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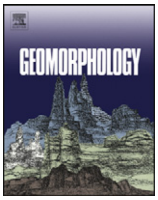

Review

New insights into the mechanics of fluvial bedrock erosion through flume experiments and theory

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ABSTRACT

River incision into bedrock drives the topographic evolution of mountainous terrain and may link climate, tectonics, and topography over geologic time scales. Despite its importance, the mechanics of bedrock erosion are not well understood because channel form, river hydraulics, sediment transport, and erosion mechanics coevolve over relatively long time scales that prevent direct observations, and because erosive events occur intermittently and are difficult and dangerous to measure. Herein we synthesize how flume experiments using erodible bedrock simulants are filling these knowledge gaps by effectively accelerating the pace of landscape evolution under reduced scale in the laboratory. We also build on this work by providing new theory for rock resistance to abrasion, thresholds for plucking by vertical entrainment, sliding and toppling, and by assessing bedrock-analog materials. Bedrock erosion experiments in the last 15 years reveal that the efficiency of rock abrasion scales inversely with the square of rock tensile strength, sediment supply has a dominant control over bed roughness and abrasion rates, suspended sediment is an efficient agent of erosion, and feedbacks with channel form and roughness strongly influence erosion rates. Erodibility comparisons across rock, concrete, ice, and foam indicate that, for a given tensile strength, abrasion rates are insensitive to elasticity. The few experiments that have been conducted on erosion by plucking highlight the importance of block protrusion height above the river bed, and the dominance of block sliding and toppling at knickpoints. These observations are consistent with new theory for the threshold Shields stress to initiate plucking, which also suggests that erosion rates in sliding- and toppling-dominated rivers are likely transport limited. Major knowledge gaps remain in the processes of erosion via plucking of bedrock blocks where joints are not river-bed parallel; waterfall erosion by toppling and plunge-pool erosion; feedbacks between weathering and physical erosion; erosional bedforms; and morphodynamic feedbacks between channel form and erosion rates. Despite scaling challenges, flume experiments continue to provide much needed tests of existing bedrock-erosion theory, force development of new theory, and yield insight into the mechanics of landscapes.

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1. Introduction

Models of landscape evolution driven by fluvial bedrock erosion are used to simulate feedbacks between mountain growth, lithospheric deformation, and global climate change (e.g., Willett, 1999); the structure of mountain belts (e.g., Howard, 1994); and the spacing of hills and valleys (e.g., Perron et al., 2008). Inversely, these models are used to reconstruct the tectonic and uplift history of continents (e.g., Whipple, 2004; Kirby and Whipple, 2012; Roberts et al., 2012; Croissant and Braun, 2014), decipher the imprint of glaciation and precipitation on topography (e.g., Brocklehurst and Whipple, 2007; Ferrier et al., 2013), and quantify the history of rainfall on Titan (Black et al., 2012) and on early Mars (e.g., Howard, 2007). The vast majority of these models drive landscape change through simple rules for river incision into bedrock by assuming that fluvial erosion rates (E) are a function of drainage area and local channel slope, often referred to as the stream-power erosion model (Howard and Kerby, 1983),

$$E = KA^m S^m \tag{1}$$

where A is the drainage area; S is the channel slope; and K, m, and n are empirical constants. Recent developments in exposure-age dating have revealed that catchment-averaged erosion rates (which typically average over 10^3 to 10^4 years) tend to follow Eq. (1) but that the coefficients in Eq. (1) vary widely in different landscapes (e.g., Ouimet et al., 2009; DiBiase et al., 2010), often attributed to differences in rock type and climate. These findings cast doubt on the predictive power of Eq. (1) outside of the landscapes and time scales for which the model has been calibrated.

To build more robust predictive models, the past 15 years have seen a surge in research focused on advancing new theory for the rate of bedrock river incision that attempts to incorporate the mechanics of specific erosion processes while remaining computationally tractable for landscape evolution simulations over geologic time. Much of the new insight to drive quantitative theory has come from simulating bedrock erosion in laboratory flume experiments, where bedrock erosion and channel evolution in the laboratory manifest over hours to weeks rather than the thousands of years that would be required to observe equivalent dynamics in nature. Outside of a few rare, extreme events (e.g., Lamb and Fonstad, 2010; Cook et al., 2013), annual-to-decadal observations of fluvial bedrock erosion in nature are limited to millimeters-to-centimeters of change (Fig. 1), resulting in negligible channel evolution and precluding direct observations of long-term feedbacks between water flow, sediment transport, bedrock erosion, and channel form. In contrast, flume experiments now allow direct measurements of these feedbacks through the development of erodible bedrock simulants and downscaling channel size that together speed the pace of bedrock erosion and channel evolution.

This paper is a synthesis of some of the key new developments in the mechanics of fluvial bedrock erosion from flume experiments, including new theories that have emerged as a result of experimentation. The paper is mostly a review of previous work; however, we do offer a few new ideas on bedrock erosion mechanics including bedrock-strength scaling, entrainment thresholds for plucking, and an assessment of bedrock analogs for experimentation. We focus solely on the mechanics of abrasion of rock by impacting fluvially transported particles and plucking of blocks of fractured rock. We focus on these two processes because they are arguably the most important erosion processes in bedrock rivers (e.g., Hancock et al., 1998; Whipple et al., 2000), they have received the most attention in recent experiments, and they have not been covered in detail in other review papers (Thompson and Wohl, 1998; Paola et al., 2009; Whipple et al., 2013). Consequently, a number of important processes are not within the scope of this paper. These processes include cavitation and groundwater sapping that have been suggested to play a role in bedrock-river erosion but to date lack conclusive field evidence (Whipple et al., 2000; Lamb et al., 2006). Entrainment of cohesive bed sediment from clear-water flows has been studied extensively experimentally (e.g., Dzulynski and Sanders, 1962; Shepherd and Schumm, 1974; Annandale, 1995; Brooks, 2001), but application of these results to bedrock rivers is unclear because rock erosion typically involves brittle fracturing (Engle, 1978). Corrosion, the collective weathering processes that weaken rock fabric and joints, is important in fluvial bedrock erosion, but to date has received little study experimentally (Hancock et al., 2011; Small et al., 2012; Whipple et al., 2013). Debris flows also erode bedrock channels, and there is growing work on debris-flow erosion mechanics from experiments (e.g., Hsu et al., 2008). Finally, a number of exciting experimental studies have been conducted to simulate the large-scale response of drainage basins or mountain ranges to climatic and tectonic forcing through use of sediment tables with tightly packed noncohesive sediment, rainfall misters, and base-level control (e.g., Hasbargen and Paola, 2000; Bonnet and Crave, 2003; Lague et al., 2003). These studies do not explicitly include the mechanics of abrasion and plucking, and we refer the reader to Paola et al. (2009) for a recent review.

With our focus set on the mechanics of abrasion and plucking from experiments and theory, we first discuss some of the issues in scaling laboratory experiments focusing on the relationship between rock strength and rock erodibility, which ultimately opens the door to quantitative-scaled experiments of bedrock erosion by abrasion. Second, we discuss how zero-dimensional bedrock abrasion experiments reveal a dominant and dual role of sediment supply in setting the rate of erosion, including the importance of bedload and of suspended sediment. Third, we review experiments that reveal strong feedbacks