Mechanisms of river incision into bedrock: Implications for Grand Canyon formation

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Abstract

Bedrock erosion in a river channel is commonly proposed to be proportional to stream power, the rate of energy expenditure of a flow (stream power model). However, laboratory experiments have demonstrated a non-linear relationship between sediment supply, grain size, rock tensile strength, and bedrock erosion rate (saltating bed load model). By relating the stream power model to bedrock incision in the Grand Canyon, we determine that channel slope must have adjusted to accommodate changes in incision rate. By comparison, the saltating bed load model allows an additional degree of freedom for channel adjustment; the Colorado River may have changed bed rock exposure to accommodate changes to incision rate, sediment supply, or bed rock tensile strength. We discuss the implications of the saltating bed load model for bedrock incision and future changes to sediment supply in the Grand Canyon.

Goals

The goal of this report is to compare two bedrock incision models and to discuss the implications of these models for Grand Canyon formation. A secondary goal of this report is to explore the importance of sediment supply and grain size to bedrock incision and to consider how current and future changes to sediment supply will influence incision and bedrock exposure in the Grand Canyon.

Literature synthesis

The Colorado River, or its predecessor, carved much of the Grand Canyon. While the timing of Grand Canyon incision is still debated (ie.Trexler, 2014), the processes that sculpted the canyon are worth considering because of their influence on the canyon's form. Here we describe the process of river incision into bedrock. We begin by discussing a simple and widely used model for river incision into bedrock, the stream power model. Secondly, we describe a set of experiments that demonstrated the importance of sediment supply and grain size to bedrock incision. We discuss the implications of this saltating bed load model to Grand Canyon form over human and geologic timescales.

Bedrock incision: Stream Power Model

The stream power river incision model is commonly applied to bedrock incision problems. The stream power incision model assumes that the rate of erosion is proportional to stream power, Ω, where stream power is the the rate of energy expenditure of the flow. Thus, bedrock erosion rate, E, can be expressed as,

$$E = \frac{K_p \Omega}{W} = \frac{K_p \rho g S Q_w}{W}, (1)$$

where E is the in units of volume of bedrock eroded per channel bed area per time, S is channel slope, ρ is fluid density, g is gravity, W is channel width, Q_w is channel discharge, and K_p is a dimensionless coefficient of incision efficiency. This relationship can be further simplified by assuming that discharge varies with drainage area such that,

$$Q_w = K_a A^r, (2)$$

where A is drainage area, and K_a and r are dimensionless coefficients. Further, channel width is often expressed as a function of discharge such that,

$$W = K_b {Q_w}^b, (3)$$

where K_b and b are dimensionless coefficients. Equations (1), (2), and (3) can be combined to express erosion rate as a function of drainage area and slope such that,

$$E = KA^m S^n \text{ (4).}$$

This power law relationship describe erosion rate as a function of drainage area and channel slope. Given the observation that the rate of bedrock incision tends to match the rate of uplift, this model suggests that (given a constant drainage area) a doubling in the rate of uplift will result in a doubling of the channel slope. By applying this model to the Grand Canyon, the implication is that a change in uplift rate of the Colorado Plateau would result in a proportional change in channel slope.

However, this model does not include a mechanistic theory for how bedrock is eroded. By comparison to this stream power model, Sklar and Dietrich (1998) suggest that channel incision depends non-linearly on sediment supply rate, grain size, and the degree of bedcover by sediment.

Saltating bed load model

Sklar and Dietrich (2001) demonstrated a non-linear relationship between sediment supply and grain size to the rate of bedrock erosion. Through laboratory experiments where sediment was introduced to a mill with a bedrock plate at the bottom (Figure 1), Sklar and Dietrich (2001) discovered that the rate bedrock plate erosion depends on the supply and grain size of sediment. The rate of erosion increases with sediment supply until sediment covers the bedrock plate and provides a shield against additional erosion.

Sediment size also played a crucial role to erosion rate. This is because small sediment suspended within the water column does not act as an effective tool for abrasion. This result is notable because only a small fraction of a river's total sediment load travels as bed load (instead

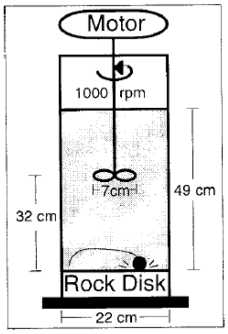

Figure 1: Experimental set-up (bed rock abrasion mill) from Sklar and Dietrich (2001).

of wash load). Thus, a small portion of the sediment flux exerts a disproportionate control on channel geometry.

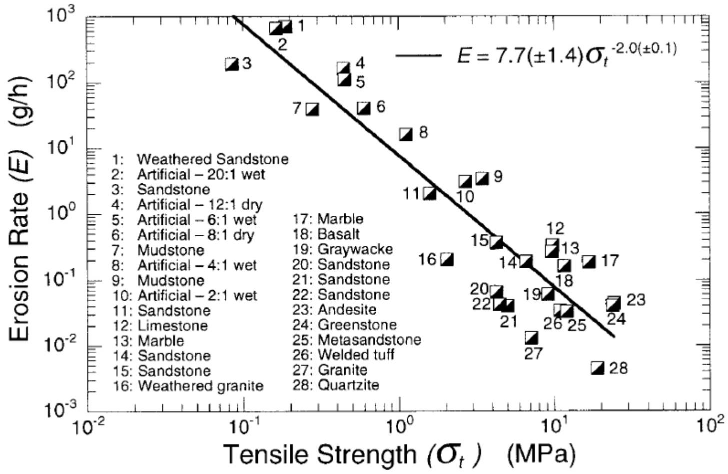

Figure 2: Results from Sklar and Dietrich (2001). Erosion rate is demonstrated to be a function of the tensile strength bedrock.

In addition, erosion rate was also found to be a function of the tensile strength of the bedrock plate. Erosion rate scaled with the square of rock tensile strength (Figure 2.) This is one of the few observations that quantitatively link a rock property to a process that influences geomorphic form.

Sklar and Dietrich (2004) determined from the theory by Sklar and Dietrich (1998, 2001) that the erosion rate in a bedrock channel can be expressed as,

$$E = \frac{0.08 R_b g Y}{K_v \sigma_t^2} q_s \left(\frac{\tau^*}{\tau_c^*} - 1\right)^{-1/2} \left(1 - \frac{q_s}{q_t}\right)\left(1 - \left(\frac{u_s}{w_f}\right)^2\right)^{3/2}, \quad (5)$$

Where R_b is the non-dimensional buoyant density, Y is Young's modulas of elasticity, K_v is a rock resistance coefficient, σ is rock tensile strength, q_s is sediment supply per unit width, $\frac{\tau^*}{\tau_c^*}$ is transport stage, q_t is transport capacity per unit width, u_s is horizontal sediment velocity, and w_f is particle fall velocity.

These results provide insight into the process of particle abrasion that erodes bedrock and that formed the Grand Canyon. Sklar and Dietrich (2001) demonstrated that erosion rate is a non-linear function of sediment supply, grain size, and bedrock tensile strength. This is important because the coupling between bedcover and erosion provides a mechanism for channels to self-regulate incision rate. The scale of this process is impressive given that abrasion by particles is responsible for at least most of the Grand Canyon's more than five kilometers of relief (Figure 3).

Implications for the Grand Canyon

Figure 3: The Colorado River in the Grand Canyon. Note the impressive scale of the vertical relief (>5km not entirely shown in this image).

If uplift of the Colorado Plateau was long and steady, common geomorphic theory suggests that the rate of incision equilibrated to match the rate of uplift. By applying the stream power model to this scenario, the result is that channel slope adjusted to the incision rate prescribed by uplift. However, the saltating bed load model implies that sediment supply, size, and (to a lesser extent) tensile rock strength controls channel erosion rate. The saltating bed load model has important implications for how incision rate adjusts to changes in uplift, sediment supply, and bedrock tensile strength.

Firstly, the saltating bed load model provides the Colorado river with an extra degree of freedom to adjust to changes in uplift rate. Instead of changing bed slope, the river can simply alter the degree of bedrock exposure. The timescale for bedrock exposure adjustment is short (because small changes in slope can lead to large changes in bedrock exposure) compared to the timescale for large slope adjustments.

Secondly, the sediment supplied to the channel exerts a first-order control on channel incision. This is because sediment size controls whether a particle travels as wash load or bed load and thereby is an abrasion tool for incision. Currently, the influence of lithology, climate, and uplift rate on sediment supply and size to a channel are not well understood. However, debris flows greatly influence sediment delivery to the Grand Canyon (Buer, 2005; Griffiths et al., 2004). At locations where new abrasion tools are supplied to the river (ie. debris flow and tributary inflow locations), saltating bed load theory suggests an adjustment to incision rate, bedrock exposure, and/or slope.

Lastly, saltating bed load theory predicts a change in incision rate based on the tensile strength of the underlying bedrock. Thus, as the Colorado cut through more than five km of differing lithologies, the degree of bedrock exposure may have changed to maintain a specific incision rate.

Global Change

Two of the newest and most influential features on the Colorado River are Lake Mead and Lake Powell. These reservoirs regulate flow, trap sediment, and change the base level of the river. Lake Powell and Lake Mead will modify bedrock incision by changing sediment availability for bedcover and abrasion and stream power. It is difficult to predict how these changes will influence bedrock incision due to the non-linear relationships between sediment supply and incision. However, from saltating bed load theory we can predict that the Colorado will adjust bed exposure in response to changes in supply and stream power. Moreover, bedrock exposure may be important to local ecology, however discussion about ecology is outside the scope of this report.

Over longer timescales, anthropogenic changes to climate may influence the size and supply of sediment to the Colorado (ie. through changes in the frequency of debris flows). As demonstrated by Sklar and Dietrich (2001), sediment supply exerts a fundamental control on river incision. Changes to climate may influence sediment supply and therefore landscape evolution in the Colorado River Basin and basins worldwide. However, current landscape evolution theory cannot quantitatively describe the influence of climate on sediment supply (Dietrich et al., 2003).

Conclusions

This report describes two models for bedrock incision: the stream power model and the saltating bed load model. While the stream power model is appealing due to its simplicity, stream power theory does not include the important influences of sediment supply and grain size. By comparison, the saltating bed load model describes a non-linear relationship between sediment supply, grain size and erosion rate. The non-linearity between sediment supply, grain size, and erosion rate has important ramifications for the Grand Canyon: 1. the Colorado River may have responded to changes in uplift rate by altering bed exposure rather than slope; and 2. spatial and temporal variation in sediment supply, grain size, and lithology on the bed surface will influence incision, channel slope, and/or bed exposure. This coupling between sediment supply, grain size, erosion rate, channel slope, and stream power is important within the context of modern change. Changes in sediment supply, either though the presence of Lake Mead and Lake Powell or by changing tributary and debris flow inputs, fundamentally influences bed cover and possibly incision rate.

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