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Abstract
Landscapes respond to climate, tectonic motions and sea level, but this response is mediated by sediment transport. Understanding transmission of environmental signals is crucial for predicting landscape response to climate change, and interpreting paleo-climate and tectonics from stratigraphy. Here we propose that sediment transport can act as a nonlinear filter that completely destroys ("shreds") environmental signals. This results from ubiquitous thresholds in sediment transport systems; e.g., landsliding, bed load transport, and river avulsion. This "morphodynamic turbulence" is analogous to turbulence in fluid flows, where energy injected at one frequency is smeared across a range of scales. We show with a numerical model that external signals are shredded when their time and amplitude scales fall within the ranges of morphodynamic turbulence. As signal frequency increases, signal preservation becomes the exception rather than the rule, suggesting a critical re-examination of purported sedimentary signals of external forcing.

Keywords
fractal, self-organized criticality, sequence stratigraphy, climate change, stochastic

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

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Shredding of environmental signals by sediment transport

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[1] Landscapes respond to climate, tectonic motions and sea level, but this response is mediated by sediment transport. Understanding transmission of environmental signals is crucial for predicting landscape response to climate change, and interpreting paleo-climate and tectonics from stratigraphy. Here we propose that sediment transport can act as a nonlinear filter that completely destroys (“shreds”) environmental signals. This results from ubiquitous thresholds in sediment transport systems; e.g., landsliding, bed load transport, and river avulsion. This “morphodynamic turbulence” is analogous to turbulence in fluid flows, where energy injected at one frequency is smeared across a range of scales. We show with a numerical model that external signals are shredded when their time and amplitude scales fall within the ranges of morphodynamic turbulence. As signal frequency increases, signal preservation becomes the exception rather than the rule, suggesting a critical re-examination of purported sedimentary signals of external forcing. **Citation:** Jerolmack, D. J., and C. Paola (2010), Shredding of environmental signals by sediment transport, *Geophys. Res. Lett.*, *37*, L19401, doi:10.1029/2010GL044638.

1. Introduction

[2] Changes in solar insolation (e.g., Milankovitch cycles) drive cyclic variation in precipitation, sediment supply and sea level over geologic time. Uplift and subsidence of the Earth’s crust create sources and sinks for sediment while changes in relative sea level drive the shoreline across the landscape. We generally assume that these processes are recorded in landscape patterns and sedimentary rocks (Figure 1), albeit with some level of distortion and filtering. In particular, it is generally assumed that even when external processes interact on similar time scales to autogenic (internally generated) ones, the latter act as a kind of noise that still allows some vestige of the external signal to be recorded. Assuming a one-to-one correlation between environmental forcing and sediment response requires that the sedimentary system either remain in equilibrium [*Kim and Jerolmack*, 2008], or respond to the forcing in a near-linear manner [*Paola et al.*, 1992; *Swenson*, 2005]. Typical landscape systems comprising a set of linked transport subenvironments can have multiple time scales, not all of which are currently well understood [*Allen*, 2008]; moreover, for most systems many external climatic, tectonic, and sea-level signals of interest have time scales well below any plausible equilibrium time [*Castelltort and Van Den Driessche*, 2003]. Thus we are faced with the problem of determining how sedimentary systems respond to relatively rapid external forcing.

2. Autogenic Fluctuations in Sediment Transport

[3] Even under steady boundary conditions, sediment transport rates in alluvial rivers [e.g., *Ashmore*, 1991; *Nikora et al.*, 2002; *Singh et al.*, 2009], hillslopes and mountain catchments [*Hasbargen and Paola*, 2000; *Lancaster and Casebeer*, 2007], river deltas [*Kim et al.*, 2006; *van Dijk et al.*, 2009; *Reitz et al.*, 2010], and dry granular flows [e.g., *Frette et al.*, 1996] undergo large-scale fluctuations (Figure 2). These transport fluctuations are a manifestation of the broader phenomenon of autogenic (self-organized) behavior in sedimentary systems [e.g., *Beerbower*, 1964; *Gaffin and Maasch*, 1991; *Muto and Steel*, 2001; *Kim et al.*, 2006; *Van De Wiel and Coulthard*, 2010; *Clarke et al.*, 2010]. Beginning with the classic *Bak et al.* [1987, hereafter BTW] sandpile model and studies of self-organized criticality, theoretical investigations suggested that the movement of sediment in some systems is driven by nonlinear threshold processes which result in power-law fluctuations of transport rate [see also *Hwa and Kardar*, 1992; *Van De Wiel and Coulthard*, 2010] (although other systems may actually undergo periodic fluctuations [*Kim and Jerolmack*, 2008; *Reitz et al.*, 2010], a topic not discussed here). There is even evidence that the signature of these nonlinear dynamics is preserved in some sedimentary deposits [*Rothman et al.*, 1994; *Gomez et al.*, 2002; *Schumer and Jerolmack*, 2009]. Based on simple numerical experiments with an externally fed version of BTW’s model, *Paola and Foufoula-Georgiou* [2001] suggested that autogenic transport fluctuations might strongly interfere with high-frequency input signals.

[4] In large-scale natural systems, transport fluctuations are often not directly observable owing to the time and space scales involved and/or the difficulty of separating them from stochastic external forcing (e.g., variable river discharge). We therefore examine time series of sediment transport rate, $q(t)$, from two different laboratory experiments: bed-load transport in a turbulent shear flow, using data from *Singh et al.* [2009]; and sediment efflux data from a pile of rice (see auxiliary material), after *Frette et al.* [1996]. The bed-load experiments simulate conditions of a small river, where turbulent fluid velocity fluctuations, grain-grain interactions and bed form migration are thought to contribute to sediment transport pulsing [*Nikora et al.*, 2002; *Singh et al.*, 2009]. Rice pile experiments serve as an analogue for landsliding [*Frette et al.*, 1996] and stick-slip sediment movement generally. The stochastic nature of transport

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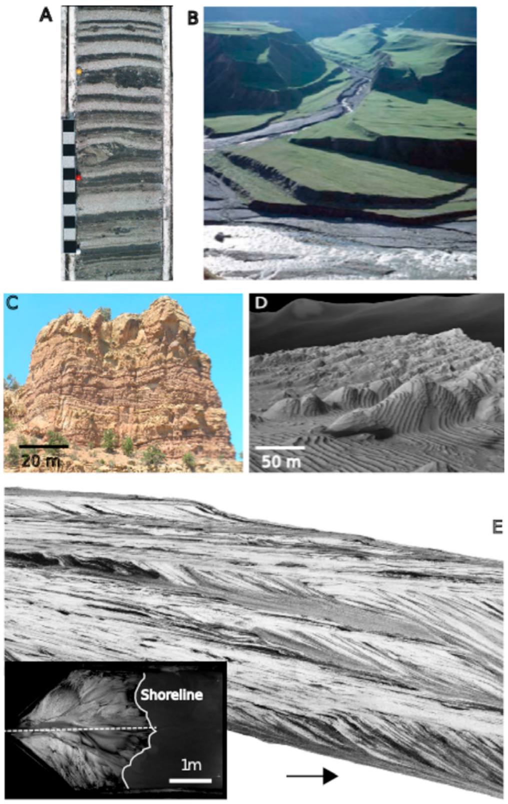

Figure 1. Deposition and landscape patterns may reflect external forcing or autogenic sediment transport dynamics. (a) Glacial varves (lake deposits) from Champlain Valley, New York. Scale bar markings are 1 cm. (Credit: Tufts University, North American Glacial Varve Project.). (b) Eroded river terraces. Scale Unknown. (Credit: http://www.coolgeography.co.uk/A-level/AQA/Year%2012/Rivers,%20Floods/Rejuvenation/Rejuvenation.htm.). (c) Ancient river deposits from the Book Cliffs, Utah. (d) Sequences of cyclic sedimentary rock layers exposed in Arabia Terra, Mars [*Lewis et al.*, 2008]. (Credit: Topography: Caltech; HiRISE Images: NASA/JPL/Univ. of Arizona.). (e) Deposits from eXperimental EarthScape Facility (run XES02) of a laboratory river delta (inset) with signatures of both autogenic dynamics and externally-forced sea level cycles. Arrow indicates flow direction. Inset shows plan view of delta; sediment was input at left edge, dotted line indicates stratigraphic dip section shown, shoreline of the delta is outlined.

fluctuations under steady forcing is evident for both systems (Figure 2). Here we define the magnitude of fluctuations, q', as the root mean square deviation of q over a given time t. Power spectra of $q(t)$ reveal the same general pattern for both systems. At short timescales there is a non-stationary regime in which spectral density increases as a power-law function of period (Figure 2). Physically this means that larger-scale fluctuations have larger characteristic timescales, and also suggests that fluctuations are correlated across a wide range of timescales. Fluctuations cannot increase without bound, however; system size (L) and the input rate of sediment (q_0) set an upper limit on the magnitude of q'. The characteristic timescale (T_x) associated with saturation of q' is a classic finite-size effect [*Hwa and Kardar*, 1992], which is expected to scale as

$$T_x \sim L^2/q_0. \tag{1}$$

At longer times spectra show a white-noise regime, which indicates that $q(t)$ is stationary and q' is uncorrelated at timescales $t > T_x$. The similarity in transport dynamics from these two very different systems suggests that the structure of the power spectra is a generic result of nonlinear transport.

[5] To test this hypothesis and the generality of equation (1) we examine the one-dimensional numerical rice pile model of *Frette* [1993]. Despite its simplicity, the model reproduces the generic behavior of the rice pile and bed-load experiments (Figure 3), and is consistent with dynamics from more complex models of landscape evolution [*Van De Wiel and Coulthard*, 2010]. This is because sediment transport fluctuations in both the experiments and the model result from a common mechanism: storage of sediment within the transport system, exceedance of some critical failure threshold, and release of sediment during relaxation following failure. T_x for the rice pile model is well predicted by equation (1) (Figure S1). The timescale of the largest avalanche is dictated by the time it takes to build a wedge of sediment to the critical angle. *Jerolmack and Paola* [2007] found the same behavior in a two-dimensional river delta model that simulated river channel creation and abandonment due to the threshold process of avulsion. For this system, T_x represented the time required for the entire channel to deposit to the critical threshold height for avulsion. The time scale condition $t > T_x$ is a necessary (though not sufficient) condition for sediment transport and deposition to reach steady state.

3. Modulated Turbulence and Signal Shredding

[6] Transport fluctuations seen in models and experiments (Figures 2 and 3) are reminiscent of fluid velocity fluctuations in turbulent flows. Velocity fluctuations (u') in the inertial regime increase as a power law function of the eddy turnover timescale (t) [*Frisch and Kolmogorov*, 1995]. The maximum eddy size is determined by flow depth (L), which – by Taylor's hypothesis – causes a peak in u' at the maximum eddy turnover timescale, $T_x \sim L/u_0$ (where u_0 is the average fluid velocity), in a manner exactly analogous to equation (1). In studies of modulated turbulence, the response of u' to periodic forcing of input energy has been found to be principally frequency dependent [*Binder et al.*, 1995]. For periods $T > T_x$, flow is quasi-steady and responds instantaneously to the gradually-varying boundary conditions. For periods $T < T_x$ the input energy is greatly modified by turbulence; in the limit $T \ll T_x$, variations in input energy have little influence on the statistics of the flow field [*Binder et al.*, 1995; *Cadot et al.*, 2003; *von der Heydt et al.*, 2003]. Turbulent velocity fluctuations thus behave as a nonlinear, frequency-dependent filter that destroys input signals having a period smaller than that of the largest eddies.

[7] It has long been recognized that the response of landscapes to variations in environmental forcing is also frequency dependent, because sediment transport imparts an inherent response time [*Paola et al.*, 1992; *Castelltort and Van Den Driessche*, 2003; *Swenson*, 2005; *Allen*, 2008]. But in general, it has been assumed that the filtering of the

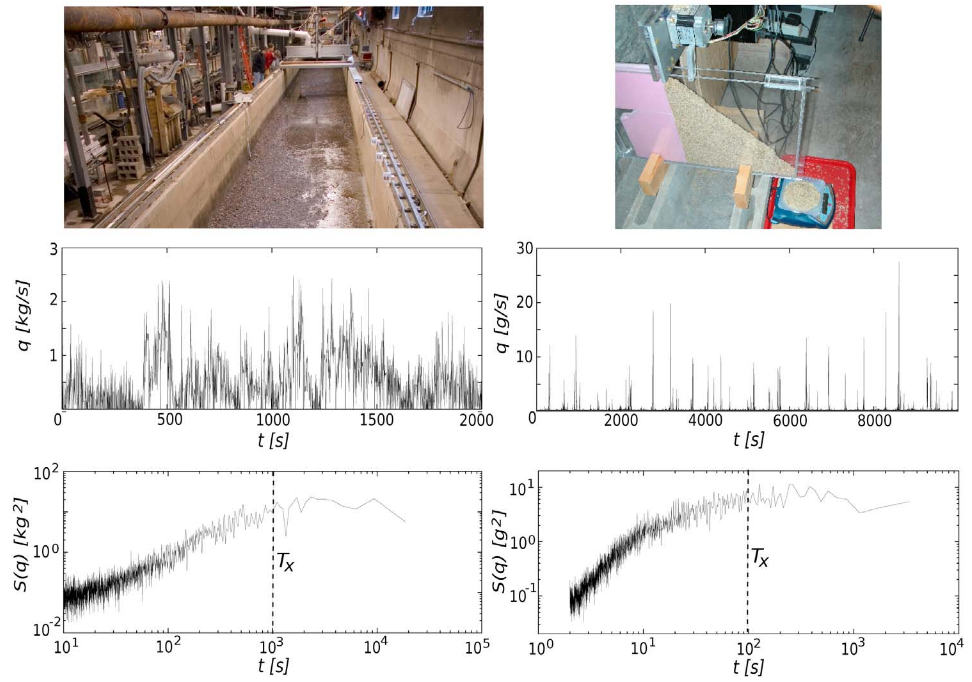

Figure 2. Experimental sediment transport data. (top, left) Bed load river transport [*Singh et al.*, 2009], where flow is from top to bottom. (right) Rice pile, where sediment is fed at a constant rate to the top of the pile while efflux is measured using an electronic balance. (middle) Instantaneous sediment transport rates, q, and (bottom) resultant (ensemble-averaged) power spectra. T_x is the empirically-determined saturation timescale.

input signal is linear in character, i.e. that while the signal may be damped, phase-shifted, and/or masked by noise, it is still present and in principle recoverable with the right kind of inverse filtering. Modulated turbulence, however, is an example of nonlinear filtering in which this is not the case. Previous workers have suggested analogies between landscape dynamics and turbulence [*Paola*, 1996; *Paola and Foufoula-Georgiou*, 2001]. The generic scaling of "morphodynamic turbulence" in the models and experiments presented here, and its similarity to the scaling of fluid turbulence, suggests (Figures 2 and 3) at least two different time-dependent regimes. In the nonstationary regime ($t < T_x$), spectra indicate correlations in transport fluctuations across a wide range of scales. Energy injected at one scale should smear across many scales, so environmental signals with a period $T < T_x$ are expected to be strongly modified as they propagate through the system. In the white noise (uncorrelated) regime ($t > T_x$) a perturbation should pass unimpeded (though with added noise), because the output signal is essentially a linear convolution of the input signal with a white noise. We explore this frequency dependence in the numerical rice pile model by imposing an environmental perturbation in the form of cyclically varying sediment supply (q_0), and analyzing $q(t)$ from the model outlet (Figure 4). For cycle period $T > T_x$, periodicity of the input signal is recorded in the output flux; sediment transport is quasi-steady and responds directly to the time-varying boundary condition. For $T < T_x$, the amplitude of the input signal decays rapidly with decreasing T over a narrow range, analogous to modulated turbulence [*von der Heydt et al.*, 2003]; for $T/T_x \leq \sim 0.6$, there is no evidence of periodicity in the output flux meaning that transport fluctuations obliterate the time-varying input signal (Figure S1). We confirmed that frequency-dependent signal shredding also occurred in the delta [*Jerolmack and Paola*, 2007] model.

[8] Signal amplitude must somehow play a role as well. In particular, a sufficiently large-amplitude input signal must be able to overwhelm the autogenic dynamics and pass through the transport system regardless of its time scale. Models suggest a clear upper magnitude limit to possible autogenic signals, associated with a single failure that extends over the whole length of the system. We term these events "system-clearing" events; for example a landslide or channel avulsion involving threshold exceedance over the whole system length. The magnitude M of the system-clearing event is set by the system size and threshold con-

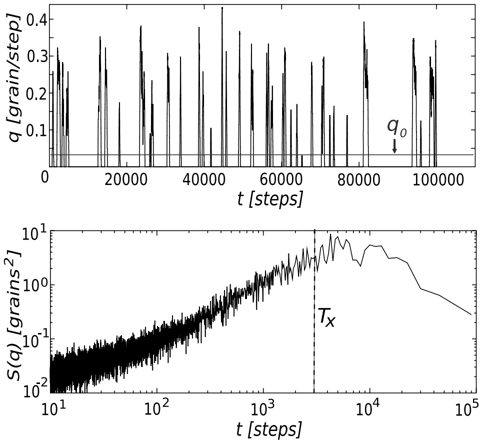

Figure 3. Numerical results for the rice-pile model, as in Figure 2. q_0 corresponds to the constant input rate of sediment.

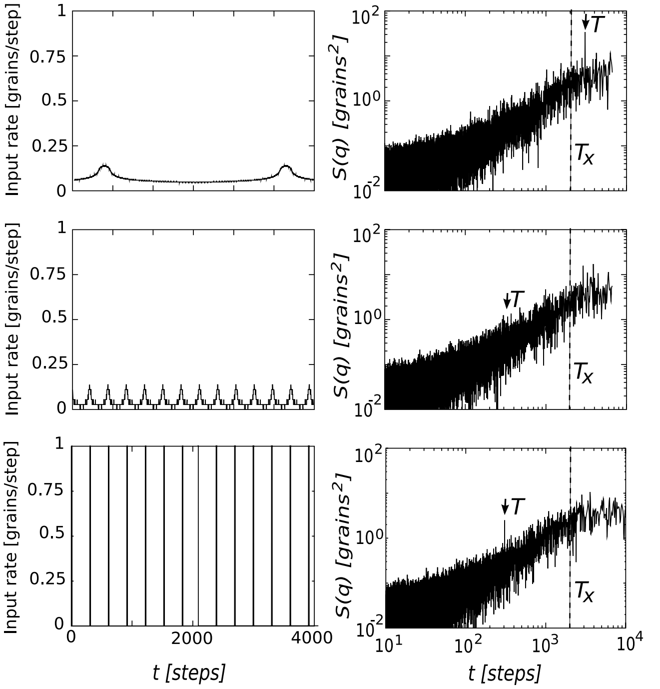

Figure 4. Numerical rice-pile results showing (left) variable cyclic sediment input rate and (right) the power spectra of sediment efflux. The arrows show the period, T, of the sediment input. (top) When $T > T_x$, the input perturbation is recorded in the output. (middle) For $T < T_x$, the input signal is shredded unless the magnitude of the perturbation is very large, i.e., (bottom) $M > M_{max}$. Note that signal propagation is not sensitive to the shape of the perturbation (e.g., sinusoid, saw-tooth, square wave, etc.).

dition; for example, in a 1D model with a threshold failure slope S_c, the limiting magnitude $M_{max} \sim L^2 S_c$. Figure 4 shows that an input signal with $T < T_x$ but $M > M_{max}$ is indeed passed through the transport system in the numerical rice pile model.

4. Challenges and Opportunities

[9] Most landscape evolution models predict that the equilibrium timescale (T_x) is an advection [*Whipple and Tucker*, 1999] or diffusion [e.g., *Paola et al.*, 1992] timescale, and that environmental signals with period $T < T_x$ are simply damped and lagged as they propagate through a transport system. We suggest that T_x is analogous to the maximum eddy turnover time that results from "morphodynamic turbulence". Signals with $T < T_x$ will be obliterated unless they are sufficiently large to overwhelm the autogenic fluctuations, i.e. $M > M_{max}$. Thus, the nonlinear dynamics of sediment transport sets a hard lower limit on the ability of stochastic transport systems to pass and record physical environmental signals. For a typical river delta system, for example, observed avulsion frequencies suggest that T_x could be several thousand years for large deltas such as the Mississippi [*Tornqvist et al.*, 1996]. Indeed, the stratigraphic record of continental shelf deposits indicates non-steadiness for timescales up to ~10^4 yr [*Jerolmack and Sadler*, 2007], while recent experimental results imply autogenic time scales that could be substantially longer than those associated even with major avulsions [*Kim and Paola*, 2007]. We estimate M_{max} to be on the order of *Lh* [*Reitz et al.*, 2010] for a river of depth *h*; i.e. about 5 km² for a Mississippi-scale river with a system length of 500 km and a depth of 10 m. It seems unlikely that a short-term external signal would exceed this threshold.

[10] Despite similar scaling, it is unlikely that morphodynamic turbulence is a dissipative effect like the turbulent energy cascade of a fluid. A hallmark of avalanching-type models is that damage propagates from small to large scales, such that the introduction of a single grain may cause a system-clearing event [*Bak et al.*, 1987; *Hwa and Kardar*, 1992]; hence, if anything, the cascade may be reversed. In addition, modulated turbulence studies have demonstrated a resonance behavior such that for perturbations with $T = T_x$, the magnitude of the signal is actually amplified [*Binder et al.*, 1995; *Cadot et al.*, 2003]. There are hints of this behavior in the numerical rice pile model (Figure S1), but the effect, if present, is not strong. Carefully controlled experiments, analogous to those of modulated turbulence [*Cadot et al.*, 2003], are needed to validate numerical models of signal shredding in sedimentary systems and determine its mechanistic basis. One way to maximize the preservation of externally applied signals is to eliminate nonlinearity. In a fluid, laminar flow minimizes the advective nonlinearity of transport such that mixing is significantly reduced. Quiescent sedimentary environments, such as deep-sea basins or small lakes that have minimal potential for stick-slip transport processes, may be the morphodynamic equivalent of laminar flows. These examples show how T_x and M_{max} provide a new tool for assessing landscape response to environmental perturbations and a motivation for better understanding of the mechanisms and length, time, and amplitude scales of autogenic dynamics.

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