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Fluvial erosion of physically modeled abrasion-dominated slot canyons

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Abstract

Abrasion-dominated fluvial erosion generates slot canyons in massive bedrock with intricately undulating walls. Flows in slot canyons are unusual in that the walls comprise a significant portion of the wetted perimeter of the flow during geomorphically effective floods. In Wire Pass, Utah, the upper Paria River incises through massive, crossbedded Navajo Sandstone. Incision in Wire Pass and related slots occurs only during flash floods; paleoflood debris indicates that the width/depth ratios of these flows are at times as low as 1:1. Submeter resolution field mapping of a 20-m length of Wire Pass shows that the wall morphology is a complicated combination of in-phase (meander-like) and out-of-phase (pinch and swell) undulations.

In order to investigate evolution of slot canyons and the influence of their wall shapes on flow dynamics, we recorded the evolution of four distinct canyon wall morphologies in a 2.4 m flume box at the St. Anthony Falls Laboratory. In a substrate consisting of ~3:2 mixtures of F110 sand and Plaster of Paris, we molded canyons with in-phase and out-of-phase undulations, and wide (6.5 cm) and narrow (4 cm) straight initial wall profiles. Discharges ranged from 1.4 L/s to 2.9 L/s, and wall and bed morphology were measured at 5 h intervals at 0.5 cm resolution.

Results show efficient back-eddy erosion in the undulating canyon walls and related erosional bedforms in all channels created by vortices in the flow. Maximum filaments of velocity are depressed and asymmetric, and the implied shear stress distribution varied in space and time on the channel beds. Flow width/depth ratios strongly influence the flow structure and distribution of shear stress in a slot and appear to be a factor in dictating whether a bedrock channel widens its walls or incises its bed.

Keywords: Bedrock channel; River incision; Channel width; Physical modeling

1. Introduction

Bedrock channel incision is an important component of landscape evolution. As bedrock channels set the boundary condition for surrounding hillslopes in tectonically active regions, they pace the evolution of the surrounding landscape (Anderson, 1994; Howard, 1998; Sklar and Dietrich, 1998). Most bedrock channels erode through a combination of abrasion, quarrying, and dissolution. In this study, we examine slot canyons, an end-member case in which erosion is abrasion-dominated. Field measurements of slot canyons guided the design of laboratory models, which

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we used to explore the evolution of slot canyon wall morphology.

There are gaps in the current knowledge of bedrock incision. The current paradigm for bedrock incision assumes that erosion is proportional to stream power, Ω, expressed as

$$\Omega = \rho \cdot g \cdot Q \cdot S \tag{1}$$

where ρ is the density of water, g is the acceleration of gravity, Q is discharge and S is channel slope, or to specific stream power, ω, the power loss per unit area of the bed:

$$\omega = \frac{\rho \cdot g \cdot Q \cdot S}{W} \tag{2}$$

where W is channel width. Given the importance of channel width, a proper erosion law should allow for both lowering of the bed and widening of the walls.

Lave and Avouac (2001) acknowledged the importance of accounting for each variable in river incision and suggested that channel width is a dynamic part of the system. They found that, in Himalayan rivers with relatively high peak discharges, channel width is inversely related to incision rate. These rivers appear to decrease their width, rather than increase their slope, to accommodate the uplift of rock. In rivers with lower peak discharges, both slope and width adjust to account for higher incision rates (Lave and Avouac, 2001). Hancock and Anderson (2002) attempted to accommodate valley-wall widening by assuming that channel wall erosion is similar to channel incision in that it is related to specific stream power. They propose that

$$\frac{\mathrm{d}w}{\mathrm{d}t} = W \cdot K_W \cdot \omega, \tag{3}$$

where $\mathrm{d}w/\mathrm{d}t$ is the lateral erosion rate, and K_w reflects the susceptibility of rock to erosion and relates stream power to channel wall erosion. The rate of widening was also tied to the ratio of channel width to valley width in order to acknowledge the probability that the channel has a bedrock wall.

Recently, Finnegan et al. (2005) proposed that channel width in bedrock rivers should be expressed as

$$W = [\alpha(\alpha + 2)^{2/3}]Q^{3/8}S^{-3/16}n^{3/8}, \tag{4}$$

where α is the width-to-depth ratio and n is roughness. This equation is the first to incorporate the width-to-depth ratio of flow in a prediction of width in bedrock channels.

With these few exceptions, little attention has been given to what sets channel width, its evolution through time, or the details of the channel wall erosion processes. We turn to the end-member case of abrasion-dominated slot canyons to explore these issues.

2. Slot canyons

Slot canyons are extremely narrow (usually <5 m) channels cut deeply (up to 100 m) into bedrock (Fig. 1). The smooth, often nearly vertical canyon walls are often cut into massive sandstone formations. Many slot canyons fill with water only during flash floods, making flood prediction, warning, and field study of flow dynamics difficult. While some slot canyons contain standing or slow-moving water for most of the year, the less frequent, high-flow events erode the channels.

Slot canyon walls undulate in wallforms, in analogy with the bedforms that ornament the floors of a channel (Wohl et al., 1999). Large-scale canyon orientation often depends on pre-existing fractures and regional joint patterns. While the average canyon direction may be straight, wallforms on opposing walls undulate in and out of phase with one another (Fig. 1). The mechanism that sets the style of undulations is unknown, but Wohl et al. (1999) and Wohl and Merritt (2001) suggested that out-of-phase undulations allow the high velocity flow in the center of the channel to incise downward rather than widen the channel. The amplitude of the undulations may be limited by the amount of energy available after lateral flow separation around wall bumps extracts energy (Wohl et al., 1999; Wohl and Merritt, 2001). Wallforms likely act as hydraulic energy diffusers much like traditional bedforms, effectively reducing velocity and minimizing energy expenditure between each pinch and swell (Yang, 1971; Cherkauer, 1973; Keller and Melhorn, 1978; Carling, 1989; Wohl et al., 1993; Wohl et al., 1999). Previous studies of bedrock channels suggest that wallforms might be remnants of potholes abandoned after knickpoint propagation (Angeby, 1951; Shepard and Schumm, 1974; Bishop and Goldrick, 1992; Wohl, 1993, 1998; Wohl et al., 1999). In these situations, the style and rate of pothole growth is important to determining channel incision rates (Springer and Wohl, 2002; Springer et al., 2005).

3. Previous physical modeling of bedrock channels

Previous physical models of channel incision used either weak or hard substrates, and examined the role of different variables in incising channels and developing erosional bedforms. With weak substrates of mud settled out from suspension, Dzulynski (1965) used turbidity