6-2011

The Stratigraphic Filter and Bias in Measurement of Geologic Rates

Rina Schumer

Douglas J. Jerolmack
University of Pennsylvania, sediment@sas.upenn.edu

Brandon McElroy

Recommended Citation

Schumer, R., Jerolmack, D. J., & McElroy, B. (2011). The Stratigraphic Filter and Bias in Measurement of Geologic Rates. *Geophysical Research Letters, 38* (11), L11405-. http://dx.doi.org/10.1029/2011GL047118

The Stratigraphic Filter and Bias in Measurement of Geologic Rates

Abstract
Erosion and deposition rates estimated from the stratigraphic record frequently exhibit a power-law dependence on measurement interval. This dependence can result from a power-law distribution of stratigraphic hiatuses. By representing the stratigraphic filter as a stochastic process called a reverse ascending ladder, we describe a likely origin of power-law hiatuses, and thus, rate scaling. While power-law hiatuses in certain environments can be a direct result of power-law periods of stasis (no deposition or erosion), they are more generally the result of randomness in surface fluctuations irrespective of mean subsidence or uplift. Autocorrelation in fluctuations can make hiatuses more or less heavy-tailed, but still exhibit power-law characteristics. In addition we show that by passing stratigraphic data backward through the filter, certain statistics of surface kinematics from their formative environments can be inferred.

Keywords
deposition, erosion, hiatus, landscape evolution, power-law, stratigraphy

Disciplines
Earth Sciences | Environmental Sciences | Physical Sciences and Mathematics | Sedimentology

The stratigraphic filter and bias in measurement of geologic rates

Rina Schumer,[1] Douglas Jerolmack,[2] and Brandon McElroy[3]

Received 28 February 2011; revised 7 April 2011; accepted 9 April 2011; published 10 June 2011.

[1] Erosion and deposition rates estimated from the stratigraphic record frequently exhibit a power-law dependence on measurement interval. This dependence can result from a power-law distribution of stratigraphic hiatuses. By representing the stratigraphic filter as a stochastic process called a reverse ascending ladder, we describe a likely origin of power-law hiatuses, and thus, rate scaling. While power-law hiatuses in certain environments can be a direct result of power-law periods of stasis (no deposition or erosion), they are more generally the result of randomness in surface fluctuations irrespective of mean subsidence or uplift. Autocorrelation in fluctuations can make hiatuses more or less heavy-tailed, but still exhibit power-law characteristics. In addition we show that by passing stratigraphic data backward through the filter, certain statistics of surface kinematics from their formative environments can be inferred.

Citation: Schumer, R., D. Jerolmack, and B. McElroy (2011), The stratigraphic filter and bias in measurement of geologic rates, *Geophys. Res. Lett.*, *38*, L11405, doi:10.1029/2011GL047118.

1. Introduction

[2] It has been three decades since *Sadler* [1981] first demonstrated a ubiquitous pattern in the sedimentary record: measured deposition rate decreases as a power-law function of the interval of time over which it is measured, a phenomenon known as the "Sadler effect" [*Tipper*, 1983; *Strauss and Sadler*, 1989; *Pelletier*, 2007]. Original scaling trends were derived from global compilations of rates by depositional environment, leading some to question whether these results were an artifact of mixing data from different locations. Recent work shows, however, that individual basins [*Schumer and Jerolmack*, 2009] and landscapes [*Pelletier*, 2007] also exhibit scale-dependent rates when the stratigraphic record is largely incomplete. Incompleteness refers to the notion that only a small fraction of Earth surface evolution is preserved in the sedimentary record [*Sadler*, 1981], commonly the case because short term rates of erosion and deposition are typically orders of magnitude greater than the rate of generation of accommodation space [*Vail et al.*, 1977].

[3] Estimating rates of geologic processes is fundamental to determining the nature and tempo of Earth surface evolution. Measured erosion and deposition rates have been used to infer temporal changes in Earth's climate through geologic time [*Mills*, 2000; *Zhang et al.*, 2001] and abrupt increases in landscape evolution resulting from human activity [*Montgomery*, 2007; *Wilkinson and McElroy*, 2007]. However, correcting for the Sadler effect when interpreting the geologic record can alter conclusions drawn from straightforward rate analysis. For example, the apparent increase in global Earth-surface evolution during the last 10 million years [*Molnar*, 2004] can be explained by the Sadler effect [*Schumer and Jerolmack*, 2009; *Willenbring and von Blanckenburg*, 2010].

[4] Many models have been advanced to explain the Sadler effect. While *Sadler's* [1981] demonstration used periodic and deterministic variation of deposition rates, most others involve stochastic deposition/erosion via a random walk. Recent work shows that a power-law decrease in rate with measurement interval results from a power-law distribution of hiatuses (waiting times) between recorded events in the geologic record [*Schumer and Jerolmack*, 2009]. Power-law stratigraphic hiatus distributions can be a straightforward result of power-law periods of stasis with no surface erosion or deposition [*Ganti et al.*, 2011]. Here we provide a theoretical framework for demonstrating that all different types of randomness in the temporal evolution of Earth-surface elevation are converted to power-law hiatus distributions through the stratigraphic filter. This filter also allows us to infer the nature of randomness using apparent temporal scaling of geologic rates.

2. Theory

[5] We proceed with modeling the evolution of elevation of the Earth surface, $S_n(t)$, using a random walk (Figure 1) [*Kolmogorov*, 1951; *Dacey*, 1979; *Tipper*, 1983; *Strauss and Sadler*, 1989; *Pelletier and Turcotte*, 1997]. Positive and negative "jumps", X_1, X_2,…, represent episodes of surface deposition and erosion that occur in a constant time interval, Δt. We assume that these elevation fluctuations are identically distributed random variables, with distribution $F(x) = P(X_i)$, that may or may not be independent of one another. The position of the surface at epoch n is the sum of these fluctuations: $S_0 = 0$, $S_n = X_1 + \ldots + X_n$ (Figure 1a). If jumps have exponentially decaying tails, in the long time scaling limit S_n will be governed by Brownian motion. If jump distributions have heavy tails (decay more slowly than exponential), their sum will be governed by Levy motion [*Samorodnitsky and Taqqu*, 1994]. Correlation in identically distributed jumps leads to fractional Brownian (or fractional Levy) motion [*Bouchaud and Georges*, 1990]. We chose Brownian motion as the null case for surface motions. Alternatively, heavy-tail jumps might result from a deposition process that exhibits avalanching behavior, such as stacked deep-sea turbidites generated by gravity flows down the continental slope [*Rothman et al.*, 1994] while correlated (or anticorrelated) jumps might result from topographically-controlled erosion

[1]Division of Hydrologic Sciences, Desert Research Institute, Reno, Nevada, USA.
[2]Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, Pennsylvania, USA.
[3]Columbia Environmental Research Center, U.S. Geological Survey, Columbia, Missouri, USA.

0094-8276/11/2011GL047118

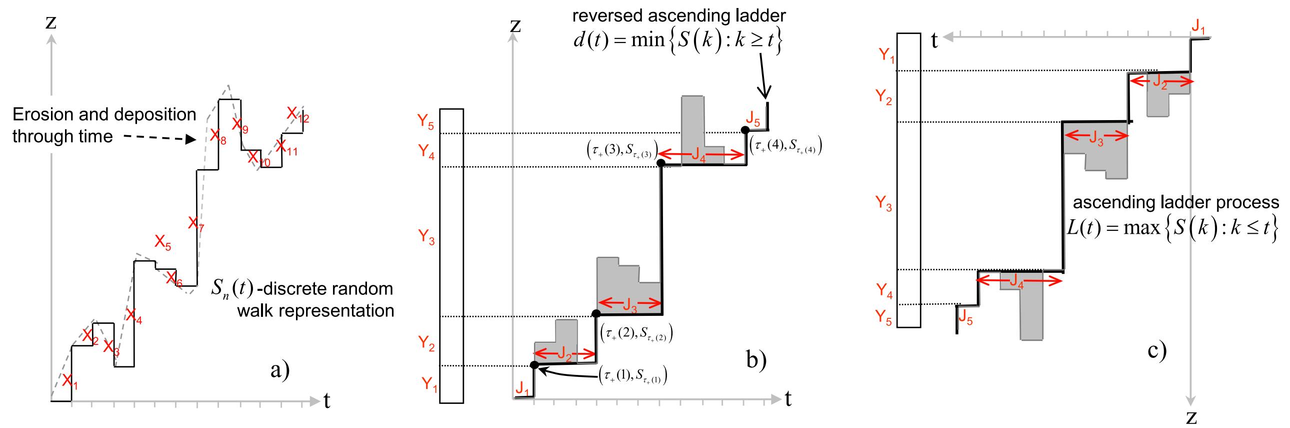

Figure 1. (a) The time series of surface location and its representation by a discrete random walk with random jump sizes over constant intervals. (b) The conversion of the random walk to its reversed ascending ladder process by the stratigraphic filter. Shaded area represents time not represented in the stratigraphic record. (c) If the random walk occurs backwards in time and space, the reversed ascending ladder process of Figure 1b becomes an ascending ladder process, recording running maxima.

and deposition such as diffusive processes [*Jerolmack and Sadler*, 2007; *Pelletier*, 2007].

[6] The stratigraphic filter converts Earth surface evolution $S_n(t)$ into the sedimentary record $d(t)$ by recording the lowest surface elevation (relative to a datum in the underlying rock column) that occurs after the present time: $d(t) = \min\ \{S(k) : k \geq t\}$ [*Pelletier and Turcotte*, 1997; *Molchan and Turcotte*, 2002]. The stratigraphic filter, $d(t)$, is a stochastic process known as a *reversed* ascending ladder [*Stam*, 1977]. This process mathematically summarizes the geological intuition that each stratum is a record of the most recent interval during which the surface occupied the corresponding stratigraphic position. Preserved portions of the depositional history, recorded in $d(t)$, are characterized by random hiatus lengths J_i with distribution G and random jumps Y_i corresponding with bed thickness (Figure 1b).

[7] Our goal is to relate the distribution governing deposition/erosional jumps F with the distribution of stratigraphic hiatuses G. We can rely upon results for ascending ladder processes, commonly used as tools in development of theory for maxima of stochastic processes, to relate these distributions because the reversed ladder process of a forward random walk (Figure 1b) corresponds with the ladder process $L(t) = \max\ \{S\ (k) : k \leq t\}$ of a reversed random walk (Figure 1c). Further, the distributions governing hiatuses and jump length densities of the reversed and non-reversed processes are identical [*Stam*, 1977]. We define random variables for a stochastic ascending ladder process as done by *Asmussen* [2003] or *Feller* [1971]; for the random walk with location $S_n = X_1 + \ldots + X_n$ we have $\tau_+ = \inf\ \{n \geq 1 : S_n > 0\}$ is the first ascending ladder epoch or entrance time to $(0, \infty)$, where $\inf\{\cdot\}$ is the infimum, or greatest lower bound, of the set in brackets and the colon in the brackets is read "such that". Also, $S_{\tau+}$ is the first ascending ladder height with distribution G^+, *i.e.*$P(S_{\tau+} \leq x) = G^+(x)$. It is possible to define whole sequences $\{\tau_+\ (n)\}$ of ladder epochs by iterating the definition of τ_+ so that successive ascending ladder points are independent and identically distributed (iid) replicates of each other: $\tau_+(1) = \tau_+$, $\{\tau_+\ (n+1) + \inf k > \tau_+\ (n) : S_k > S_{\tau+}(n)\}$. That is, the distribution of all fluctuations is the same (including the first ascending increment), regardless of the preceding elevation of the surface $\{S_n - S_{n-k}\}_0^n = \{S_k\}_0^n$. In this way, a random stratigraphic column can be built.

[8] The pairs $(\tau_+\ (n),\ S_{\tau_+(n)})$ are called ascending ladder points [*Asmussen*, 2003]. Importantly, $(\tau_+(n))$ is a discrete time renewal process (a stochastic model for events that occur randomly in time), and the ascending ladder height process $\{S_{\tau+}(n)\}$ is a renewal process governed by G+ [*Feller*, 1971]. These renewal processes have been used to describe hiatuses and bed thickness [*Schumer and Jerolmack*, 2009].

[9] Unless explicitly stated, the results described below were originally developed for ladder processes, rather than the *reversed* counterpart. For brevity, we use the terms *ladder heights* and *ladder epochs* when referring to jump sizes and waiting times of a stratigraphic renewal process. We rely upon results from ladder process theory to relate deposition and accumulation and consider an active surface undergoing continuous change. In this scenario, length of time represented in the stratigraphic record is a small fraction of total elapsed time because hiatuses in the sedimentary record result from incomplete preservation of up and down surface jumps, rather than periods of time where no surface elevation change occurred (as in *Ganti et al.* [2011]). Others have considered the distribution of deposition period length and hiatus length in modeling the stratigraphic record [*Molchan and Turcotte*, 2002].

[10] The distribution of stratigraphic hiatus length $\{J_n\}$ is uniquely determined by $P\{S_n > 0\}$ and vice versa via the Spitzer Baxter identities [*Feller*, 1971]:

$$\log \frac{1}{1 - J(s)} = \sum_{n=1}^{\infty} \frac{s^n}{n} P\{S_n > 0\}. \tag{1}$$

These calculations are not tractable for all forms of $P\{S_n > 0\}$ Focus instead has been on the existence of moments of the hiatus length density $J(s)$. Thus, information about the tails of the hiatus-length density gives information about the statistics of deposition and erosion. In the following sections, we identify and interpret the relationship between stratigraphic hiatus length density and patterns of erosion/deposition relevant to a variety of geologic settings.

3. Examples of Depositional Settings and Characteristics of Preserved Strata

[11] In a recent summary of Sadler's sediment accumulation data for fluvial and marine environments, scaling exponents were observed in the range $0.1 \leq \gamma \leq 0.5$ for timescales up to 10^4 yr [*Jerolmack and Sadler*, 2007]. *Pelletier* [2007] found $\gamma \approx 0.5$ for records of dust deposition over similar timescales. These settings with intermittent accumulation tend to show rates that decrease with increasing measurement interval as longer intervals are more likely to incorporate larger hiatuses. Similar logic explains erosion rates that appear to increase with measurement interval [*Kirchner et al.*, 2001] because infrequent pulses of extreme erosion are more likely to be captured in longer intervals. At longer timescales, all depositional environments in Sadler's data show γ approaching 1 (i.e., constant deposition rate), which *Jerolmack and Sadler* [2007] interpreted as (almost) steady drift driven by tectonic subsidence. The crossover timescale to (nearly) steady accumulation rate varies with environment: quiescent environments with less "noise," such as deep marine deposits, converge at relatively short timescales (10^2 yr), while more energetic environments such as alluvial plains do not converge until 10^4 yr or longer. By relating density F governing deposition/erosional increments $\{X_n\}$ and density G governing the random stratigraphic hiatus periods $\{J_n\}$ that render the record incomplete, we can determine the source of intermediate scaling. Note that both continuous, invariant deposition without erosion and deposition with a single, invariant erosion rate (the latter a geologically non-interpretable case) produce surface elevation that grows linearly with time. If stratigraphic hiatuses are heavy-tailed, the location of the surface grows sub-linearly [*Schumer and Jerolmack*, 2009].

3.1. Deposition Governed by a Classical Random Walk

[12] Under our null setting, Earth surface elevation follows a classical random walk (i.e., both deposition and erosion events are thin-tailed). Small drift, related to subsidence, may exist in this model. Since the depositional/erosional increments of the random walk are thin-tailed, the classical Central Limit Theorem [*Feller*, 1971] specifies that the random location of the surface S_n after a long time will be governed by a Gaussian density. In the long time limit, surface location is governed by Brownian Motion. The Spitzer-Baxter identities (equation 1) lead to the tail-behavior of the density governing stratigraphic hiatuses in this case [*Feller*, 1971]:

$$P(J > n) \sim n^{-1/2} \textit{ if } P(X > x) \sim x^{-\alpha}, \alpha \geq 2. \qquad (2)$$

A lack of heavy tails in random fluctuations produces a very heavy tail in hiatuses - that is, the probability of exceedance for large hiatuses decays as a power law with exponent less than one. These results support *Pelletier's* [2007] random walk model for dust accumulation. If there is not a strong bias between deposition and erosion, it is likely that large periods of time will be erased from the record leaving a large probability of extreme hiatus length. Equation (2) also holds for symmetric random walks with heavy tails, where F is in the domain of attraction of a symmetric stable law [*Doney*, 1980].

3.2. Deposition Governed by a Classical Random Walk With Significant Drift

[13] Thick accumulations of sediment require persistent generation of accommodation space, typically as a result of land surface subsidence. Subsidence may be thought of as a bias or drift in deposition that is added onto random fluctuations in erosion and deposition [*Jerolmack and Sadler*, 2007].This random walk model can be formulated as in Section 3.1 as a single density governing deposition/erosion with constant drift, or as the sum of random depositional $\{X_i\}$ and erosional increments $\{Z_i\}$ accommodating random (thin-tailed) subsidence rates: $S_n = (X_i - Z_i)$. In this case, we again find $P(J > n) \sim n^{-1/2}$, but only until the overall average deposition rate exceeds the variability in elevation fluctuations and there is convergence to exponential hiatuses and linear growth [*Asmussen and Schmidt*, 1993].

3.3. Deposition With Correlated Depositional Events

[14] In previous sections, we considered cases in which increments of deposition and erosion were uncorrelated in time. To relax this assumption, we use a fractional Brownian motion with drift to allow cases in which increments were positively (with Hurst coefficient $0.5 < H < 1$) or negatively correlated ($0 < H < 0.5$). An example of the latter comes from *Pelletier and Turcotte* [1997], who found that depositional increments in fluvial systems have $H = 0.25$ due to topographic diffusion. Examples of the former are not known in sediment deposition, but positively correlated increments have been observed in the motion of gravels in a river due to particle inertia [*Nikora et al.*, 2002].We are unaware of exact results regarding the ladder point densities for stochastic processes with long-range correlation, such as fractional Brownian motion, although *Molchan and Turcotte* [2002] show that they may fall off more slowly or quickly than the exponential distribution depending on H. We find numerically that for correlated increments, stratigraphic hiatuses decay as t^{-H}, $0 < H < 1$ (heavier tails than the null case for $H < 0.5$ and less heavy for $H > 0.5$) for a portion of the density and becomes thinner in the tails, particularly with drift. This implies that constant deposition rate will appear to decay as t^{H-1} and then converge to a constant value at late time. From a geological perspective, this means that a power-law distribution of hiatus density also could be directly attributed to long-range correlations in Earth surface processes.

4. Discussion and Conclusions

[15] The extent of stratigraphic completeness reflects the balance between deposition and erosion. The extent of incompleteness can be measured through the relative dependence of measured rate on measurement scale. The exponents measured in plots of rate against time provide a direct measure of the hiatus density distribution, γ. We can use the hiatus density distribution to move backwards through the stratigraphic filter. If the deposition process that gave rise to γ were (fractional) Brownian motion, then γ can be used to estimate the Hurst coefficient H that describes the nature of correlations in deposition increments. Preservation of heavy-tail magnitudes of deposition is likely limited to avalanching-type processes like landslides and turbidites, that deliver large pulses of sediment to locations where it is unlikely to be re-eroded. Although such a process would affect the

distribution of bed thickness, it should not yield a power-law stratigraphic hiatus distribution. Available depositional data suggest that most active sedimentary systems are either governed by Brownian motion or a fractional Brownian motion with negative correlations, across timescales up to 10^6 yr. Negative correlation means that a location experiencing deposition in one increment is less likely to experience deposition in the next increment. This concept is consistent with the notion of "compensational stacking," the tendency for sediment transport systems to preferentially fill topographic lows through deposition [*Straub et al.*, 2009].

[16] The analysis performed here has important implications for interpreting stratigraphy. The Earth's surface is continually reworked by bedform and river channel migration; landslides; debris flows and turbidity currents; and a host of other physical, chemical, and biological processes. Because kinematic rates of surface evolution typically can be orders of magnitude greater than the long-term rate of generation of accommodation space (e.g., subsidence), only a small fraction of Earth surface evolution is permanently preserved in the geologic record. This is the stratigraphic filter. Since virtually all depositional and erosional processes contain some degree of randomness, a natural framework for describing the stratigraphic filter is that of stochastic processes. With knowledge of the statistics of surface fluctuations, we may pass through the filter to predict bias in measurement rates – and potentially correct for it. Using Sadler plots of rate bias, we also may pass backward through the filter to determine the statistical nature of surface fluctuations. This scaling puts constraints on physical dynamics that govern deposition and erosion, and may represent a target for transport models.

[17] **Acknowledgments.** RS was supported by NSF grant EAR-0817073 and by NCED under NSF EAR-00120914. We thank the STRESS working group cosponsored by NCED and UIUC Hydrologic Synthesis (NSF EAR-0636043). The authors would like to thank Greg Tucker, Vamsi Ganti, Kyle Straub, Andy Petter and an anonymous reviewer for helpful comments.

[18] The Editor thanks the two anonymous reviewers for their assistance in evaluating this paper.

References

Asmussen, S. (2003), *Applied Probability and Queues*, 2nd ed., 438 pp., Springer, New York.

Asmussen, S., and V. Schmidt (1993), The ascending ladder height distribution for a certain class of dependent random walks, *Stat. Neerl.*, *47*(4), 269–277, doi:10.1111/j.1467-9574.1993.tb01423.x.

Bouchaud, J.-P., and A. Georges (1990), Anomalous diffusion in disordered media: statistical mechanisms, models and physical applications, *Phys. Rep.*, *195*(4–5), 127–293, doi:10.1016/0370-1573(90)90099-N.

Dacey, M. F. (1979), Models of bed formation, *J. Int. Assoc. Math. Geol.*, *11*(6), 655–668, doi:10.1007/BF01031890.

Doney, R. A. (1980), Spitzer's condition for asymptotically symmetric random walk, *J. Appl. Probab.*, *17*, 856–859, doi:10.2307/3212980.

Feller, W. (1971), *An Introduction to Probability Theory and Its Applications*, 2nd ed., 669 pp., John Wiley, New York.

Ganti, V., K. M. Straub, E. Foufoula-Georgiou, and C. Paola (2011), Space-time dynamics of depositional systems: Experimental evidence and theoretical modeling of heavy-tailed statistics, *J. Geophys. Res.*, doi:10.1029/2010JF001893, in press.

Jerolmack, D. J., and P. Sadler (2007), Transience and persistence in the depositional record of continental margins, *J. Geophys. Res.*, *112*, F03S13, doi:10.1029/2006JF000555.

Kirchner, J. W., R. C. Finkel, C. S. Riebe, D. E. Granger, J. L. Clayton, J. G. King, and W. F. Megahan (2001), Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales, *Geology*, *29*(7), 591–594, doi:10.1130/0091-7613(2001)029<0591:MEOYKY>2.0.CO;2.

Kolmogorov, A. N. (1951), *Solution of a Problem in Probability Theory Connected With the Problem of the Mechanism of Stratification*, *Am. Math. Soc. Transl*, *53*, 171–177.

Mills, H. H. (2000), Apparent increasing rates of stream incision in the eastern United States during the late Cenozoic, *Geology*, *28*(10), 955–957, doi:10.1130/0091-7613(2000)28<955:AIROSI>2.0.CO;2.

Molchan, G. M., and D. L. Turcotte (2002), A stochastic model of sedimentation: Probabilities and multifractality, *Eur. J. Appl. Math.*, *13*, 371–383, doi:10.1017/S0956792502004850.

Molnar, P. (2004), Late Cenozoic increase in accumulation rates of terrestrial sediment: How might climate change have affected erosion rates?, *Annu. Rev. Earth Planet. Sci.*, *32*, 67–89, doi:10.1146/annurev.earth.32.091003.143456.

Montgomery, D. R. (2007), Soil erosion and agricultural sustainability, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(33), 13,268–13,272, doi:10.1073/pnas.0611508104.

Pelletier, J. D. (2007), Cantor set model of eolian dust deposits on desert alluvial fan terraces, *Geology*, *35*, 439–442, doi:10.1130/G23367A.1.

Pelletier, J. D., and D. L. Turcotte (1997), Synthetic stratigraphy with a stochastic diffusion model of fluvial sedimentation, *J. Sediment. Res.*, *67*(6), 1060–1067.

Rothman, D. H., J. P. Grotzinger, and P. Flemings (1994), Scaling in turbidite deposition, *J. Sediment. Res. Sect. A*, *64*(1), 59–67.

Sadler, P. M. (1981), Sediment accumulation rates and the completeness of stratigraphic sections, *J. Geol.*, *89*(5), 569–584, doi:10.1086/628623.

Samorodnitsky, G., and M. S. Taqqu (1994), *Stable Non-Gaussian Random Processes: Stochastic Models With Infinite Variance*, 632 pp., Chapman Hall, London.

Schumer, R., and D. J. Jerolmack (2009), Real and apparent changes in sediment deposition rates through time, *J. Geophys. Res.*, *114*, F00A06, doi:10.1029/2009JF001266.

Stam, A. J. (1977), The reversed ladder of a random walk, *J. Appl. Probab.*, *14*, 190–194, doi:10.2307/3213272.

Straub, K. M., C. Paola, D. Mohrig, M. A. Wolinsky, and T. George (2009), Compensational stacking of channelized sedimentary deposits, *J. Sediment. Res.*, *79*(9), 673–688, doi:10.2110/jsr.2009.070.

Strauss, D., and P. M. Sadler (1989), Stochastic-models for the completeness of stratigraphic sections, *Math. Geol.*, *21*(1), 37–59, doi:10.1007/BF00897239.

Tipper, J. C. (1983), Rates of sedimentation and stratigraphical completeness, *Nature*, *302*(5910), 696–698, doi:10.1038/302696a0.

Vail, P. R., R. G. Todd, and J. B. Sangree (1977), Seismic Stratigraphy and Global Changes of Sea Level: Part 5. Chronostratigraphic Significance of Seismic Reflections, in *Application of Seismic Reflection Configuration to Stratigraphic Interpretation*, *AAPG Mem.*, 26, 99–116.

Wilkinson, B. H., and B. J. McElroy (2007), The impact of humans on continental erosion and sedimentation, *Geol. Soc. Am. Bull.*, *119*(1–2), 140–156, doi:10.1130/B25899.1.

Willenbring, J. K., and F. von Blanckenburg (2010), Long-term stability of global erosion rates and weathering during late-Cenozoic cooling, *Nature*, *465*(7295), 211–214, doi:10.1038/nature09044.

Zhang, P., P. Molnar, and W. R. Downs (2001), Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates, *Nature*, *410*(6831), 891–897, doi:10.1038/35073504.

D. Jerolmack, Department of Earth and Environmental Science, University of Pennsylvania, Hayden Hall, 240 S. 33rd St., Philadelphia, PA 19104-6316, USA.

B. McElroy, Columbia Environmental Research Center, U.S. Geological Survey, 4200 New Haven Rd., Columbia, MO 65201, USA.

R. Schumer, Division of Hydrologic Sciences, Desert Research Institute, 2215 Raggio Pkwy., Reno, NV 89512, USA. (rina@dri.edu)