belts can be mapped for more than 20 km in the downstream direction. The median thicknesses for the mapped channel-belt deposits of A and B are 25 m and 40 m, respectively. The median widths for the A and B deposits are 300 m and 3,720 m, respectively. Access to this seismic volume was provided by WesternGeco®.

5.2. Continental Margin Deposits

Seismic volumes, combined with well logs and borehole data, provide a remarkable picture of the lateral stacking and variability of sedimentary deposits and of strange ordinariness at large scales. **Figure 11** presents seismic imaging of Late Miocene fluvial deposits of the greater Mississippi River delta located ~75 km southwest of New Orleans, Louisiana, USA, at a subsurface depth roughly 1,670 m below sea level. The fluvial stratigraphy imaged by this seismic volume has been studied at the individual channel-belt (Armstrong et al. 2014) and basin-filling (Straub et al. 2009) scales. Nanofossil biostratigraphic markers recovered from wellbores define a constant, geologic sediment accumulation rate of 260 m/Myr for the past 10 Myr—a rate 37 times greater than that for the cratonic sequence discussed in the previous section. Despite this difference, seismic imaging reveals a stratigraphy dominated by lateral migration of channel bends that produced channel-belt deposits and lateral shifting of these channel-belt deposits via river avulsions (**Figure 11**).

Researchers have carefully mapped 43 individual channel to channel-belt-filling deposits of Late Miocene to Pliocene age within a seismic volume covering an area of 1,375 km^2 and a vertical thickness of 1.5 km (Armstrong et al. 2014). The widths for these deposits range from 70 to 31,000 m, and thicknesses range from 11 to 90 m. The streamwise extent of the individual mapped deposits ranges from 4,100 to 29,600 m before being cut out by younger channel forms. Channel-belt deposits A and B in **Figure 11** are positioned within the same 100-m section of strata but record strikingly different channels. Channel belt A was produced by a channel that over the course of its history laterally migrated less than one width, while channel belt B was produced by a channel having bends that over its history migrated laterally to build a belt width that is up to 10–15 times the channel width. In addition to the final channel-belt form, the sweetness seismic attribute illustrates that channel belt A is primarily filled with muddy deposits, while channel belt B is primarily filled with sand-rich deposits (**Figure 11**) (Armstrong et al. 2014). In spite of these differences, both channel-belt-filling deposits look similar to and fall within the range of modern channel belts observed on the greater Mississippi River delta (Armstrong et al. 2014, Blum et al. 2013, Fernandes et al. 2016).

At the reported geologic sediment accumulation rate, it would take between 40,000 and 350,000 years to deposit the range of measured channel-belt thicknesses. Although we do not know the avulsion time for the late Miocene to Pliocene systems shown here, avulsion periods ranging from 500 to 5,000 years have been found for Holocene channels and delta lobes of the Mississippi River delta (Törnqvist 1994), consistent with those of other large rivers. The most likely explanation of the timescale disparity is that the channels were active for only a small fraction of the total deposition time and were then abandoned. The system thus provides a field-scale example of stasis, since little or no accumulation occurred for most of the time interval. It also illustrates strange ordinariness at large scales, as the complete morphology of the channel is preserved, rather than the fragments that would result from extensive reworking.

6. LABORATORY EXAMPLES

Laboratory experiments on the evolution of depositional landscapes have opened a new window onto the storage of time in stratigraphy. The advantages and shortcomings of such experiments have been reviewed elsewhere (Kleinhans et al. 2010, Malverti et al. 2008, Paola et al. 2009); for our purposes, the main point is that, because laboratory experiments allow us to measure topographic evolution comprehensively at high spatial and temporal resolution, the time of deposition of essentially every particle introduced is known. Physical laboratory experiments also greatly speed up time: Reducing system size generally reduces overall process timescales, and most experiments are continuously forced, unlike natural systems in which transport events—e.g., floods—are highly intermittent.

Here we examine results from channelized fan-delta experiments subject to long-term generation of accommodation, either from absolute subsidence or from sea-level rise. We look first at results from experiments that focus on the one-dimensional evolution of stratigraphic sections. While the numerical models discussed in Section 3 rely on prescribed distributions of elevation fluctuations and truncation scales, physical experiments provide the advantage that these attributes arise naturally from morphodynamics. These morphodynamics produce two conditions important for studying time in stratigraphy: (*a*) Elevation time series are spatially correlated as a result of the movement of coherent features like channels and bars, and (*b*) any point on an experimental surface is subject to significant periods of stasis, when the active sediment transport system is located elsewhere. The distribution of periods of inactivity is determined by the movement of transport elements over the landscape. For example, Sheets et al. (2002) showed that stratigraphy was mostly built by short-lived, localized, rapid deposition events, despite forcing conditions being held constant.

The experimental delta study of Ganti et al. (2011), in addition to showing that stasis is the predominant state even for a situation in which external forcing was continuous and strong, also showed that important morphodynamic distributions, including the magnitude of elevation fluctuations and waiting times between these fluctuations, follow truncated Pareto distributions. The Pareto is an example of a power-law (heavy-tail) distribution—the decay of probability with magnitude is slow enough that it leaves a significant chance for large events and long waiting times—and is a fundamental distinguishing feature of the distributions used in the studies discussed in Section 3. Pareto distributions applied to real events are typically truncated because of physical limitations. Ganti et al. (2011) found that the truncation scale of the distribution of waiting times between events was related to an internally derived timescale that we refer to as the stratigraphic integral scale, T_i, equal to the depth of the largest channels in a system divided by the long-term aggradation rate.

Straub & Esposito (2013) explored the influence of T_i on the completeness of one-dimensional stratigraphic sections using a suite of physical experiments, all subject to constant forcing, though the forcing varied between experiments. In each experiment, stratigraphic completeness increased as a function of the timescale of discretization, δt, following an approximate power law. Normalization of δt by T_i effectively collapsed data from individual experiments onto one growth trend, with 100% completeness reached at a discretization timescale equal to T_i. Straub & Esposito removed the small residual difference between the completeness trends of the individual experiments following normalization by T_i by incorporating an additional internally derived timescale, T_{cb}, the time necessary for channels to migrate and visit all basin locations.

The experimental setting allows investigation of the cause of missing time. We estimate the relative fraction of time missing due to stasis versus erosion using another physical fan-delta experiment subject to constant forcing, similar to those discussed above (Straub et al. 2015) (**Figure 12*a–d***). The evolution of this system was monitored at high spatial and temporal scales relative to the morphodynamics in the system. Similar to plots presented by Straub & Esposito (2013), in this plot, $\delta t/T_i$ influences the fraction of time steps that are either recorded in stratigraphy, absent in the final record due to continuous periods of stasis, or absent from the record due to subsequent erosion. At short discretization intervals, the primary cause for the incompleteness is stasis. This result is easy to understand: In the limit as $\delta t \rightarrow 0$, the maximum theoretical completeness of a record is the average fraction of the surface that has active transport. Interestingly, as the discretization timescale increases, the relative fraction of the record associated with erosion increases at first. These longer time windows allow transport systems to translate laterally and rework previously deposited sediment. Eventually, the relative influence of long-term aggradation prevails, and the fraction of time steps missing due to both erosion and stasis decreases with increasing temporal discretization.

The importance of T_i for stratigraphic storage of environmental time series in stratigraphy has been noted in a number of other experimental studies. For example, Li et al. (2016) found that this timescale partially controls the stratigraphic storage of sea-level signals in stratigraphy. Sea-level cycles that are shorter in duration than T_i and are also of a magnitude less than the vertical scale of autogenics are generally destroyed prior to storage. Foreman & Straub (2017) found that temporal gaps in the stratigraphic record imposed by internal dynamics make recovery of geochemical proxy signals impossible from stratigraphy unless the period of the signal is at least $2T_i$, a kind of Nyquist sampling problem in stratigraphy.

A key aspect of physical experiments is that topographic evolution can be monitored in multiple dimensions. Mahon et al. (2015) used this fact to explore the stratigraphic completeness of a fundamental boundary in most sediment transport systems, the shoreline. Using an experiment with dynamic forcing conditions but with a net generation of accommodation, Mahon et al. investigated the stratigraphic completeness of delta shoreline trajectories. The forcing in their experiment resulted in shoreline transgressions and regressions and sea-level lowstand valleys formed through incision. Although a mixture of stochastic internal dynamics and external forcings resulted in periods of stasis, deposition, and erosion, Mahon et al. found that the completeness of the deltaic shorelines was substantially greater than any stationary one-dimensional point on the experimental surface. Given the importance of this boundary for environmental reconstructions, this is welcome news.

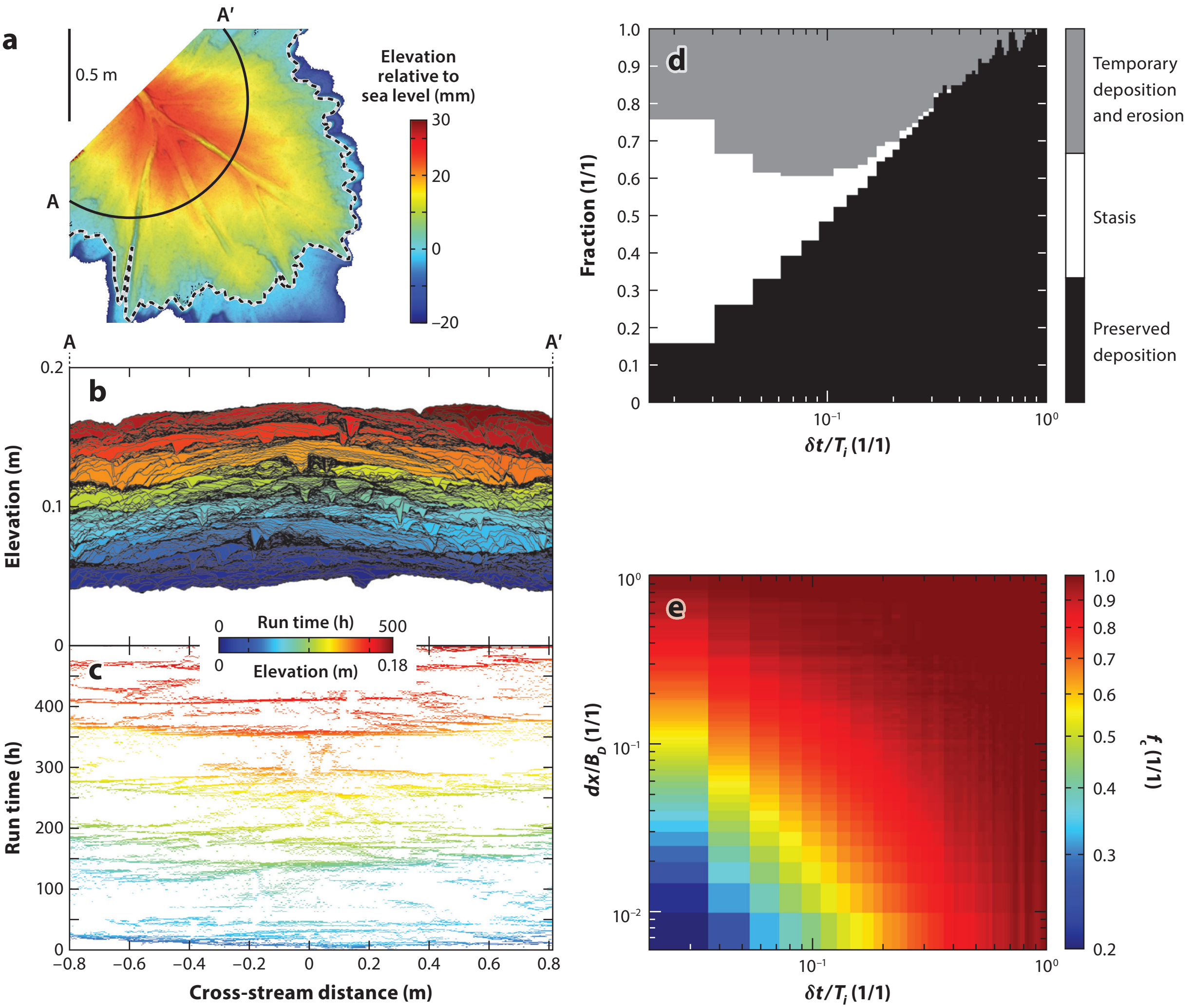

Figure 12

Results documenting the storage of time in an experimental deltaic deposit. The experimental deposit, referred to as TDB-15S2 by Straub et al. (2015), evolved in response to a constant supply of water and sediment and a constant rate of sea-level rise. The total run time of the experiment was 500 h, and topography was measured every 1 h. (*a*) Digital elevation model (DEM) of the experimental surface at run hour 399. (*b*) Cross section of synthetic stratigraphy generated from stacked DEMs, clipped for erosion. Deposits are colored by time of deposition. Solid black lines are contours of constant time. (*c*) Time–space map of preserved elevation for the cross section presented in panel *b*. White regions in the map represent time–space pairs where either stasis or erosion resulted in a lack of preserved time. (*d*) Data defining how stratigraphic completeness and the relative contributors to incompleteness change as a function of the timescale of discretization. (*e*) Matrix defining how stratigraphic completeness changes as a function of both the timescale of discretization and the width of the observation window.

Physical experiments also allow investigation of how expanding the lateral field of observation improves recovery of temporal information from stratigraphy. We illustrate this using data originally reported by Straub et al. (2015). We start by measuring stratigraphic completeness with $\delta t/T_i$ set to its minimum possible value and with the width of the sections, dx, equal to the grid spacing of our topographic scans. This is analogous to measuring the completeness of one-dimensional columns, as discussed above. We then sequentially widen the field of observation by multiples of dx. For a given value of dx we ask if preserved deposition occurred in any of the grid cells in the field of observation for each time step. We apply the definition from Section 2: If preserved deposition occurred in any of the cells in the field of view, we consider that time step preserved. As the field of view widens, the average completeness of records increases. The length scale necessary to reach a 100% complete record appears to be the maximum distance between channels in the experiment, B_D, which sets the maximum width of regions in stasis. It is important to note that the average completeness of a record depends on both the width of the section analyzed and on δt. This suggests a two-dimensional phase space of completeness: $\delta t/T_i$ versus dx/B_D (**Figure 12*e***).

7. SYNTHESIS

The highlights of our review of physical controls on preservation of time can be summed up in four dichotomies:

1. that between the traditional vertical (aggradational) view of completeness and the emerging evidence for a horizontal (progradational) view;
2. that between a unified, generalized random-walk view of topographic evolution in a single vertical section and a hierarchical view that breaks topographic elements into different types according to scale;
3. that between thinking of temporal hiatuses as event sequences lost to subsequent erosion and thinking of them as periods of stasis; and
4. that between the extreme rarity of preservation—such that, in the limit, preserved time is nothing more than a fractal dust—and the apparently humdrum character of the preserved events themselves, which we term strange ordinariness. This view stands in contrast to the neocatastrophist view of strata as dominated by rare, extreme transport events.

The first of these dichotomies contributes directly to the idea of developing a space–time dynamics of preservation, in terms of stratal geometry, time preservation, and event selection. The tools for doing this include new field methods for high-resolution measurement of stratal geometry, increasingly available high-resolution seismic data, and new modeling techniques that draw on some of the concepts reviewed here.

The second dichotomy is more apparent than real. The (possibly fractional) Brownian random-walk models reviewed above are characterized by power laws that imply an absence of characteristic scales. They inhabit the world of fractals and multifractals, in which a carefully curated hierarchy of named elements seems foreign. The elements in the hierarchy of dynamical forms—bedforms, bars, channels, and the array of other features familiar to field sedimentologists—are, while not necessarily fractal in themselves, part of a mosaic the internal distinctions of which can be fuzzy and the scale ranges of which overlap. Anyone who has followed the lengthy and inconclusive debates about how to classify river channel patterns, or bedforms, will find it easy to imagine how, with only a little blurring of vision, one could capture important features of the overall system with a single, generic, and scale-free dynamical representation.

We think the third and fourth dichotomies are important. The question of whether the time gaps—hiatuses—in the stratigraphic record mostly record erosion or stasis is, we believe, fundamental not only to understanding how Earth records its own history but also to thinking about how much time is really represented in strata. The fact that during stasis time the recorder is set to pause rather than to erase leaves open the possibility that information may still be preserved, even if in the most tenuous of ways. Such information could conceivably be recovered as better tools are developed, but information that has been actively destroyed is lost. As researchers, it seems unnatural to focus on what is not there, but we see missing time, as well as the development of new methods to constrain it, as a major new area for stratigraphic research, especially at short time and length scales where at present we have almost no information.

The idea of a recording process shot through with pauses helps make sense of the fourth dichotomy. It seems clear that the explanation of strange ordinariness must lie in extreme preservation events, and the easiest way to create those seems to be short-lived intervals of rapid deposition that trap the mundane goings-on of a randomly chosen fragment of time—a temporal insect in amber. These rare preservation events make more sense when seen as the risers in the Devil's staircase. It also helps to realize that the elements of the topographic hierarchy that directly record transport conditions have short wavelengths, where their preservation is controlled by the dynamics of elements at the next higher levels rather than by overall sediment supply and subsidence. The natural complement to the study of absent time would be the development of better ways to constrain rates of deposition and topographic climb on short time and length scales.

The title of this review includes a quote from T. S. Eliot's *The Dry Salvages* alluding to time beyond that which we experience. Our understanding of the strange ordinariness of the stratigraphic record suggests that, while recorded planetary time is unimaginably longer and more fragmentary than human time, the events it records are nonetheless arrestingly familiar. In ways that we are only beginning to understand, the process that salts away a vanishingly sparse sample of all that transpired mostly chooses not the dramatic but the mundane. These are "frozen accidents" indeed: temporal specks of a strangely ordinary world.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank the editor and reviewer for helpful comments that improved the manuscript, Peter Sadler for sharing the data used in **Figure 4**, and Doug Jerolmack for insightful discussion of aspects of this review. The work was supported in part by the US National Science Foundation (NSF) via the National Center for Earth-surface Dynamics (NCED), grant EAR-1246761, and the Delta Dynamics Collaboratory, grant EAR-1135427. K.M.S. and V.G. acknowledge support from, respectively, US NSF grant EAR-1024443 and the Imperial College London Junior Research Fellowship.

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Annual Review
of Earth and
Planetary Sciences

Volume 46, 2018

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Errata

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