Experimental evidence for fluvial bedrock incision by suspended and bedload sediment

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ABSTRACT

Fluvial bedrock incision sets the pace of landscape evolution and can be dominated by abrasion from impacting particles. Existing bedrock incision models diverge on the ability of sediment to erode within the suspension regime, leading to competing predictions of lowland river erosion rates, knickpoint formation and evolution, and the transient response of orogens to external forcing. We present controlled abrasion mill experiments designed to test fluvial incision models in the bedload and suspension regimes by varying sediment size while holding fixed hydraulics, sediment load, and substrate strength. Measurable erosion occurred within the suspension regime, and erosion rates agree with a mechanistic incision theory for erosion by mixed suspended and bedload sediment. Our experimental results indicate that suspension-regime erosion can dominate channel incision during large floods and in steep channels, with significant implications for the pace of landscape evolution.

INTRODUCTION

River incision into bedrock controls the flux of sediment to basins, links hillslopes to channels, and dictates the rate at which landscapes evolve (e.g., Whipple et al., 2013). Bedrock incision theory allows predictions of fluvial response to external perturbations, and the most commonly used models assume that erosion is proportional to stream power or bed shear stress (e.g., Howard and Kerby, 1983). Such models have been widely used in landscape evolution modeling (e.g., Tucker and Slingerland, 1994), as well as in studies examining feedbacks between climate, tectonics, and topography (e.g., Willett, 1999). However, stream-power models do not explicitly capture the physical processes of river erosion (i.e., the coupling of fluid flow, sediment transport, and channel erosion), limiting their predictive ability.

An alternative approach is to more directly account for processes eroding rock. The saltation-abrasion model (Sklar and Dietrich, 2004) predicts river-bed abrasion from single-sized sediment transported in bedload over a planar bed, and several of its basic tenets have been confirmed in laboratory and field settings (e.g., Sklar and Dietrich, 2001; Johnson and Whipple, 2010). This has led the model, and other similar models (e.g., Turowski et al., 2007), to be widely adopted in predicting reach-scale erosion (e.g., Cook et al., 2012), river-profile evolution (e.g., Crosby et al., 2007), and landscape evolution (e.g., Egholm et al., 2013). The saltation-abrasion model differs from the stream-power model in important and sometimes counterintuitive ways. For example, the saltation-abrasion model predicts decreased erosion rates for heightened bed shear stresses, leading to slower transient river network response to base-level change (Crosby et al., 2007; Gasparini et al., 2007), the preservation of relief in tectonically inactive mountain ranges over much longer time scales than with stream-power modeling (Egholm et al., 2013), and the formation of landforms that do not arise in stream-power modeling, such as permanent fluvial hanging valleys (Crosby et al., 2007) and static knickpoints that can grow infinitely in height (Sklar and Dietrich, 2008). In addition, in sand- and silt-bedded rivers and deltas where the majority of bed sediment is transported in suspension during floods, the saltation-abrasion model predicts zero erosion, counter to stream-power predictions and field observations of fluvial incision into consolidated sediment (Nittrouer et al., 2011; Shaw et al., 2013).

Differences between the saltation-abrasion and stream-power models arise, in part, because the saltation-abrasion model assumes an infinite hop length for particles transported within the suspension regime, such that particles are assumed not to impact the bed and erosion rates are predicted to be zero (Sklar and Dietrich, 2004, 2006). The transition from the bedload regime to the suspension regime is often defined as the point in which bed shear velocity, u_* (a fluid turbulence proxy), surpasses particle terminal settling velocity, w_s (Bagnold, 1966; McLean, 1992), such that turbulence strongly influences particle trajectories. In the suspension regime, some particles are advected high into the water column by turbulence (i.e., the suspended load); however, the largest concentration of particles is still near the bed (Rouse, 1937) where particles impact the bed via rolling, sliding, and saltation (i.e., bedload), and there is active exchange of particles between the bedload layer and suspended load above (e.g., McLean, 1992; Garcia and Parker, 1993). To account for erosion due to particle-bed impacts within the suspension regime, the saltation-abrasion model was recast (by Lamb et al., 2008) in terms of near-bed sediment concentration rather than particle hop lengths (herein referred to as the total-load model). The saltation-abrasion and total-load models produce similar results for erosion within the bedload regime, but within the suspension regime the total-load model predicts nonzero erosion rates that increase with increasing fluid bed stress, leading to contrasting predictions for landscape evolution, especially during large floods and in steep channels where bed sediment is suspended.

Laboratory experiments offer a means to test the validity of existing bedrock-erosion theories under controlled conditions that are otherwise difficult to achieve in natural rivers. Previous experimental work suggests that channel-bed erosion in the suspension regime is possible (Sklar and Dietrich, 2001; Cornell, 2007; Chatanantavet et al., 2010), but experiments have not been conducted that allow full testing of existing models within the suspension regime. Herein we present results from controlled abrasion mill experiments and find significant rates of erosion within the suspension regime, in agreement with the total-load erosion model; these results have important implications for landscape evolution.

EXPERIMENTAL SETUP

In natural river channels, erosion rates are likely influenced by multiple sediment sizes in transport, complex bed topography, and jointed rock that may promote plucking (e.g., Hancock et al., 1998). Our goal is not to reproduce this complexity, but rather to test the competing predictions of the saltation-abrasion and total-load erosion models under the simplest possible scenarios and in accordance with inherent assumptions in the models, including single-sized sediment, and a planar river bed of massive, unjointed rock. Testing existing models under these simplified conditions is important because such baseline tests have yet to be performed, and the existing theories are widely applied to natural landscapes and used in landscape evolution simulations despite these assumptions (e.g., Cook et al., 2012; Egholm et al., 2013).

To explore bedrock erosion rates over a wide range of transport conditions, we conducted experiments in abrasion mills (Fig. 1) identical to those used by Sklar and Dietrich (2001) in their study of erosion rates in the bedload regime. In abrasion mills, suspension of sedi-

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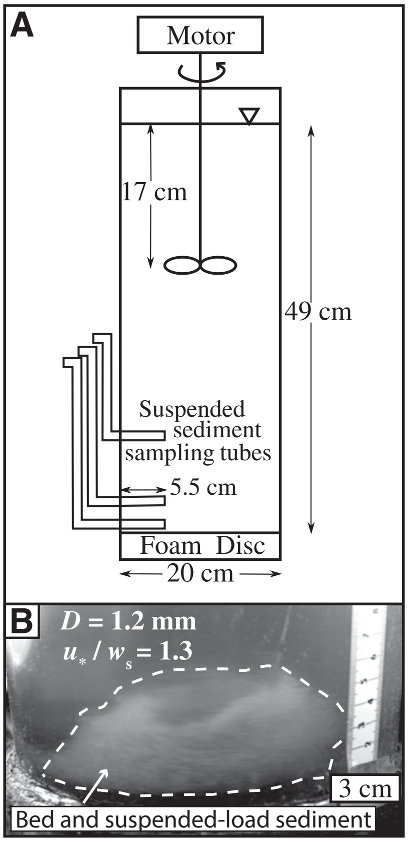

Figure 1. A: Schematic diagram of abrasion mill and sediment concentration measurement system (modified from Sklar and Dietrich, 2001). B: Contrast-enhanced, side-view photograph of suspension-regime transport within an abrasion mill. *D*—grain diameter; u_*—bed shear velocity; w_s—particle terminal settling velocity.

ment can be achieved by increasing the flow speed (i.e., increasing u_*), decreasing the sediment size (i.e., decreasing w_s), or both. Increasing flow speed to suspend gravel in the abrasion mills is problematic, however, because higher flow speeds require larger diameter mills to eliminate covarying changes in secondary flow circulation. Thus, we chose to conduct experiments by varying sediment diameter ($0.46 < D < 44$ mm; Table DR1 in the GSA Data Repository[1]) to achieve flow conditions spanning both the suspension and bedload regimes ($0.15 < u_*/w_s < 2.9$), while holding propeller speed (1000 rpm, $u_* \approx 0.15$ m/s; Sklar and Dietrich, 2004) and total sediment load (70 g) constant to match previous experiments (Sklar and Dietrich, 2001). Note that under the imposed conditions of constant sediment load and flow speed, finer sediment will necessarily produce smaller erosion rates, regardless of whether transport is in the suspension regime, because of smaller particle mass and fall velocity. Erosion rates should also approach zero with decreasing grain size as impacts become viscously damped for particle Stokes numbers (St, a nondimensional number that weights the kinetic energy of particle impacts to the fluid viscosity) below ~10–100 (Joseph et al., 2001).

To achieve measurable erosion rates, we used low-tensile-strength ($\sigma_T = 0.32$ MPa) polyurethane foam as a highly erodible bedrock simulant rather than natural rock. Tests show that foam follows the same erosion-rate scaling relationship with tensile strength as observed by Sklar and Dietrich (2001) for rock and concrete (see the Data Repository, and Fig. DR1 therein), allowing our results to be properly scaled to natural rock.

For each experiment, we secured a 38-mm-thick foam disc to the base of the abrasion mill, loaded the mill with siliciclastic, well-sorted, subangular to subrounded sediment, and filled the mill to a depth of 49 cm with water. A propeller induced flow and sediment transport, and experiments were run long enough for measurable wear of the foam disc by either volume loss (using a submillimeter-precision laser scanner) or mass loss (using a 0.1 g precise scale), depending on total volume eroded. For grain diameters $D \le 2.4$ mm we collected flow samples at 3 elevations above the bed (1, 3, and 10 cm) to quantify the suspended sediment concentration profile (Fig. 1; see the Data Repository).

SEDIMENT TRANSPORT

Using a transparent mill, we observed that grains with $D \ge 7$ mm ($u_*/w_s \le 0.44$) were transported exclusively in bedload, moving via rolling, sliding, and saltating along the bed, grains with $D \le 1.2$ mm ($u_*/w_s \ge 1.3$) moved in both bedload and suspended load, and grains with D ~2.0–2.4 mm ($0.61 \le u_*/w_s \le 1.0$) were intermediate between exclusive bedload and intermittent suspension (Fig. DR2; Movies DR1–DR4). In the radial direction, sediment concentrated in an annulus around the center of the mill due to secondary circulation (Sklar and Dietrich, 2001, 2004); however, secondary circulation was typically <~10% of the mean azimuthal flow velocity and did not appear to strongly influence erosion rates (see the Data Repository).

Measurements of sediment concentration, c, for $D < 2$ mm had vertical profiles (Fig. 2) comparable to that predicted by classic theory (Rouse, 1937),

$$c = c_b \left[\frac{\left(\frac{1}{z}\right) - \left(\frac{1}{H}\right)}{\left(\frac{1}{H_b}\right) - \left(\frac{1}{H}\right)} \right]^{\frac{w_s}{\beta \kappa u_*}}, \quad (1)$$

where z is height above the bed, H is flow depth, c_b and H_b are near-bed sediment concentration and bedload layer thickness (calculated

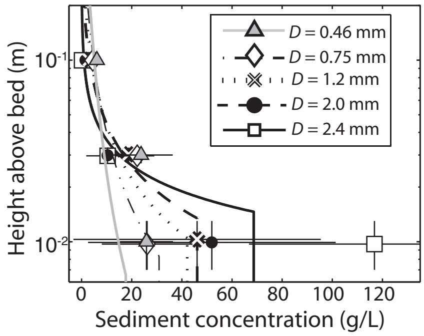

Figure 2. Rouse sediment concentration profiles (dashed and solid lines) for different grain diameters (*D*) with β = 2 (β is a dimensionless constant weighting the diffusivities of sediment relative to fluid momentum), for total sediment load of 70 g. Symbols correspond to mean of sediment concentration measurements (n = 3); x- and y-error bars represent geometric standard deviation of measurements and radius of sampling tubing (3 mm), respectively.

following Lamb et al., 2008), β is a dimensionless constant weighting the diffusivities of sediment relative to fluid momentum, and $\kappa = 0.41$ is von Karman's constant. Despite the different flow hydraulics in abrasion mills versus the unidirectional, steady, turbulent boundary layer assumed in the derivation of Equation 1, the Rouse model shows reasonable agreement with our measurements for $\beta = 2$ (Fig. 2), a value similar to that found in unidirectional flows (e.g., $\beta = 0.5$–3; Graf and Cellino, 2002).

BEDROCK EROSION

Measurable erosion of synthetic bedrock occurred in all experiments, including those within the suspension regime. Under fixed total sediment load, erosion rates decreased with decreasing grain size from ~10^2 cm^3/h for the largest grains that were transported in the bedload regime ($D = 40$ mm, $u_*/w_s = 0.15$) to ~10^{-2} cm^3/h for the smallest grains that were transported in the suspension regime ($D = 0.46$ mm, $u_*/w_s = 2.9$) (Fig. 3A; Table DR1). The observed erosion rate versus grain-size relationship for the bedload regime matches that observed by Sklar and Dietrich (2001) for grains eroding limestone, except that we observed higher erosion rates due to the use of a lower tensile strength substrate. To directly compare our results to those of Sklar and Dietrich (2001) we scaled volumetric foam erosion rates ($E_{v\text{-}f}$) to equivalent values for erosion of limestone ($E_{v\text{-}ls}$) using the tensile-strength scaling relationship proposed by Sklar and Dietrich (2001) and confirmed here (Fig. DR1B):

$$E_{v\text{-}ls} = E_{v\text{-}f} \left(\frac{\sigma_{T\text{-}ls}}{\sigma_{T\text{-}f}} \right)^{-2}, \quad (2)$$

where $\sigma_{T\text{-}f}$ and $\sigma_{T\text{-}ls}$ are the tensile strengths of foam (0.32 MPa) and limestone (9.8 MPa),

[1]GSA Data Repository item 2014185, supplementary text, figures, movies, and tables, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

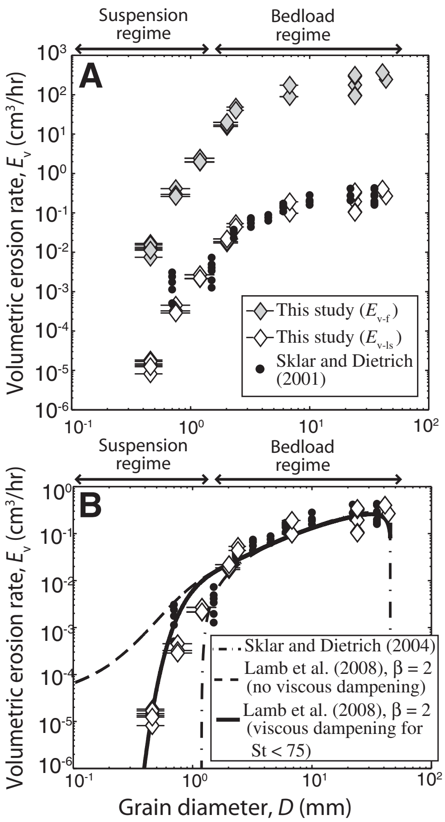

Figure 3. A: Volumetric erosion rate (E_v) versus grain diameter (D) in this study and from previous experiments eroding limestone. We show both measured foam erosion rates ($E_{v\text{-}f}$) and limestone-equivalent rates ($E_{v\text{-}ls}$; see Equation 2). Error bars correspond to limits of unimodal grain size distributions as reported in Table DR1 (see footnote 1). B: As in A; lines show theoretical predictions of saltation-abrasion model (Sklar and Dietrich, 2004), and total-load model (Lamb et al., 2008) with and without viscous dampening. Cover term was neglected due to low sediment loading, and nondimensional constant k_v was set to 3×10^5 to account for the fact that particle tensile strength was greater than substrate tensile strength (for details, see Sklar and Dietrich, 2004). St—Stokes number.

respectively. The scaled foam data collapse to nearly the same values found by Sklar and Dietrich (2001), and extend the combined data set to smaller sediment sizes with higher u_*/w_s (Fig. 3A).

The saltation-abrasion model (Sklar and Dietrich, 2004) predicts zero erosion for $D < \sim 2$ mm due to the onset of suspension; this does not match our data (Fig. 3B). The total-load model (Lamb et al., 2008), however, overpredicts erosion rates within the suspension regime when viscous dampening of impacts is neglected. The best model fit to the data is the total-load abrasion model where impacts are viscously damped for St < 75; this value is within the range of partial dampening found in particle-wall collision studies (e.g., Joseph et al., 2001).

DISCUSSION AND IMPLICATIONS

Our experimental results provide direct evidence for fluvial incision in the suspension regime, show that viscous dampening reduces erosion rates for low-energy impacts, and support the use of the total-load model for predicting erosion in both the bedload and suspension regimes. Our observations show that suspension-regime erosion occurs because particles are transported both in a bedload layer with high sediment concentrations near the bed, and in a more dilute suspended-load layer above (e.g., Fig. 2; Fig. DR2), with active interchange of particles between the two layers and active particle-bed impacts. Erosion rates in our experiments decreased across the bedload to suspension regime primarily because we decreased grain size while holding sediment load and flow speed constant, and, under these conditions, smaller particles have lower kinetic energy upon impact, regardless of the transport mode. The total-load model predicts that suspension-regime erosion rates would be of a magnitude similar to that of bed-load-regime rates if experiments were instead conducted by varying u_* while holding grain size constant (Fig. 4), and would outpace bedload regime rates by several orders of magnitude if sediment load increases with u_* (see the Data Repository; Fig. DR3). Although more difficult experimentally, these alternate scenarios are likely in natural rivers during floods, suggesting that erosion by sediment in the suspension regime may be more important in natural rivers than demonstrated in our experiments.

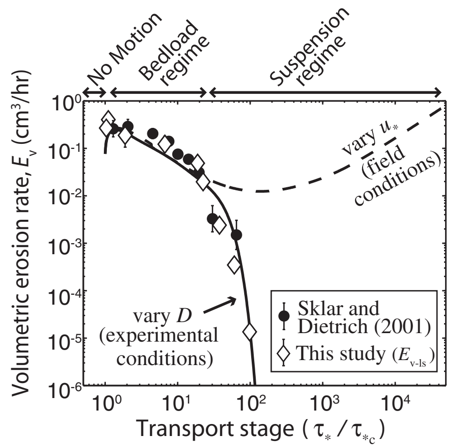

Figure 4. Volumetric erosion rate, E_v, versus transport stage, τ_*/τ_{*c}, for abrasion mill experiments, where τ_* and τ_{*c} are the Shields stress and critical Shields stress, respectively. Lines show theoretical predictions of total-load model (Lamb et al., 2008) for transport stage varied by changing grain size (diameter, D, solid line), as was done in the abrasion mill experiments, and by changing shear velocity (u_*) with constant flow depth (dashed line). Symbols show mean and 1σ standard deviation of erosion rates for abrasion mill experiments, with foam erosion rates converted to limestone-equivalent rates ($E_{v\text{-}ls}$) using Equation 2 (see text). Models include viscous dampening of impacts for particle Stokes number < 75, β = 2, $k_v = 3 \times 10^5$ (nondimensional constant), and neglect cover.

In natural rivers, the relative efficiency of erosion within the suspension regime depends strongly on the ability of a flood to suspend bed sediment. Bankfull floods in gravel-bed rivers rarely suspend bed material (Parker et al., 2007), such that, for typical mass flux ratios of bed to suspended load, erosion from gravel and cobbles moving exclusively in bedload likely outpace suspension-regime erosion from sand and silt, which have smaller impact velocities, and impacts may be viscously damped.

Suspension-regime erosion will dominate fluvial abrasion when bed sediment is suspended, however, which regularly occurs in sand-bedded rivers, in coarse-grained rivers during large floods, and in steep channels and knickzones. For example, the total-load model successfully predicts erosion of consolidated mud in the Wax Lake Delta (Louisiana), where the majority of grain sizes present on the bed are transported in the suspension regime during bankfull flows (Shaw et al., 2013). These conditions are common in other lowland distributary rivers (e.g., Nittrouer et al., 2011), where the dominance of suspension-regime transport would cause the saltation-abrasion model to erroneously predict zero erosion. Suspension of bed material can also occur during large-magnitude storms in coarse-bedded mountain rivers. For example, typhoon-induced floods in the Da'an River, Taiwan, resulted in ~20 m of vertical incision over a 4 yr period (Cook et al., 2012). We calculate that grains as large as 1 m in diameter were within the suspension regime in the narrowest portion of the gorge, where erosion was rapid (see the Data Repository); this is far larger than the median grain diameter of the bed material (15 cm; Cook et al., 2012), suggesting that the bulk of erosion occurred within the suspension regime.

In landscape evolution modeling, suspension-regime erosion causes erosion rates to increase on steep channel slopes, similar to stream-power models (Fig. DR3), and may prevent formation of oversteepened, nonreoding reaches that develop in simulations that use the saltation-abrasion model (e.g., Wobus et al., 2006; Crosby et al., 2007; Sklar and Dietrich, 2008). Suspension-regime erosion also allows steep river reaches to propagate more rapidly through a landscape, resulting in faster transmission of changes in base level than observed with saltation-abrasion models (Crosby et al., 2007; Gasparini et al., 2007), and this in turn may influence the predictions of morphology and lifespan of mountain ranges. For example, recent predictions using the saltation-abrasion model attribute the long-term preservation of relief in tectonically inactive mountain ranges to landslide-modulated sediment supply to river networks (Egholm et al., 2013). However, including suspension-regime erosion in modeling should yield higher erosion rates, which will more rapidly reduce relief both on steep slopes and under high rates of sediment supply if bed sediment is suspended (e.g., Fig. DR3).

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