Sediment and rock strength controls on river incision into bedrock

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ABSTRACT

Recent theoretical investigations suggest that the rate of river incision into bedrock depends nonlinearly on sediment supply, challenging the common assumption that incision rate is simply proportional to stream power. Our measurements from laboratory abrasion mills support the hypothesis that sediment promotes erosion at low supply rates by providing tools for abrasion, but inhibits erosion at high supply rates by burying underlying bedrock beneath transient deposits. Maximum erosion rates occur at a critical level of coarse-grained sediment supply where the bedrock is only partially exposed. Fine-grained sediments provide poor abrasive tools for lowering bedrock river beds because they tend to travel in suspension. Experiments also reveal that rock resistance to fluvial erosion scales with the square of rock tensile strength. Our results suggest that spatial and temporal variations in the extent of bedrock exposure provide incising rivers with a previously unrecognized degree of freedom in adjusting to changes in rock uplift rate and climate. Furthermore, we conclude that the grain size distribution of sediment supplied by hillslopes to the channel network is a fundamental control on bedrock channel gradients and topographic relief.

Keywords: rivers, sediment supply, grain size, erodibility, landscape evolution, erosion.

INTRODUCTION

The topography of mountainous landscapes is created by the interaction of rock uplift and erosion. River incision into bedrock is the key erosional process that controls the rate of landscape response to changes in rock uplift rate and climate (Howard et al., 1994). Numerical models of landscape evolution (e.g., Howard, 1994; Tucker and Slingerland, 1994; Willett, 1999) commonly assume that incision rate is proportional to stream power (Seidl and Dietrich, 1992), or equivalently shear stress (Howard and Kerby, 1983), and lump the influence of rock strength, sediment supply, grain size, and other factors into a poorly defined ''rock erodibility'' coefficient. This simple ''stream power'' bedrock-incision model has also been used in analysis of real landscapes to infer patterns of crustal deformation (Kirby and Whipple, 2001) and the possible influence of climate change on late Cenozoic mountain uplift (Whipple et al., 1999). Studies of river longitudinal profiles suggest, however, that the stream power model may be too simple to explain observed variations in incision rates (Stock and Montgomery, 1999) and profile shape (Sklar and Dietrich, 1998). In addition, theoretical investigations (Sklar and Dietrich, 1998; Slingerland et al., 1997) suggest that the influences of sediment supply and grain size are too complex to fit into a linear coefficient and must be explicitly represented in models of bedrock incision. Our goal here is to pry open the conceptual black box of ''rock erodibility,'' and explore experimentally the role of sediment supply, grain size, and rock strength in controlling bedrock erosion rates.

Gilbert (1877) was the first to propose that the quantity of sediment supplied to the river should influence bedrock-incision rates in two essential yet opposing ways: by providing tools for abrasion of exposed bedrock and by limiting the extent of exposure of bedrock on the channel bed. According to Gilbert's hypothesis, the maximum rate of incision should occur when the stream receives a moderate supply of sediment, relative to its sediment transport capacity. Incision rate is limited at lower supply rates by a shortage of abrasive tools (the ''tools effect'') and at higher supply rates by partial burial of the bedrock substrate beneath transient sediment deposits (the ''coverage effect''). The size distribution of sediment grains supplied to the channel should also influence incision rates, because only the coarser fraction is capable of forming an alluvial cover in actively incising river channels and because the finer fraction is carried in suspension and rarely collides with the bedrock bed.

Various alternative incision models explicitly include sediment supply through simple parameterization of the tools effect (Foley, 1980), the coverage effect (Beaumont et al., 1992), or both (Slingerland et al., 1997). We previously derived an incision rate law from the mechanics of saltating bedload (Sklar and Dietrich, 1998) that predicts a nonlinear dependence of incision rate on sediment supply, similar to Gilbert's qualitative hypothesis. Our model also predicts a nonlinear dependence of incision rate on grain size due to the twin constraints that for a grain to erode bedrock it must be small enough to be in motion, yet large enough to move as bed load rather than as suspended load; thus, predicted incision rates are highest for intermediate grain sizes. In every model we are aware of, bedrock resistance to erosion is treated as a free parameter unrelated to any objective measure of rock strength.

ABRASION EXPERIMENTS

Because of the inherent difficulty of measuring bedrock erosion and sediment supply rates in the field, we developed an experimental bedrock abrasion mill designed to replicate the small-scale interaction of coarse bed load with the rock floor of an actively incising river channel. We bolted 20-cm-diameter disks of rock to the bottom of a set of 10 vertical water-filled cylinders, in which motor-driven propellers circulated water (Fig. 1). We added sediment of various amounts and sizes, which moved primarily as saltating bed load across the surface of the bedrock disks in response to the tractive force of the rotating water. In all the experiments reported here, we held the rotational velocity of the water constant. In a river, this would be equivalent to holding channel slope, cross-sectional area, and water discharge constant. The walls and base of one abrasion mill were made of transparent material to allow observation of sediment mo-

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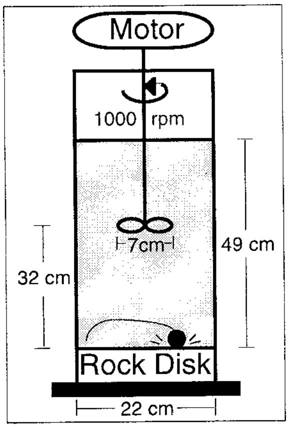

Figure 1. Schematic of bedrock abrasion mill.

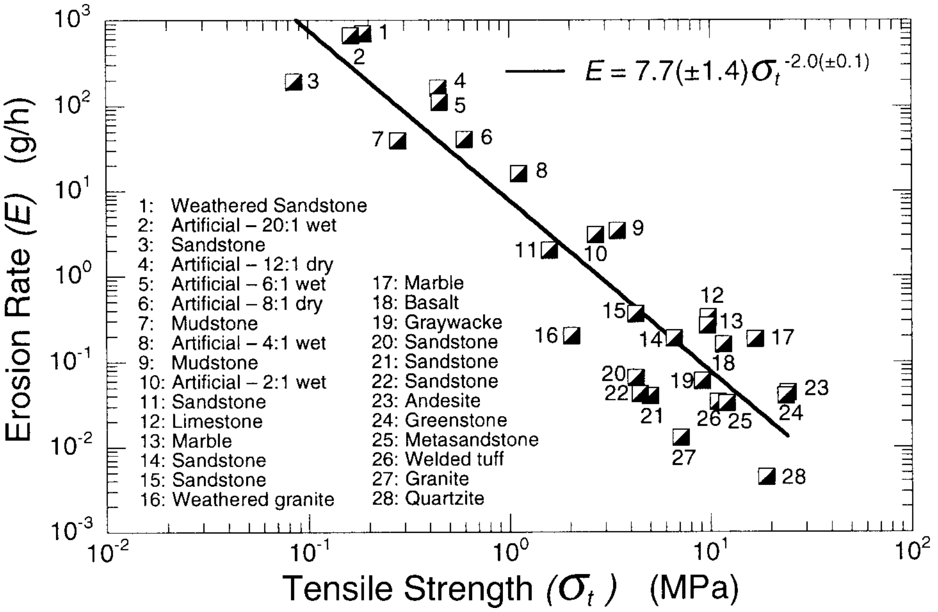

Figure 2. Variation in measured erosion rate with rock tensile strength. Sediment loading for this set of runs was 150 g of 6-mm-diameter gravel. Each data point represents mean of 12 to 20 measurements of tensile strength and two to six replicate erosion runs; error bars are omitted because standard errors of these means are smaller than data symbols. Uncertainty in best-fit log-linear regression line is standard error. Sand:cement ratios and curing conditions are listed for artificial rocks.

tion. Bedrock abrasion occurred primarily due to impacts by saltating grains. We determined the erosion rate by weighing the rock disks before and after each run and dividing the mass lost by the run duration. Rock samples were kept saturated and gently toweled off prior to weighing to remove ponded water. Replicate weight measurements reduced typical standard error to below 0.2 g. Run duration ranged from 0.25 to 72 h.

We eroded a suite of 22 lithologies, including highly resistant greenstone, quartzite, and granite, moderate strength basalt, limestone, and sandstone, and weakly cemented sandstone and mudstone. Samples were collected from the beds and banks of actively incising bedrock channels, from in-channel boulders, and from quarries. We also tested a set of six artificial sandstones, composed of various mixtures of fine sand and portland cement, to supplement the range of rock strengths. Because rocks fail in tension when subjected to low-velocity particle impacts (Johnson, 1972), tensile strength is the mechanistically appropriate rock strength parameter for characterizing rock resistance to fluvial abrasion. We used the Brazilian tension splitting test (Vutukuri et al., 1974) to determine the tensile strength of each rock type, because this test produces valid results over the widest possible range of rock strengths.

To measure the influence of rock tensile strength on bedrock erosion rates, we varied bedrock lithology while holding constant the number, size, and lithology of abrasive gravel grains. Erosion rates increased rapidly with decreasing tensile strength (Fig. 2). The data are well fit by a power-law relationship where erosion rate varies inversely with the square of tensile strength. To make sure that this result was not an artifact of changing the relative strength difference between the mobile gravel and stationary bedrock, we compared wear rates for rocks abraded by gravel composed of the same lithology with wear rates for rocks abraded by quartzite, a particularly strong rock type. Although disks of weaker bedrock abraded by the strong quartzite gravel eroded up to three times as fast as when abraded by gravel made from the same weaker lithology (Fig. 3), the exponent in the power law relationship between erosion rate and tensile strength did not change.

To measure the influence of sediment supply on incision rates, we varied the total mass of sediment placed in the abrasion mills, while holding constant the grain size and the lithology of both bedrock and sediment. Because the motor speed and thus water velocity were held constant throughout, we were able to effectively vary the ratio of sediment supply to sediment transport capacity. At relatively low supply rates, erosion rates increased rapidly as we increased the mass of abrasive sediment (Fig. 4A). However, as we continued to increase sediment mass, erosion rates peaked and then declined. The peak and subsequent decline in wear rate corresponded to the formation and growth of a deposit of immobile sediment that protected parts of the underlying bedrock (Fig. 4B). The sediment deposit formed initially around the center of the bedrock disk where the concentration of mobile sediment was greatest. As we supplied more sediment, the deposit grew outward, bridged to the walls and eventually covered the entire surface of the disk. Erosion continued at a very slow rate even when the rock disks were fully covered by a thin layer of sediment, presumably because of the force imparted by mo-

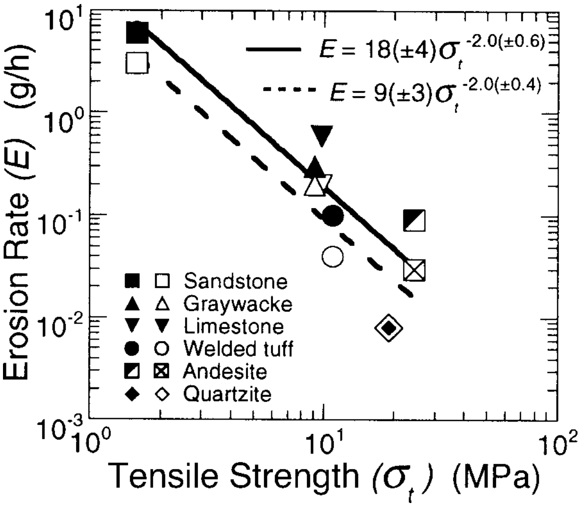

Figure 3. Variation in measured erosion rate with rock tensile strength for rocks eroded by quartzite gravel (solid symbols, solid line) and rocks eroded by gravel composed of same rock (open symbols, dashed line). Sediment loading for this set of runs was a single 30-mm-diameter 70 g grain. Note that quartzite bedrock data symbols are superimposed because this point is included in both regressions.

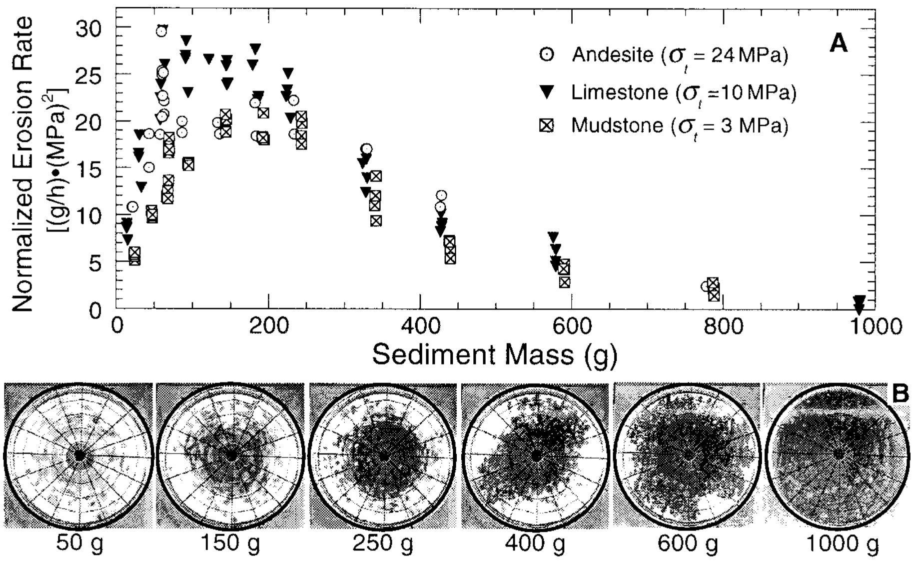

Figure 4. A: Variation in erosion rate with sediment loading. Data for three rock types are collapsed by multiplying erosion rate (g/h) by square of tensile strength (MPa). Sediment flux at erosion rate peak was ~0.01 kg · s^{-1} · m^{-1}. Additions of gravel mass did not increase flux much beyond this level but rather increased the mass of the stationary deposit. Grain diameter for these runs was 6 mm. B: Photographs showing gradual alluviation with increasing sediment loading, taken from below abrasion mill looking up through glass bottom.

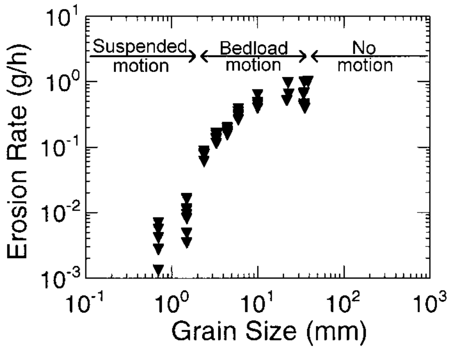

Figure 5. Variation in erosion rate with sediment grain size. Data are for limestone eroded by total gravel mass of 70 g. Transport mode was observed in clear-walled mill.

bile grains impacting stationary grains resting on the bedrock surface, and by occasional sliding of the alluvial bed.

We also measured the influence of sediment grain size on incision rates by simultaneously varying the mean grain diameter and the number of grains such that the total mass of sediment remained constant. For example, assembling a total sediment mass of 70 g required approximately 3000 grains of 0.7-mm-diameter sand, only 150 grains of 6-mm gravel, or just a single grain of 35-mm gravel. We chose this low level of sediment loading to avoid the confounding influence of partial bed coverage. Measured erosion rates peaked near the coarse end of the range of grain sizes tested and declined rapidly with decreasing grain size, becoming negligible for grain sizes smaller than coarse sand (Fig. 5). Unlike gravel, which moved as bed load, we observed sand (<2 mm diameter) moving primarily in suspension, rarely interacting with the bedrock bed. Grain sizes larger than 35-mm produced negligible erosion because there was insufficient shear stress to keep them in motion.

DISCUSSION

Our experimental results provide the first empirical confirmation of Gilbert's hypothesis and are consistent with observations of sediment dynamics in mountain river channels. Mixed bedrock-alluvial bedded channels are common in actively incising terrain (Howard, 1998). Temporal and spatial variations in the extent of bedrock exposure have been shown to depend on fluctuations in sediment supply (Howard and Kerby, 1983) and on subtle changes in channel slope, and thus sediment transport capacity (Montgomery et al., 1996). In our experiments, the coverage effect controls erosion rates over a much larger range of sediment supply rates than does the tools effect (Fig. 4A). This may be analogous to many actively incising river networks where channel beds are mostly mantled with a continuous alluvial cover. In these rivers, bedrock erosion may occur only during high-flow events when the entire alluvial bed is put into motion or when temporary local scour exposes bedrock.

We now have experimental evidence to support our hypothesis (Sklar and Dietrich, 1998) that the grain size distribution of sediment supplied to the channel is a key control on river incision rates (Fig. 5). The majority of sediment mass transported by mountain rivers is typically in the sand-, silt-, and clay-size fractions (e.g., Nordin, 1985), and it moves suspended in the water column. The rapid decline in rock erosion rate with decreasing grain size in our experiments suggests that finer sediments are inefficient tools for abrading bedrock river beds, compared to coarser sediments that travel as bed load. The observed low erosion rates of fine sediments may be due to both the reduced frequency of contact with the bed and the possible existence of a threshold impact intensity that must be exceeded to detach a fragment of bedrock. Suspended sediments may be most important in abrading blocks of rock that protrude high into the flow above the reach of bed load (Whipple et al., 2000a) and in abrading the walls of narrow bedrock channels (Whipple et al., 2000b).

Both the threshold of suspension and the threshold of motion bracket the range of grain sizes capable of effectively lowering a bedrock river bed. In our experiments, the largest grains tested (>35 mm) produced no measurable wear, because they moved infrequently or not at all. In rivers, the minimum channel slope necessary for incision to occur is set by the threshold of motion for the coarsest grain sizes that, if supplied in sufficient quantity, would accumulate and bury the bed in the absence of regular transport and particle breakdown (Sklar and Dietrich, 1998; Howard, 1998).

Our data show that rock resistance to fluvial abrasion, defined here as the inverse of erosion rate, scales with the square of rock tensile strength, providing the first determination of a quantitative relationship between rock resistance to fluvial erosion and an objective measure of rock strength (Fig. 2). In field studies of bedrock incision, quantitative comparisons among rock types can now be made by testing the tensile strength of bedrock samples. Where nonuniform lithology presents a confounding variable, erosion rate data can be collapsed by normalizing by tensile strength, as we have done in Figure 3. In experimental studies of bedrock incision, where weak materials are needed to accelerate rock erosion rates, tensile strength measurements can be used to scale the relative resistance to wear. The inverse square relationship between tensile strength and erosion rate can be used as a diagnostic test to ensure that simulated bedrock reliably reproduces the wear-resistant properties of natural rock, as our artificial sandstone does.

These results should have wide applicability even though we eroded bedrock that was not strongly jointed or fractured and thus did not capture the mechanism of wear by clear water plucking of loosely held rock fragments. In our experience, massive bedrock in channel beds is common. Moreover, the fracture spacing in jointed rock is often wide enough that the rate of bed lowering is limited by the intact strength of the intervening blocks. Furthermore, the efficiency of all bedrock erosional mechanisms, with the possible exception of dissolution, should depend on the size and supply rate of sediment carried by incising rivers. Bed coverage by alluvial deposits insulates underlying bedrock not only from wear by abrasion, but also from wear by plucking and cavitation. Abrasion by coarse bed load can create small-scale bed irregularities that promote cavitation where local flow separation occurs. Even in weak, finely jointed rock, where plucking is often inferred to be the primary erosional mechanism, bed-load impacts may be responsible for weakening and ultimately overcoming the forces holding jointed blocks in place (Whipple et al., 2000a).

IMPLICATIONS

The complex role of sediment in influencing bedrock incision rates has important implications for understanding the controls on river slope and basin relief and the time scale of landscape response to changes in rock uplift rate and climate. When subjected to prolonged steady rock uplift, river channel slopes tend to adjust so that incision rate matches rock uplift rate. According to the stream power view of river incision, slope is determined, for a given drainage area, by rock resistance and uplift rate; slopes roughly twice as steep would be required for rock twice as resistant, or for uplift rates twice as rapid.

Sediment supply and grain size effects, however, may produce an entirely different dependence of channel slope on uplift rate and rock strength, because the minimum slope that allows a river to incise into bedrock is set primarily by the threshold of motion of the coarse fraction of the sediment load. Increments in channel slope above the minimum will depend on the total load of bed-load-size sediment, which controls the extent of bedrock exposure in the channel bed. For steady-state landscapes, the total sediment load is proportional to the rock uplift rate; however, the fraction that moves as bed load will depend on the grain size distribution of sediment supplied by hillslopes and how that distribution evolves as it moves downstream. At present, little is known about how rock uplift rate and rock strength influence the grain size distribution of sediment entering the channel network. The initial grain size distribution is likely to depend on the bedrock lithology and its tectonic history, the climatically influenced weathering rate and style, and hillslope sediment transport processes.

Partial bedrock exposure, controlled by the rate and size of sediment supplied to the channel, introduces a previously unrecognized degree of freedom for channel adjustment. Because small changes in channel slope can produce large changes in the extent of bed exposure and consequently large changes in the rate of incision into bedrock, we might expect rivers flowing over more resistant rocks, or subject to faster uplift rates, to have marginally steeper slopes but much greater extents of bedrock exposure. Moreover, because basin relief is simply the integral of local channel slopes along the length of the river, it follows that relief may be much less sensitive to differences in lithology or rates of rock uplift than previous studies using the stream power law (Whipple and Tucker, 1999) have suggested. Similarly, where landscapes are subjected to changes in the rate of rock uplift, or to long-term shifts in climate, river incision rates may adjust through changes in the extent of bedrock exposure over a period of time that is relatively short compared to the long time required (Whipple and Tucker, 1999) for significant changes in relief to occur.

In summary, the experimental results reported here suggest that understanding and modeling the dynamic coupling of climate, tectonics, and topography will require explicitly accounting for the role of sediment supply and grain size in controlling rates of river incision into bedrock.

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