Hillslope evolution by nonlinear creep and landsliding: An experimental study

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ABSTRACT

Landscape evolution models are widely used to explore links between tectonics, climate, and hillslope morphology, yet mechanisms of hillslope erosion remain poorly understood. Here we use a laboratory hillslope of granular material to experimentally test how creep and landsliding contribute to hillslope erosion. In our experimental hillslope, disturbance-driven sediment transport rates increase nonlinearly with slope due to dilation-driven granular creep, and become increasingly episodic at steep slope angles as creep gives way to periodic landsliding. We use spectral analysis to quantify the variability of sediment flux and estimate the slope-dependent transition from creep to landsliding. The power spectrum of sediment flux steepens with hillslope gradient, exhibiting fractal 1/*f* scaling just below the creep-landsliding transition. By evolving the experimental hillslope under fixed base-level boundary conditions, we demonstrate how disturbance-driven transport generates hillslope convexity. The transient evolution is consistent with numerical predictions derived from a recently proposed nonlinear transport model, as initially steep hillslopes are lowered rapidly by landsliding before slopes decay slowly by creep-dominated transport.

Keywords: geomorphology, landscape evolution, hills, sediment transport, landslides, soil mechanics.

INTRODUCTION

Hillslope erosion regulates topographic relief, sediment yield, and geomorphic response to tectonic forcing and climate change (Penck, 1953; Burbank et al., 1996; Small and Anderson, 1998; Whipple et al., 1999). Many models of hillslope erosion have been proposed (e.g., Culling, 1960; Ahnert, 1976), but supporting evidence is sparse because hillslope processes can be stochastic, slow, and difficult to measure. Davis (1892) and Gilbert (1909) first hypothesized that in the absence of overland flow, the upward convex form of soil-mantled hillslopes results from local, episodic disturbances (e.g., tree throw, animal burrowing, and wet-dry cycles) that detach and transport sediment downslope. Culling (1960) hypothesized that sediment flux varies proportionally with hillslope gradient, and ever since, this linear transport model has been widely used to simulate hillslope erosion and predict landscape response to tectonic forcing and/or climatic change (e.g., Koons, 1989; Rinaldo et al., 1995). Field studies support a linear transport model for hilltops, where gradients are low (McKean et al., 1993; Small et al., 1999), but below the ridge crest, hillslopes become increasingly planar, inconsistent with the constant-curvature form predicted by the linear model (Anderson, 1994; Howard, 1994; Roering et al., 1999). Nonlinear models (that indicate that sediment flux rises rapidly as slopes approach a critical value) help to explain the observed downslope decrease in hillslope convexity. Whereas previous studies suggest that as hillslopes steepen, increasing landslide frequency may generate a nonlinear increase in sediment flux (Kirkby, 1984; Anderson, 1994; Howard, 1994), it has been proposed that the nonlinearity may result from disturbance-driven (or creep) mechanisms alone (Roering et al., 1999). Here we use an experimental, laboratory-scale hillslope to quantify transport processes and their influence on hillslope morphology and evolution.

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EXPERIMENTAL HILLSLOPE

To quantify the relationship between sediment flux and gradient over observable time scales, we used a laboratory hillslope of granular material (0.7-mm-diameter sand), enclosed in a Plexiglas box (120 cm long by 60 cm high by 10 cm wide) with open ends. We set the ratio of grain diameter to box width greater than 120 to negate boundary effects, such as grain arching (Aalto et al., 1997; Grasseli and Herrmann, 1997). In natural soil-mantled landscapes, soils typically exhibit high frictional strength and/or significant cohesion due to interparticle forces or root reinforcement (e.g., Schroeder and Alto, 1983). In order for sediment transport to occur, disturbances (such as biogenic activity, tree throw, and wet-dry cycles) must overcome the shear strength afforded by friction and cohesion to transport soil downslope. Similarly, sand grains in our experimental hillslope are stabilized by frictional contacts with neighboring grains, such that disturbances are required to displace grains on slopes below the angle of repose. To simulate natural, disturbance-driven soil transport processes, we vibrated our model hillslope with noise from a large speaker coupled to the sandbox. This acoustic mechanism allowed for consistent, repeatable, and efficient disturbance of a thin layer of grains along the sandpile surface. To minimize potential frequency bias in our sandbox, we used random acoustic noise with intensity equal to 0.05 W/m^2 to drive sediment transport.

The steady vibration causes a thin layer of sand grains along the sandpile surface to dilate and creep downslope (e.g., Ristow, 1996), while the underlying grains remain static (Fig. 1A). This behavior is similar to that observed on natural, soil-mantled hillslopes, where a thin ($<$1 m) veneer of mobile regolith mantles the underlying bedrock. In our experimental hillslope, the vibration magnitude is small enough that creeping grains maintain constant frictional contact with their neighbors. With the cessation of vibration, granular motion stops immediately, suggesting that vibration imparts inertial forces that are small relative to gravitational and frictional forces acting near the sandpile surface. As in soil transport on natural hillslopes (e.g., Young and Rapp, 1978), the thickness of the actively creeping sand layer is a small fraction of the total hillslope relief (Fig. 1A) and grain flow is approximately slope parallel, with velocities highest at the sandpile surface and decreasing rapidly with depth (Fig. 1B).

Natural hillslopes remain soil-mantled only if the landscape lowering (or erosion) rate does not exceed the rate at which bedrock is converted to soil (Heimsath et al., 1997). While our experimental hillslope does not account for weathering, cohesion, and variable soil properties that occur in natural landscapes, it may capture the high shear strength character of coarse hillslope soils. Although our exper-

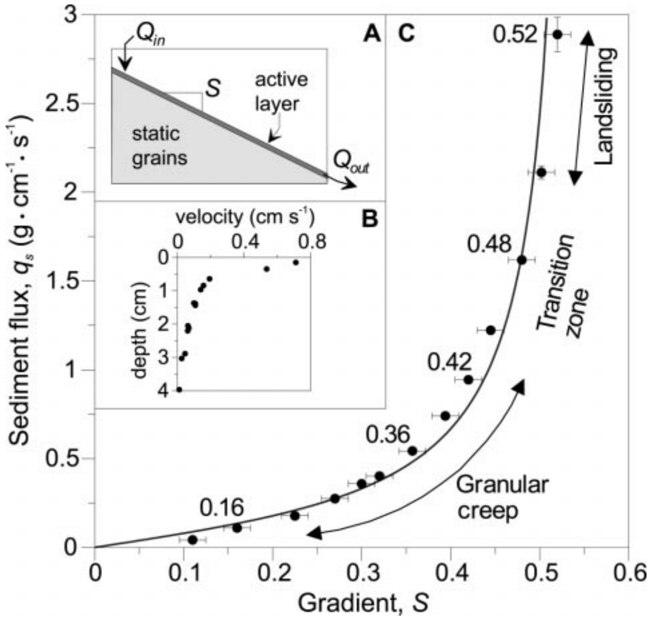

Figure 1. A: Schematic of steady-state sediment transport experiments. Sand was fed at constant rate onto top of hillslope. Active grain transport only occurs within thin surface layer ~5% of entire sandpile thickness. Spatially uniform, steady-state equilibrium slope gradient, *S*, is measured when $Q_{in} = Q_{out}$, where Q is sediment flux. B: Typical grain velocity profile (measured normal to surface) for sandpile with gradient equal to 0.4. C: Relationship between sediment flux and slope gradient in our experimental hillslope. Curve indicates flux predicted by equation 1 with calibrated values of K = 0.77 ± 0.05 g·cm^{-1}·s^{-1} and S_c = 0.56 ± 0.02 (obtained by minimization of least normal squares). Data labels indicate gradient values for time series and spectra shown in Figure 2. Gradient-dependent creep-landsliding transition was deduced from sediment flux time series illustrated in Figures 2 and 3.

imental mechanism for disturbing sediment clearly differs from the mechanisms that operate in nature (such as biogenic disturbances or rheologic creep related to wet-dry cycles), the resulting transport of a thin sediment layer may mimic the disturbance-driven, dilatational behavior of naturally transported soils.

VARIATION OF SEDIMENT FLUX WITH SLOPE GRADIENT

To measure the relationship between sediment flux and hillslope angle, we used the experimental hillslope to quantify sediment transport rates along slope sections with constant gradient. Specifically, we fed sand at a uniform rate onto the top of the sandpile and established a steady-state transport regime, in which the average fluxes into and out of the sandbox were equal and the transport rates were spatially uniform (Fig. 1A). We measured the spatially uniform, steady-state hillslope angle at different sediment supply rates, thereby determining the relationship between sediment flux and slope. Sediment flux on our laboratory hillslope increases linearly with slope at low gradients (0.1–0.3), but becomes highly nonlinear at gradients greater than ~0.3 (Fig. 1C). This empirical flux curve is inconsistent with the linear transport law, but is well described by a two-parameter, nonlinear transport model (Andrews and Bucknam, 1987; Roering et al., 1999) in which sediment mass flux, q_s, varies with hillslope gradient, S, according to:

$$q_s = \frac{KS}{1 - (S/S_c)^2}, \qquad (1)$$

where K is a mass transport rate constant (g·cm^{-1}·s^{-1}) and S_c is a critical gradient. According to this model (for which the only previous supporting evidence is topographic data; Roering et al., 1999), sediment transport increases linearly with gradient when $S \ll S_c$, but rises rapidly toward infinity as S approaches the critical value S_c. The derivation of equation 1 assumes that simple disturbance-driven soil creep, not landsliding, underlies the nonlinearity.

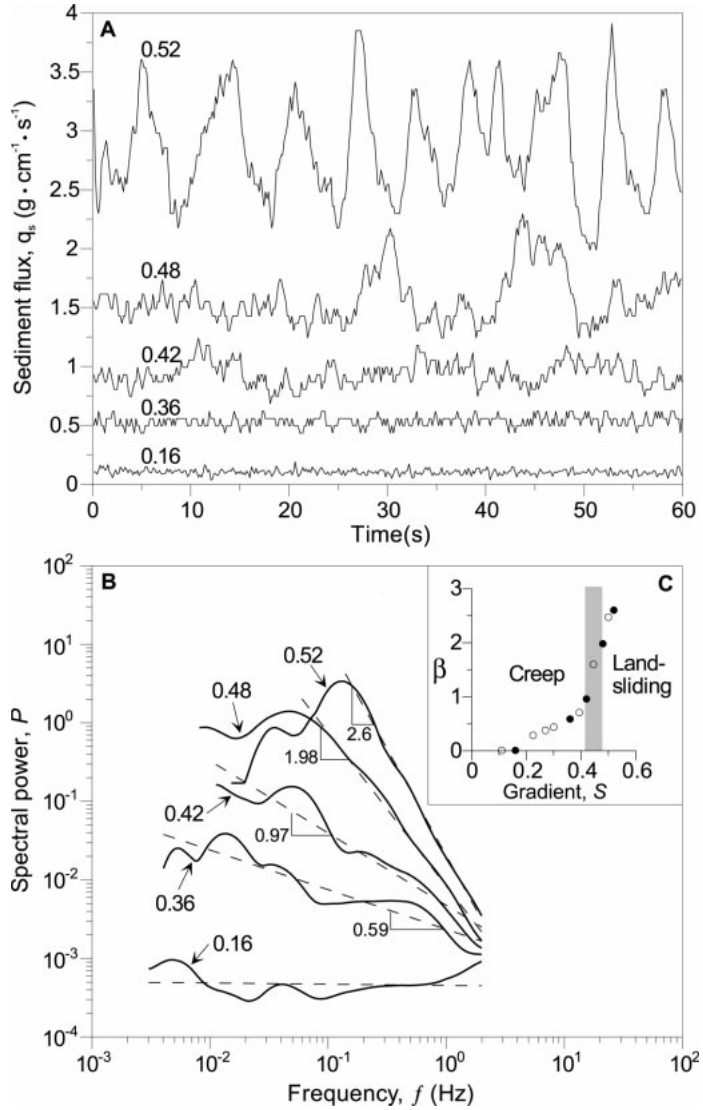

Figure 2. A: Typical flux time series for five labeled points in Figure 1C. Rapid pulses of sediment flux indicate landsliding. Sediment flux from our laboratory hillslope was measured with computer-interfaced digital balance (sampling frequency = 6 Hz). B: Average flux power spectra for time series shown in A. For each gradient (denoted with bold numbers and arrows), we calculated fast Fourier transform of several flux time series and averaged the resulting spectra (black solid lines). Dashed lines and slope measurements denote power-law fits to individual spectra and corresponding values of power-law exponent, β, where P ∝ $f^{-\beta}$. For gradients greater than 0.42, we fit β for frequencies greater than spectral peak (i.e., steep, right side of spectra). C: Variation of spectral power-law exponent, β, with sandpile gradient. Closed circles indicate values for spectra shown in B. Thick gray band denotes transition from granular creep to landsliding.

MECHANISMS OF SEDIMENT TRANSPORT

Time series of sediment discharge from our laboratory hillslope (Fig. 2A) show that granular avalanches dominate transport for $S \geq 0.5$, well above the nonlinearity of our empirical flux curve. On gentle slopes, sediment transport is driven by local grain dilation and downslope creep; a typical time series for low-gradient ($S = 0.16$) transport indicates that flux rates are fairly uniform (Fig. 2A). The thin layer of mobile grains resembles a flowing carpet, moving steadily over the entire hillslope. As gradient increases, fluxes become more variable, although for slopes below ~0.48 there is no evidence of discrete sediment pulses (i.e., avalanching or landsliding). At $S \cong 0.48$, long periods of relatively uniform flux are interrupted by nonperiodic landslides of variable size and duration. With further steepening of the sandpile, we observe shorter and shorter periods of relatively steady flux and increasingly frequent granular instabilities. These slope-clearing landslides, which become prevalent when slope angles equal or exceed a critical value related to the angle of repose (Evesque, 1991; Jaeger and Nagel, 1992), are several grain diameters in depth and tend to initiate near the upper slope. Mechanistically distinct from the grain-by-grain dilation observed on low-gradient slopes, the threshold-controlled landslides develop from slope-parallel failure surfaces and travel downslope as discrete waves overriding the creep-dominated layer of mobile grains. At the highest gradient ($S = 0.52$), sediment flux variability is dominated by periodic landslides and we do not observe periods of relatively uniform flux.

The power spectra of sediment fluxes from our experimental hillslope further illustrate the transition from granular creep to periodic landsliding (Fig. 2B). At low gradients, the flux spectrum scales roughly as white noise, because there is no well-defined periodicity in the sediment outflow. As gradients increase toward $S \cong 0.48$, the slopes of the power spectra steepen, but show no evidence of periodic landsliding. For $S = 0.48$, sporadic landsliding is manifested by a broad spectral peak spanning frequencies between 0.01 and 0.08. In contrast, the sediment flux spectrum at a slightly higher gradient ($S = 0.52$) is dominated by a distinct peak, reflecting discrete, periodic landsliding with a recurrence interval of ~7 s. The onset of landsliding occurs on slopes well above the nonlinearity of our empirical sediment flux relationship (which is greatest between gradients of 0.3 and 0.42; see Fig. 1C). Our results suggest that a nonlinear relationship between sediment flux and slope may be an intrinsic property of disturbance-driven creep in granular materials, owing to the interactions between frictional and gravitational forces (e.g., Evesque, 1991; Jaeger and Nagel, 1992).

Because it is a continuum model, equation 1 cannot be used to predict how hillslope gradient affects the temporal variability of flux or triggers the transition from granular creep to landsliding (as reflected in the spectral analyses). Unexpectedly, our experiments indicate that the power-law slope of the flux spectrum, β (where $P[f] \propto f^{-\beta}$) increases with the slope of the sandpile (Fig. 2C). At $S \cong 0.42$, we observe approximate fractal $1/f$ scaling over two orders of magnitude, even though transport is dominated by granular creep rather than discrete avalanches. Models of self-organized criticality predict that the internal dynamics of a uniformly perturbed granular pile should generate avalanches with fractal $1/f$ scaling (Bak et al., 1987). Our results suggest that $1/f$ scaling may be coincident with a process threshold and thus, a transition in the dominant mechanism controlling the sediment flux variability. At steep gradients, β increases rapidly, reflecting the increasing importance of periodic landslides (Fig. 2C).

HILLSLOPE EVOLUTION: FIXED BASE-LEVEL BOUNDARY CONDITIONS

Numerical landscape evolution models have been widely applied (e.g., Ahnert, 1976; Koons, 1989; Willgoose et al., 1991; Tucker and Slingerland, 1997) to predict how tectonic and climatic forcing may affect erosion and landscape morphology. To explore the development of hillslope convexity and how the transition between creep and landsliding may affect hillslope evolution, we evolved our experimental hillslope and compared its transient behavior with numerical predictions using equation 1. Initial and boundary conditions of natural hill-

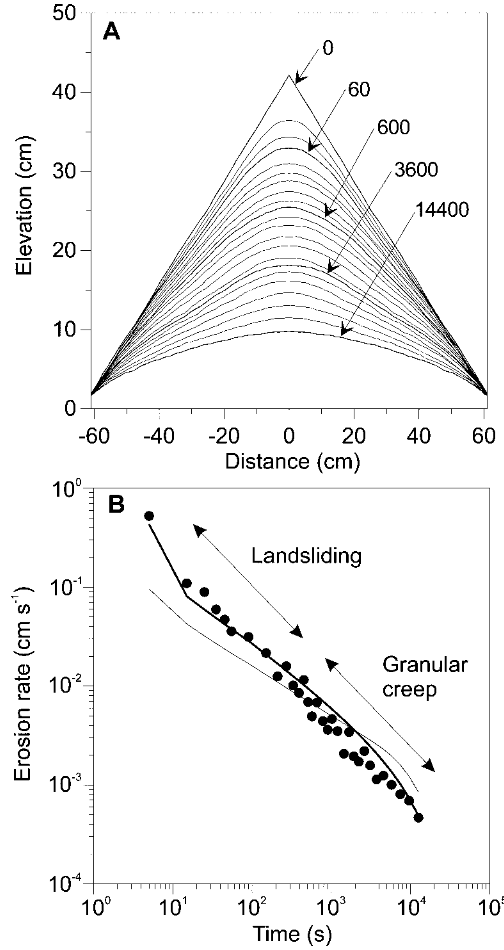

Figure 3. A: Profiles of sandpile evolution with fixed boundaries. Labeled arrows indicate simulation time in seconds. Time increments between labeled profiles increase nonlinearly with simulation time. B: Time series of average hilltop ($x = 0$) erosion rate for experimental hillslope (solid circles), nonlinear transport model (equation 1, thick line) with parameters indicated in Figure 1C, and linear transport model ($q_s = K_{lin} S$, thin line) with best-fit value of K_{lin} = 1.25 $g \cdot cm^{-1} \cdot s^{-1}$. For experimental hillslope, average hilltop erosion rates were calculated by dividing difference between successive elevations of sand hilltop by time interval. For numerical model, we calculated average hilltop ($x = 0$) erosion rates by subtracting difference between successive numerically generated profiles and dividing by time interval.

slopes are often difficult to define, so we used our experimental apparatus to simulate the simple case of an initially steep (~34°) and planar hillslope with fixed boundaries (Fig. 3A). With the onset of sediment transport, convexity spread outward from the crest as the sandpile lowered. Initially, the crest eroded rapidly as landsliding removed large amounts of material from the hillslope (Fig. 3B). Continued erosion and broadening hillslope convexity decreased the length of hillslope affected by landsliding, such that after 600 s, gradients across most of the hillslope were below 0.45 and transport occurred primarily by granular creep.

With continued erosion of the experimental hillslope, the boundary between mobile and stable grains (analogous to the soil-bedrock interface) lowered, such that transport processes remained active at the sandpile surface. This observation is consistent with Ahnert's (1987) assertion that the morphologic evolution of soil-mantled hillslopes is governed by transport processes in the mobile regolith layer and not by interactions along the soil-bedrock surface.

We used a numerical model to predict the evolution of the experimental hillslope by combining equation 1 with the one-dimensional continuity equation and calculating transient hillslope profiles with an explicit finite difference algorithm. Our nonlinear transport model predicts the initial period of rapid erosion associated with landsliding followed by slower, creep-dominated topographic decay (Fig. 3B). In contrast, even when it is fitted directly to the erosion rate time series, the linear transport model systematically deviates from the experimental data and fails to predict rapid erosion associated with landsliding on steep slopes.

DISCUSSION AND CONCLUSIONS

Whereas previous studies have relied on topographic data to evaluate and constrain sediment transport models (e.g., Howard, 1994; Roering et al., 1999), our experiments demonstrate for the first time that disturbance-driven sediment transport rates depend nonlinearly on hillslope gradient. This result has important implications for understanding hillslope morphology and how it is influenced by tectonics and climate. As elaborated by Gilbert (1909), on a uniformly eroding hillslope, sediment flux must increase systematically downslope of the hilltop. Nonlinear transport models indicate that on steep hillsides, small increases in slope correspond to large increases in sediment flux, which helps to explain why hillslopes tend to be most convex at their crest and become increasingly planar downslope. High sediment transport rates associated with steep slopes indicate that hillslopes may rapidly adjust their morphology to changing rates of base-level lowering related to tectonic forcing or climate change. In addition, nonlinear transport on hillslopes implies that gradient and relief may be insensitive indicators of tectonic forcing (Burbank et al., 1996). Contrary to previous studies, our results imply that disturbance-driven creep and the associated interaction between frictional and gravitational forces produce a nonlinear relationship between sediment flux and gradient. Time series and spectral analyses demonstrate that landsliding occurs on steep slopes in our experimental hillslope but is not required to generate the nonlinearity of our empirical flux-gradient relationship. Finally, our experiments demonstrate that disturbance-driven sediment transport generates convex hillslopes.

In our experiments, the transition from relatively uniform granular creep to episodic landsliding coincided with a small increase in hillslope gradient. This result suggests that landscape response to changing rates of uplift may regulate mechanisms of hillslope erosion, producing a discernible signature in sedimentary deposits. For example, periods of episodic sediment delivery, as recorded in local colluvial deposits, may result from landsliding associated with minor increases in hillslope steepness, as opposed to large shifts in climate.

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