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Some signals are not the same as they appear: How do erosional landscapes transform tectonic history into sediment flux records?

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ABSTRACT

A change in tectonics affects erosion rates across a mountain belt, leading to a period of non-steady sediment flux delivery downstream. The nonlinear relationship between tectonics and transient sediment delivery from an erosional catchment makes extraction of paleo-tectonic signals from stratigraphy challenging. We use a numerical landscape evolution model to explore how sediment flux from an erosional watershed responds to non-steady rock uplift. We focus on the time lag between the onset of a rock uplift change and the onset of a corresponding change in the sediment flux and the magnitude of the sediment flux relative to the steady rate. We observe that (1) sediment flux does not always record changes in the rock uplift rate when the duration of a rock uplift interval is less than 25% of landscape response time, or time for a landscape to transition from one steady state to another after a perturbation; (2) sediment flux response to variable rock uplift is positively correlated with the duration of rock uplift intervals; and (3) a nonlinear response between erosion rates and tectonic perturbations can result in increasing sediment flux through time even after rock uplift rate decreases. How quickly the sediment flux signal responds to a perturbation depends on how close the landscape was to steady state before the perturbation. These results illustrate conditions under which tectonic signals have the potential to be stored in the stratigraphic record or lost in an erosional system, and the importance of network dynamics for understanding signal propagation.

INTRODUCTION

Since Allen (1974) highlighted the complexity of source-to-sink signal propagation, several studies (Castelltort and Van Den Driessche, 2003; Allen, 2008; Armitage et al., 2011, 2013; Simpson and Castelltort, 2012; Romans et al., 2016) have explored how environmental signals are transmitted through the bypass zone or are transferred into stratigraphic records. However, internal river dynamics can lead to signal distortion or even destruction (Jerolmack and Paola, 2010; Li et al., 2016; Pizzuto et al., 2017). These studies help define the fidelity of stratigraphic records in sedimentary systems, but there remains a knowledge gap about which environmental signals are delivered to the bypass zone from an erosional landscape.

Numerical modeling studies have explored sediment flux signals from erosional landscapes (Tucker and Slingerland, 1996, 1997; Armitage et al., 2011, 2013; Forzoni et al., 2014; Mudd, 2016) and the morphology of transient erosional landscapes (Tucker and Whipple, 2002; Whipple and Tucker, 2002). These studies highlight that although parts of a landscape respond immediately to a change in rock uplift and/or climate, integrative variables like the sediment flux at the outlet of a watershed only reach a new steady state after the entire landscape has responded to a perturbation.

We use a numerical model to focus on the sediment flux time series from an erosional landscape subjected to repeated changes in the rock uplift rate. More specifically, we ask (1) under what conditions are changes in rock uplift rate simultaneously recorded in the sediment flux delivered from an erosional landscape, and (2) are all rock uplift changes recorded in the sediment flux? We frame our results using an analytical solution developed by Whipple (2001), which quantifies landscape response time as a function of variables such as climate, rock strength, and drainage area.

DESCRIPTION OF NUMERICAL MODEL AND EXPERIMENTS

We use the CHILD (channel-hillslope integrated landscape development) landscape evolution model (Tucker et al., 2001) (Fig. 1A) to examine the sediment flux response to rock uplift patterns (rock uplift is simplified to "uplift" hereafter.). We model fluvial incision using the detachment-limited stream-power model (SPM; e.g., Whipple and Tucker, 1999), which simulates bedrock incision as a power-law function of

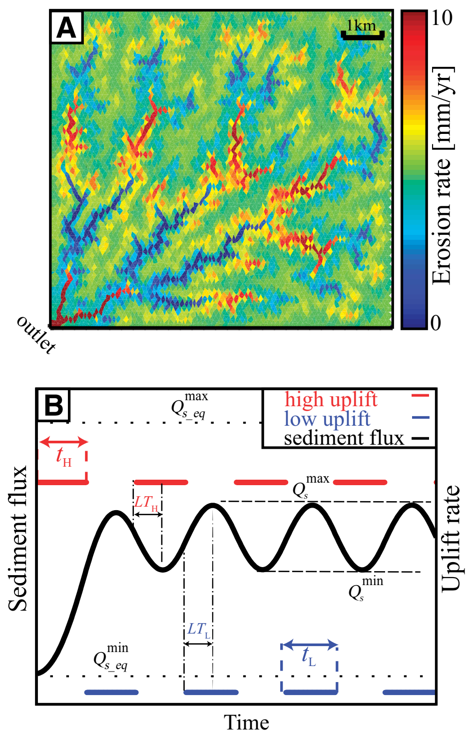

Figure 1. Maps and data from the model scenario with uplift period (*T*) = 75% of response time (*RT*) and high uplift percentage (P_H) equal to 50%. A: Erosion rate map of modeled landscape at 0.3 m.y. after the start of the perturbation of uplift rate. B: Schematic sediment flux time series. The dashed lines illustrate the maximum (Q_s^{max}) and minimum (Q_s^{min}) modeled sediment flux after the sediment flux reaches dynamic equilibrium. The dotted lines show the equilibrium sediment fluxes, $Q_{s\_eq}^{max}$ and $Q_{s\_eq}^{min}$, which are calculated as the product of drainage area of the erosional landscape and the high or low uplift rate, respectively. The dash-dot lines exhibit the low-uplift-rate sediment-flux lag time (LT_L) and high-uplift-rate sediment-flux lag time (LT_H).

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drainage area and slope, and does not allow for deposition of sediment (Table DR1 in the GSA Data Repository[1]). Sediment flux at the watershed outlet is calculated as the summation across the model domain of the product of local incision rate and local cell area. Similar to previous studies of signal propagation from an erosional system (Simpson and Castelltort, 2012; Armitage et al., 2013), we use a pulsed pattern of uplift in which the rate alternates between a low (1 mm/yr) and high value (10 mm/yr). The uplift period (T) is defined as the sum of the duration of one high (t_H) and one low (t_L) interval of uplift (Fig. 1B). The ratio of t_H to T is used to calculate the percentage of the period during which the uplift rate is high (P_H), and similarly low: $P_L = 100 \times t_L/T$.

The initial condition for all numerical experiments is a low-uplift-rate steady-state landscape. We perturb the initial steady state with the pulsed uplift pattern and vary T and P_H among the experiments. P_H and T are chosen based on the response time (RT), determined from model experiments (Table DR2 in the Data Repository). All experiments are run for 10^6 yr, allowing for at least five uplift periods. For each of the three T values, we perform four experiments with different P_H values. Based on these experiments, we conduct one more experiment with a longer period. Natural uplift histories are more complex than the repetitive uplift patterns that we model. However, we specifically use a simple experimental setup in order to maximize the potential for preserving a tectonic signal in the sediment flux.

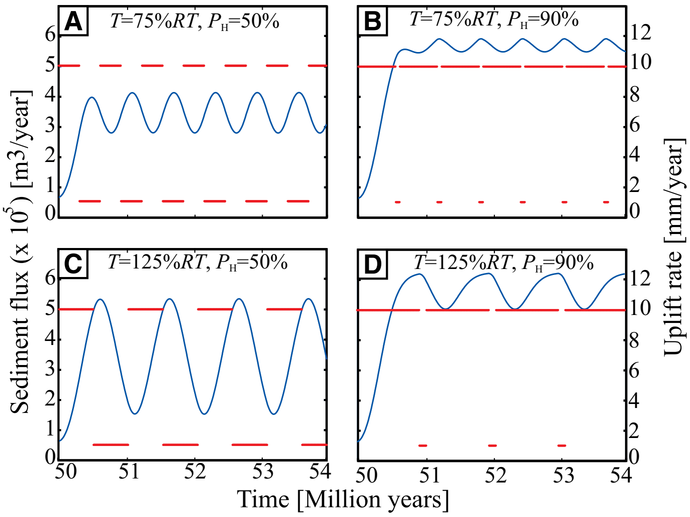

Figure 2. Time series of sediment flux for uplift perturbation experiments. Red lines represent the time series of uplift, and blue line shows how sediment flux responds to the change in uplift rate. *T*—uplift period; *RT*—response time; P_H—percentage of the period during which the uplift rate is high.

RESULTS

We first examine the time series of sediment flux at the watershed outlet (Figs. 1B and 2; Fig. DR1). A similar pattern is observed in each experiment. The sediment flux increases immediately when the uplift rate increases in the initial steady-state landscape. When uplift rate first decreases, the sediment flux does not decrease immediately except in the experiments where the duration of high uplift rate is greater than the response time (Fig. 2D; Fig. DR2). After an initial adjustment period, the duration of which varies depending on T and relative P_H, the sediment flux reaches a dynamic equilibrium with the tectonic forcing. At this point in all experiments, the sediment flux signal period is the same as that of T. However, the details of the sediment flux record, such as the time necessary for the sediment flux to respond to any given uplift change, and the magnitudes of the maximum and minimum sediment flux vary with T and P_H.

To quantify the influence of T and uplift interval duration (t_H, t_L) on sediment flux responses to the uplift change during dynamic equilibrium, we define and measure two variables: (1) the high-uplift-rate sediment flux lag time (LT_H), which is the time between the beginning of the high-uplift-rate interval and the beginning of an increase in the sediment flux; and, similarly, (2) the low-uplift-rate sediment flux lag time (LT_L) (Fig. 1B). In all experiments, the first lag time is zero because the initial landscape is in steady state.

Once dynamic equilibrium is reached, there is a time lag for the sediment flux to respond to uplift changes (both high and low), except in the experiments in which the landscape reaches steady state before uplift changes. We measure all lag times and calculate the mean dynamic equilibrium LT_H and LT_L for each experiment. In experiments with the same T, the LT_H value decreases as the t_L increases (Fig. 3A). An increase in the duration of the previous low-uplift-rate interval allows the landscape to be closer to low-uplift-rate steady state when the uplift rate increases. (Similar trends are observed with LT_L; Fig. DR3A.) By definition, LT_L

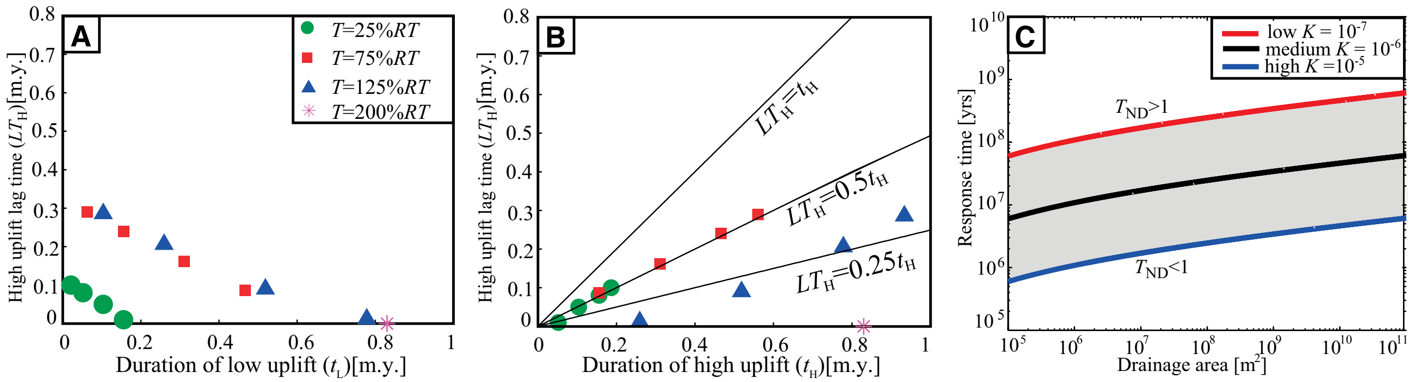

Figure 3. Variation in lag time and response time. A: High-uplift-rate sediment-flux lag time (LT_H) as a function of the duration of low uplift. *T*—uplift period; t_L —low-uplift-rate sediment-flux lag time. B: LT_H as a function of the duration of high uplift. Black lines illustrate where LT_H is equal to 25%, 50%, and 100% of the duration of high uplift rate. T_H —high-uplift-rate sediment-flux lag time. C: Response time changes with drainage area and erodibility coefficient, *K*. The blue, black, and red lines illustrate the response time as a function of drainage area for different erodibility values. Gray region shows the possible values of response time for different systems given this relatively wide range of erodibility values. If the time scale of tectonic perturbation is greater than the response time, or above the appropriate line, then non-dimensional time T_{ND} > 1, and we predict that there will be no lag time in the sediment flux response.

[1]GSA Data Repository item 2018131, supplemental discussion, Figures DR1–DR8, Tables DR1–DR3, and Movie DR1 (landscape evolution), is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

and LT_H are always smaller than t_L and t_H, respectively. For the experiments where the T is 25% of response time, LT_H approaches zero even though the duration of low uplift rate is far from the response time (Fig. 3A). In this scenario, the response in the sediment flux signal is due to an earlier change in uplift, not the most recent uplift change, but our method cannot discern this. We also noticed that the absolute value of lag times varies with spatial resolution, but the general behavior of sediment flux response to uplift changes do not vary (see Fig. DR8).

The ratio of lag time to the uplift duration indicates the degree to which the system is out of phase. For example, if $LT_H = 0.5\ t_H$, the sediment flux is continually decreasing for half of the high uplift period. There are cases in which the sediment flux is decreasing (increasing) for more than half of the high (low) uplift period (Fig. 3B; Fig. DR3B).

We also quantify the minimum and maximum observed sediment flux normalized by the equilibrium minimum and maximum sediment flux, $Q_s^{min}/Q_{s\_eq}^{min}$ and $Q_s^{max}/Q_{s\_eq}^{max}$, respectively. Comparing among the experiments with the same T, $Q_s^{max}/Q_{s\_eq}^{max}$ increases as t_H increases (Figs. 2 and 4A). This ratio also varies as a function of t_L, as illustrated by experiments with similar t_H but with different T (e.g., experiments within oval shape in Fig. 4A). Normalized maximum sediment flux only reaches 1 when t_H is equal to or greater than RT. We observe similar trends for normalized minimum sediment flux, except that $Q_s^{min}/Q_{s\_eq}^{min}$ decreases to unity as t_L increases (Fig. DR4).

These systematic changes in maximum and minimum sediment flux lead to a pattern in their difference, here referred to as ΔQ_s. For a given T, as P_H increases from 25% to 50%, ΔQ_s increases; as P_H increases from 50% to 90%, ΔQ_s decreases (Fig. DR1). However, for a given P_H, the difference between maximum and minimum sediment flux solely increases with the periodicity of uplift. These trends in ΔQ_s are observed even though the difference between the high and low uplift rates does not vary among the experiments.

To quantify how the uplift signals are preserved in the sediment flux records, we normalize ΔQ_s by the difference between maximum and minimum equilibrium sediment flux, or $\left(Q_s^{max} - Q_s^{min}\right)/\left(Q_{s\_eq}^{max} - Q_{s\_eq}^{min}\right)$. If this normalized value were 1, it would mean that the difference in observed sediment flux perfectly characterizes the expected difference based on the uplift rates. Otherwise, some information about tectonic signals is lost in the sediment flux signals. The ratio increases with increasing T (Fig. 4B, for a given t_H), which suggests the maximum and/or minimum sediment fluxes will be closer to their equilibrium values, and the implied uplift rates from the sediment flux are closer to the real uplift rates.

Even with the simple uplift patterns used here, some signals are not transmitted out of the erosional system. In the experiments with the shortest periodicity ($T = 25\%\ RT$) (see Figs. DR1A–DR1D), the sediment flux continuously increases even while the uplift rate is low during the entire first two periods. This indicates that the sediment flux might not record any information about short-duration uplift changes. This is because it takes time for uplift changes to propagate upstream (Fig. 1A). While the downstream part of the landscape can erode at a low rate due to a decrease in uplift rate, it will not be evident in the sediment flux if this signal has not reached a large enough part of the landscape. We note that signal propagation throughout an entire tributary network must be modeled to capture the lag time, and one-dimensional models might not reproduce these results (Figs DR6–DR8).

DISCUSSION

We are primarily interested in the lag time between uplift rate changes and sediment flux responses, and the necessary conditions for an uplift signal to be evident in the sediment flux record at the outlet of an erosional watershed. Although previous studies have shown that the peak erosion rate can lag behind uplift changes (Willenbring et al., 2013; Mudd, 2016), the influence of lag time on the details of the sediment flux history remains unknown. Under conditions of oscillating uplift rates, if the previous uplift interval is shorter than the response time, there will be a time lag between the sediment flux response and the uplift rate change. A change in uplift rate results in (nearly) immediate topographic adjustment only near the outlet of a watershed while most of the landscape is still adjusting to previous uplift changes. As a result, the sediment flux at the outlet of an erosional landscape, which averages erosion rates over the entire landscape, might still be dictated by previous uplift rates. As discussed by Mudd (2016), upstream signal propagation means that erosion rates measured from detrital cosmogenic radionuclides will not reflect current uplift rates.

To predict when there will be a lag time in the sediment flux response to an uplift rate, we define the ratio of the uplift duration (t_U) to the response time (RT, calculated using Whipple et al.'s [2001] equation 6, with $n = 1$) as the non-dimensional time (T_{ND}):

$$T_{ND} = \frac{t_U}{RT} = \frac{t_U}{k_a^{-m/n}\left(1-\frac{hm}{n}\right)^{-1}\left[\left(\frac{A}{k_a}\right)^{\frac{1}{h}\left(1-\frac{hm}{n}\right)} - x_c^{1-\frac{hm}{n}}\right] \Big/ K}, \quad (1)$$

where k_a and h describe the relationship between channel length (L) and drainage area (A) ($A = k_a L^h$) (Hack, 1957); K is the erodibility coefficient in the stream power model (SPM) which decreases with increasing rock strength and with less erosive climate conditions; x_c is distance from drainage divide to channel head; and m and n are the exponents on drainage area and slope, respectively, in the SPM. The response time is most sensitive to the erodibility coefficient (Fig. 3C). (Note that if $n \neq 1$, the response time will also vary as a function of the original uplift rate and the magnitude of uplift rate change.) The exponent on drainage area in Equation 1 is ~0.1 for a typical h value of 1.67 and $m = 0.5$, and $n = 1$. (For details of the parameters in Equation 1, see Table DR3). As a result, response time is not very sensitive to drainage area (Whipple and Tucker, 1999). Our modeling results suggest that: (1) there is a lag time when T_{ND} is smaller

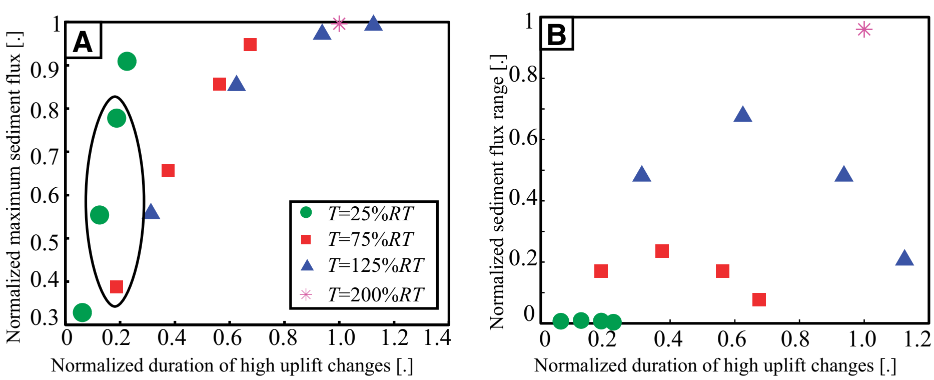

Figure 4. A: Normalized maximum sediment flux $Q_s^{max}/Q_{s\_eq}^{max}$ as a function of normalized high uplift rate duration (t_H/RT; t_H—high-uplift-rate sediment-flux lag time, RT—response time). T—uplift period. The experiments within the oval have similar t_H/RT ratio. B: Normalized sediment flux, $\left(Q_s^{max} - Q_s^{min}\right)/\left(Q_{s\_eq}^{max} - Q_{s\_eq}^{min}\right)$, as a function of t_H/RT. Dimensionless parameters are indicated by [.].

than 1; (2) the lag time increases as T_{ND} decreases; and (3) the previous uplift duration is the important value to consider for t_U (Fig. 3A). Based on Equation 1, T_{ND} is likely to be less than 1 in larger watersheds with harder rocks or less erosive climates (i.e., smaller K values).

We illustrate a number of cases in which the sediment flux is decreasing for at least half of the time when the uplift rate is high (Fig. 3B). Although these are not completely out of phase, these examples illustrate that caution should be taken when inferring recent uplift changes from sediment flux signals. Channel morphology (Kirby and Whipple, 2012), in conjunction with the sediment flux, can help one to accurately judge whether uplift rate has most recently increased or decreased. However, information on channel morphology is not usually available for past landscapes that produced the sediment flux stored in a sedimentary basin.

Similar to previous studies (Armitage et al., 2011; Forzoni et al., 2014; Mudd, 2016), our results also indicate that using sediment flux to reconstruct the magnitude of paleo-uplift rates can be incorrect without fully considering the nonlinear response of sediment flux to uplift changes, and the transient conditions of a landscape. In our study, the ratio between high and low uplift rate is constant, whereas the difference between the maximum and minimum sediment flux rate varies with the duration of high and low uplift rate (Fig. 4B; Fig. DR4B). In other words, both magnitude and duration of uplift control the normalized sediment flux difference, $\left(Q_s^{max} - Q_s^{min}\right)/\left(Q_{s\_eq}^{max} - Q_{s\_eq}^{min}\right)$, or ΔQ_s. Similar to the bypass zone and sedimentary system (Paola et al., 1992; Castelltort and Van Den Driessche, 2003; Pizzuto et al., 2017), a perturbation can be faithfully transmitted through the erosional system only when its duration is longer than the response time of the landscape. More generally, regardless of the mechanism that might filter environmental signals, signals with long periodicity have higher preservation potential than short-periodicity signals. With information on the duration of uplift rates and landscape response time, the quantitative thresholds presented in this study illustrate a condition when we can faithfully interpret past uplift rates from the sediment flux, assuming the stratigraphic filter also permits faithful signal preservation. Such conditions might occur in alluvial fans adjacent to an erosional watershed, such as in the Basin and Range Province of the United States. Even though we use a repeating pattern in uplift rate, our results are generalizable to any pattern, as it is the most recent uplift rate that matters the most.

Previous studies highlight that autogenic (internal) processes play an important role in dampening or destroying environmental signals (Jerolmack and Paola, 2010). Even without autogenic processes in our modeling, we find that relatively short duration changes in uplift rate may not translate to a signal in the sediment flux. The most likely interpretation of a sedimentary deposit in which the sediment flux steadily increased with time would not be that upstream uplift rates increased and decreased through time. However, our results suggest that this is a possibility (Figs. DR1A–DR1D).

Under the simplest of circumstances, we place a quantitative threshold similar to previous studies (Paola et al., 1992; Castelltort and Van Den Driessche, 2003) on the necessary duration for an uplift event to be clearly stored in the sediment flux record at the outlet of an erosional watershed. Lag times and dampening of the sediment flux signal with respect to what would be expected under steady-state conditions could complicate our ability to reconstruct tectonic histories. However, knowledge of the controls on lag time and ΔQ_s will help overcome some of these complications, thus reducing error in our interpretation of tectonic signals from the ancient record.

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