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 5h 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.

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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, $Q$, expressed as

$$\Omega = \rho \cdot g \cdot Q \cdot S$$  \hspace{1cm} (1)

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

$$\omega = \frac{\rho \cdot g \cdot Q \cdot S}{W}$$  \hspace{1cm} (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

$$\frac{dW}{dt} = W \cdot K_w \cdot \omega,$$  \hspace{1cm} (3)

where $dW/dt$ 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

$$W = [\alpha (\alpha + 2)^{2/3}] Q^{3/8} S^{-3/16} n^{3/8},$$  \hspace{1cm} (4)

where $\alpha$ 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 propagation 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
currents to erode channels. Allen (1969) and Karcz (1973) used settled-mud substrates and examined the bedforms produced from clear water flows. Shepard and Schumm (1974), Holland and Pickup (1976), and Gardner (1983) mixed substrates of kaolinite, sand, clay, and silt. They lowered base level to drive incision and watched knickpoint evolution and channel groove formation. Most recently, Wohl and Ikeda (1997) built models with a sand and bentonite substrate. They held all variables constant, except for gradient, and measured its effect on bedform development, evolution, and channel incision. They found that an increased gradient causes a decrease in channel width/depth ratio.

The physical models employed in our study expand on the knowledge gained from previous studies. We developed a new, resistant, cohesive substrate and examined the effects of different wallforms on channel incision and flow fields. We monitored the rate of wallform evolution and studied specifically the effects of varying wall shapes on flow velocity fields and on channel incision rates and patterns. In addition, we studied the effects of different width/depth ratios of flow and their relationship to channel widening or deepening. Our study explores specific, small-scale processes and relates them to larger-scale issues of bedrock incision. In describing bedforms and wallforms formed in our experimental canyons, we use the terminology suggested by Richardson and Carling (2005).

### 4. Field observations

#### 4.1. Field setting

Wire Pass and Buckskin Gulch, Utah, are tributaries of the Paria River, which flows from its source in Bryce Canyon National Park to the Colorado River and has its confluence with the Colorado River at Lees Ferry, Arizona, directly below Lake Powell and the Glen Canyon Dam. Located SE of center on the Pine Hollow Canyon Utah-Arizona Quadrangle 7.5′ map, Wire Pass and Buckskin Gulch incise a portion of the Navajo Sandstone before their confluence with the Paria River (Fig. 1D). Wire Pass and Buckskin Gulch range in width from <1 to ∼5 m in the slotted sections, and in depth from ∼5 to ∼40 m. Neither channel is gauged. Wire Pass has a drainage area of ∼200 km², upper Buckskin Gulch of ∼790 km² and lower Buckskin Gulch of ∼1000 km² (Wohl and Merritt, 2001). The source area for both is the Kaibab Plateau.

#### 4.2. Field methods

In April 2003, we measured canyon width and morphology in Wire Pass and Buckskin Gulch, UT, and visited Antelope Canyon, AZ, for general comparisons.
Our field goals included quantitatively characterizing the nature of undulations in slot canyon walls.

In a representative stretch of Wire Pass, we measured canyon width in order to construct a Digital Width Model (DWM). We placed a laser range finder on a tripod in the center of the canyon at successive points upchannel. At each point, we measured the vertical and horizontal distance from the range finder to several locations up the canyon wall. We measured the distance between points with the range finder as well and recorded each angular offset using a Brunton compass. When gridded, the DWMs document the morphology of each canyon wall.

4.3. Field data

The width of Wire Pass varies widely. In a 450-m section of canyon measured at 5-m resolution, the width of Wire Pass varies from 0.8 to 5.8 m. The mean width is 2.4 m with a standard deviation of 1.0 m. The wavelength of canyon widening and narrowing is highly variable but is usually between 5 and 10 m. The canyon width does not correlate with the style of wall undulations.

The DWM of a 20-m section of Wire Pass shows wall shape and undulation style (Fig. 2) with detailed wall contours at 0.1-m resolution shown for each wall. Both in- and out-of-phase undulations are highlighted.

The Wire Pass channel bed is mantled everywhere with sediment. On average, 50–60% of a 1-m² surface area section of the channel floor of Wire Pass is sand. The remaining 40–50% area contains clasts with a mean size (B axis) of 1.2 cm. The maximum grain size of the 100 randomly measured clasts was 8.6 cm, while the minimum was 0.2 cm.

In sum, our field data shows that the abrasion-dominated fluvial erosion generates intricately undulating in- and out-of-phase walls in straight-trending slot canyons.

![Fig. 2. Wire Pass Digital Width Model (DWM) and wall contours. DWM highlights both in-and out-of-phase undulating wallforms (A); contour plot of NE wall (B) and SW wall (C) show detailed wall bumps. Contour intervals in meters are measured from a canyon centerline.](image)
Because of the remoteness of the terrain and ephemeral nature of flash floods, direct field study of canyon incision processes is difficult. We turned to physical models of slot canyons in order to study the relationship of canyon walls and bed with each other and with the flow on both reach and local scales. We examined the processes that set the phase relationship of opposite walls, and we set out to understand when the canyons preferentially incise or widen.

5. Laboratory methods

Inspired by the measured morphology of slot canyons in the field, we built and tested physical models at St. Anthony Falls Laboratory, University of Minnesota. We developed an analog substrate for sandstone and constructed several preliminary and four final physical models of slot canyons. Our initial goals included monitoring the effects of different wallforms on the flow, measuring flow velocities, and watching the evolution of both wallforms and bedforms.

5.1. Analog substrate development

We tested 15 combinations of F110A silica sand, Plaster of Paris, Portland Cement Grade A, lightweight setting-type Sheetrock Joint Compound, and Quickcrete concrete acrylic fortifier in order to develop an appropriate analog substrate for the Navajo Sandstone. The properties of each mixture are listed in Table 1. We mixed each sample with water using an electric drill with a mud mixer attachment and poured them into 2 L plastic containers to set for 24 h. After setting, we removed each mixture from its plastic container and aimed a stream of water at the sample for 1 h. We evaluated each sample for structural integrity (the degree to which the sample retained its original block shape), tendency to dissolve, and erodibility on an appropriate timescale (Table 1).

5.2. Trial slot box configurations

We constructed three experimental slot box configurations to test substrate mixtures as well as different model setups. They included a standing wooden box ~1/100 scale, an in-flume flat mold with a shallow initial slot groove, and an ~1/20 scale in-flume mold with removable initial slot mold.

5.3. Final slot box configuration

We built the final experimental slot box out of wood and waterproofed it with Vulcum™ sealant. The box contained four different initial slot conditions: pinch-swell (slot A), meander-like (slot B), straight-wide (slot C), and straight-narrow (slot D) (Fig. 3). In order to set the initial conditions, we built a mold for each slot out of wood, cut foam, and plastic sheeting. We attached each slot mold to wooden planks, set them in the wooden box, and poured the substrate mixtures around them. We alternated the mixture layers #11 (50–50 sand–plaster) and a mixture with slightly less sand content than #7F (63–37 sand–plaster). In addition, we colored the layers with alternating pink, buff, and gray dye to allow easy visual tracking of layer erosion. After the substrate set, we removed the planks. Each slot started with a flat (zero) slope. A 15.2-cm inflow pipe tapped Mississippi River water, which filled the head box, flowed over a weir wall and down all four slots simultaneously. The

<table>
<thead>
<tr>
<th>Trial name</th>
<th>Sand (mL) (%)</th>
<th>Plaster (mL) (%)</th>
<th>Cement (mL) (%)</th>
<th>Joint set (mL) (%)</th>
<th>Fortifier (mL) (%)</th>
<th>Structural integrity</th>
<th>Dissolve</th>
<th>Usable timescale</th>
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<td>1</td>
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<td>60 4.0</td>
<td>800 61.5</td>
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<tr>
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river water had negligible concentration of solids; most of these solids were colloids and organics, not clastic sediment. We set a uniform base level at the end of each channel in the outflow or tail box, which drained through a drainpipe (Fig. 4). We ran the experiment in 5-h intervals with breaks for wall and bed morphology measurements for a total of 25-h.

5.4. Instrumentation

In order to monitor wall morphology and erosion rates through time, we used a laser with mirror attachment connected to a moving cart. We used a Keyance LK-500 laser in long-range mode connected to a computer-controlled moving cart. We attached a vertically adjustable point gauge to both the laser box and a 45° mirror. The laser made horizontal transects of each wall at 0.5-cm resolution in all four slots. We used the point gauge to adjust the height in 1.5-cm increments, and a manual hand crank to move the laser and cart infrastructure between each of the slots. The cart never obstructed the flow. We made wall measurements only when the water was drained from the slots.

5.5. Velocities

In each slot, we measured the two-dimensional velocity flow field. In slot A, we measured flow fields at successive pinch and swell sections of the channel. In slot B, we measured flow fields at both left and right bends in the channel, as well as a section in between bends. In slots C and D, we measured a single flow field in the middle of each reach.

A 0.5-cm diameter turbine Digiflow Velocity Flow Meter with analog output was mounted with a thin, vertical rod to the same cart that held the laser in order to adjust accurately the vertical and horizontal position of the turbine. The head of the turbine was ∼0.5-cm in diameter. We made all measurements at 1-cm resolution in both dimensions.

5.6. Sediment

We intermittently experimented with a sediment feeder in the final slot box and in several of the calibration trials. In each case, we used an AccuRate Instrumentation feeder with medium grain size (0.25–0.5 mm) Lakeland Sand. In addition, we also experimented with 0.2–1.5 cm diameter pebbles in the final slot box in order to see if they influenced significantly the morphology of the channels.

6. Laboratory data

6.1. Appropriate substrates

Out of the 15 different substrate combinations tested for use in this experiment, two combinations of sand and
plaster fit our requirements (Table 1). Substrates were evaluated on their structural integrity, ability to erode on a usable timescale, and tendency to dissolve. The substrates containing either cement or joint set tended to dissolve rather than abrade. The sand/plaster ratio determined the structural integrity of the substrate and its ability to erode on a usable timescale: the higher the proportion of sand, the weaker the substrate, and the shorter the timescale. We ultimately chose a ratio of 63% sand and 37% plaster by weight, layered with 50% sand and 50% plaster by weight.

6.2. Flow properties in each experimental channel

Each channel filled simultaneously with water from the head box. Discharges ranged from 1.4 L/s in slot D to 2.9 L/s in slot B, with slot A at 1.5 L/s and slot C at 2.6 L/s. Discharge varied between channels only because of channel geometry differences. The initially flat bed gradient in each slot required that the water surface slope toward the tailbox; the flow declined in thickness down-channel. While this situation likely is not representative of any field situation, it allowed us to evaluate a range of flow width/depth ratios simultaneously in each channel.

6.3. Surface morphology differences

The flow properties, including flow surface morphology, and one- and two-dimensional velocity profiles, varied considerably among the slots (Fig. 5). In slot A, the flow surface was hummocky; it rose before the pinches and fell as it spilled into the swells (Fig. 5A). In general, a zone of high velocity was focused down the
center of the channel and created a zone of critical and supercritical flow near the tail end of the channel where water depths were shallower, while the margins of the swells were occupied by circling eddies and subcritical flow. Wohl et al. (1999) observed a similar phenomenon in both flume and modeling studies. Foam particles dropped into the flow for particle image velocity tests confirmed this observation; they either traveled quickly and directly down the channel or became trapped in an eddy indefinitely.

In slot B, the flow surface was super-elevated around bends in the channel (Fig. 5B). Because of the in-phase shape of the walls, the flow used the entire channel instead of simply a central core as described for slot A. Foam particles dropped in the flow frequently impacted first one wall, then the opposite wall, as they traveled down the channel. The surface velocity, as seen from the foam particle velocity comparisons, was markedly slower than in the straight channel, slot C.

The flow surface morphology in slot C was distinctly flatter than both of the undulating channels, but a clear pattern of interference waves was present (Fig. 5C). Foam particles dropped in the flow did impact the walls, but not as frequently as in slot B. The flow surface morphology in slot D was much like that in slot C, with an interference wave pattern.

6.4. One-dimensional channel velocity profiles

Velocities measured in the center of each channel reached 0.7 m/s at or near the surface (Fig. 6). In slots A and B, velocities at the surface of the flow were slower than those 2–3 cm deep (Fig. 6A,B). This depression of the maximum filament of velocity is also seen in slots C and D, but to a lesser extent (Fig. 6C,D). The fluctuating water surface made it difficult to measure the entire water column in slot A.

6.5. Two-dimensional channel velocity profiles

Velocity measurements made at 1-cm gridded intervals show the full range and distribution of velocities in each channel (Fig. 7). In Fig. 7A, a two-dimensional cross-sectional velocity profile in slot A is shown at both a channel pinch and a swell. In both, a filament of the highest velocity is seen centered about 2 cm below the surface. In the swell, this filament is wider than in the pinch. Slot A is of the same general morphology as the modeled channel in Wohl et al. (1999) and it is useful to compare our empirical results with their physical and HIVEL2D models of canyons with undulating walls. In both slot A and the Wohl et al. (1999) models, the swell

![Fig. 5. Video stills of flows looking upchannel in slots A (A), B (B), and C (C). In (A), surface flow is superelevated before the pinches compared to the swells. Flow is critical and supercritical in the pinches towards the tail end of the channel. The sides of the swells have subcritical flow throughout. In (B), surface flow is deflected off channel walls and superelevated around curves. In (C), flow surface is flat with a wave interference pattern.](image-url)
and pinch widths are the same, but the wavelength of wallforms is 4 cm greater in slot A. Relative relationship values of pinch/swell surface velocities are comparable between slot A, and the Wohl et al. (1999) models. In all three cases, surface velocities in the center of pinch are highest, followed by velocities in the center of the swell. Velocities measured from the center of the swell towards the walls drop off rapidly at a distance around the width of the pinch in each experiment.

For slot B, velocity profiles are shown for a channel bend to the left, a channel bend to the right, and a crossover section between the two bends (Fig. 7B). In each channel section, the filament of highest velocity is located about 2 cm below the water surface. In the right bend, this filament clearly swings to the right side of the channel; while in the left bend, it swings to the left; and in the narrow crossover section, the high velocity filament is in center of the channel.

In slot C, the high velocity filament is centered about 3 cm below the surface (Fig. 7C). Its magnitude is less than that in slots A and B. A long, narrow zone of high velocity is seen in slot D (Fig. 7D). The highest velocities are closer to the surface than in each of the other channels, but are still depressed below the flow surface.

6.6. Channel wall erosion

All four channels eroded both their beds and their walls. However, the style and loci of maximum erosion varied greatly within and between the channels.

In slot A (pinch and swell), we found that wall erosion focused generally in the upchannel portion of the slot, with local centers of maximum erosion directly upflow of the widest points in the walls, in the lee of wall bumps. The left wall began to collapse towards the end of the experiment. An example erosion rate map of the right wall highlights the local areas of high and low erosion rate (Fig. 8A,C). The left wall shows high erosion rates resulting from the wall collapse. Erosion rates in slot A vary between negative values (where the wall collapsed forward into the canyon) and \( \sim 4.7 \text{ cm/h} \) on the left wall, and between 0 and 0.3 cm/h on the right wall (Table 2).

In slot B (meander-like), on both the left and right walls, the loci of highest erosion are on the lee (downstream side) of wall bumps, similar to slot A. The erosion rate map of slot B is shown in Fig. 8B,D. The left wall of slot B eroded at rates ranging from \( \sim 0 \) to 0.57 cm/h, while the right wall eroded at rates between \( \sim 0 \) and 0.17 cm/h (Table 2).

In slots A and B, erosion rates were higher on the left wall than the right wall in both channels. This might be explained from an asymmetry in flow reattachments on the rear side of wallforms. In a number of experimental studies of flow expansions, instabilities arise in flow expansions, and cause preferred reattachment to one side of the channel over the other (Patterson, 1938; Scott-Moncrieff, 1974; Mehta, 1979; Carling, 1989). If particles suspended in the flow or fluid stressing causes wall erosion, as discussed in Sections 7.2 and 8.3, then...
these flow instabilities may explain why in both slots there was greater erosion on the left wall.

Erosion rates in slot C (straight-wide) were highest upchannel, with most of the wall erosion near the surface and bed of the slot near the channel head (Fig. 9). The left wall of slot C eroded at rates ranging from 0.01 to 0.22 cm/h, while the erosion on the right wall ranged from 0 to 0.70 cm/h (Table 2).

In slot D (straight-narrow), we found that wall erosion rates were also highest in the upchannel portion of the slot and tapered to lower values downchannel (Fig. 10). Erosion rates on the right wall reached 0.45 cm/h, while on the left wall they reached 0.30 cm/h (Table 2).

No large-scale wallforms developed in any of the slots; but hummocky, small-scale (1–2 cm) bumps formed almost ubiquitously along the walls of each channel. Not surprisingly, we found that slots, regardless of wall shape, showed a tendency to erode weaker layers of substrate, the layers with a higher sand content, more rapidly than stronger layers.

Fig. 7. Two-dimensional velocity profiles and showing depression of the maximum filament of velocity in each channel. In slot A (A), filament of highest velocity is narrower in the pinch than in the swell. In slot B (B), filament of highest velocity bends around the outside of each curve and through the center in between curves. Slot C (C) and slot D (D) also show the depression of maximum filament of velocity.
6.7. Channel bed incision

Channel bed profiles of slots A, B, and C show incision progressing gradually from channel tail upchannel, reflecting the steady lower base level formed by the tailbox. In contrast, slot D appears to incise by the migration of a knickpoint upchannel (Fig. 11). All slots show some incision at the channel head, presumably reflecting the plunge of water from the head box. Incision rates along each channel are fairly uniform and steady in the center of the reach (Fig. 12). Bed incision rates averaged 0.23 cm/h in slot A, 0.19 cm/h in slot B, 0.19 cm/h in slot C, and 0.23 cm/h in slot D (Table 2). Erosion rates within each channel vary locally (Fig. 13).

Channel bottom topography differed significantly in each channel (Fig. 13). In slot A, flutes with external secondary structures formed directly upflow of the pinches. The flutes were close to parabolic in plan form, but some had a slight asymmetry (Fig. 14A). In slot B, flutes with both external and internal secondary structures were observed (Fig. 14B).
structures appear to launch from both walls; their plan form shapes are more crescentic than parabolic, and the ends of the crescents often converged in the channel center (Fig. 14B). We found that the bed was topographically higher on the left side in left channel bends, and on the right side in right channel bends. In slot C, bedforms began as parabolic flutes in the channel center and evolved into larger, deeper, canyon-width flutes with internal and external secondary structures through time (Fig. 14C). Some appeared to have median ridges. Canyon bottom topography varied. At times, the canyon bottom was topographically higher on the left side of the channel than on the right, and at times it was higher on the right than the left side. We found a similar left-right bottom oscillation in slot D. Bedforms in slot D were smaller in scale than in the other channels and distinctly rounder, although they should still be classified as flutes (Fig. 14D). When we added a small number of 0.2–1.5 cm diameter pebbles to the system, potholes formed readily in each of the channels. The pebble commonly became caught in an eddy and focused pothole formation. The potholes occasionally became nucleation sites for the formation of flutes downstream of the pebble. Overall, the effect of pebbles in this experiment was minor compared to those of abrasion and fluid stressing in eroding the bedforms and wallforms.

6.8. Rates of incision versus widening

Widening to deepening rates varied between the slots (Fig. 15). In general, the rate of widening versus deepening increased upchannel in each slot; slots tended to widen more readily in the head of the channel and to incise more readily in the tail (Table 2). This effect is discussed below.

7. Discussion of data and techniques

7.1. Experimental velocities

In each experimental slot, the velocity data collected in this study shows the highest velocities centered slightly below the flow surface. While the flow did bend around curves in slot B, and pinched and narrowed in slot A, a depression of the maximum filament of velocity was documented in every channel. The depression was less prominent in the straight channels than in the undulating slots (Fig. 6). In slot B, the filament was focused closer to the right wall on the right bend, and the left wall on the left bend (Fig. 7). This depression of the maximum filament of velocity is expected in channels with low width/depth ratios and has been documented in a number of experiments ranging from the 19th century to the present (Stearns, 1883; Gibson, 1909; Vanoni, 1946; Wang et al., 2001; Yang et al., 2004).

7.2. Laboratory experiment erosional mechanism

The mechanism for abrasion in the experimental slots is likely a combination of processes. Although we added some sediment as a feed to the experimental slots, we

| Table 2 Wall and bed erosion rates measured at five positions in each channel, and width/depth erosion rate ratios |
|-----------------|--------|--------|--------|--------|
| Type            | Location/Value | Slot A  | Slot B  | Slot C  | Slot D  |
| Channel bottom erosion rate (cm/h) | 5 cm | 0.652  | 0.486  | 0.778  | 0.355  |
|                 | 50 cm | 0.18   | 0.185  | 0.252  | 0.473  |
|                 | 150 cm| 0.131  | 0.203  | 0.173  | 0.248  |
|                 | 250 cm| 0.118  | 0.146  | 0.09   | 0.14   |
|                 | 350 cm| 0.158  | 0.076  | 0.134  | 0.162  |
|                 | Maximum| 1.002  | 0.7896 | 1.2588 | 1.0626 |
|                 | Minimum| 0.0468 | 0.0336 | 0.0408 | 0.0576 |
|                 | Mean   | 0.2281 | 0.1883 | 0.1895 | 0.2317 |
|                 | Standard dev. | 0.1694 | 0.114  | 0.1332 | 0.1327 |
| Left wall erosion rate (cm/h) | 5 cm | 0.302  | 0.037  | 0.112  | −0.002 |
|                 | 50 cm | 0.361  | 0.094  | 0.115  | 0.012  |
|                 | 150 cm| 0.439  | 0.059  | 0.114  | 0.036  |
|                 | 250 cm| 1.688  | 0.026  | 0.122  | 0.051  |
|                 | 350 cm| 1.066  | 0.043  | 0.123  | 0.044  |
|                 | Maximum| 4.794  | 0.57   | 0.219  | 0.3    |
|                 | Minimum| −1.126 | −0.305 | 0.012  | −0.236 |
|                 | Mean   | 0.724  | 0.056  | 0.121  | 0.033  |
|                 | Standard dev. | 0.684  | 0.04   | 0.099  | 0.02   |
| Right wall erosion rate (cm/h) | 5 cm | 0.104  | −0.004 | 0.082  | −0.01  |
|                 | 50 cm | 0.084  | −0.002 | 0.094  | −0.005 |
|                 | 150 cm| 0.107  | 0.008  | 0.105  | 0.011  |
|                 | 250 cm| 0.088  | 0.023  | 0.117  | 0.013  |
|                 | 350 cm| 0.13   | 0.036  | 0.123  | 0.027  |
|                 | Maximum| 0.304  | 0.174  | 0.699  | 0.451  |
|                 | Minimum| −0.043 | −0.073 | −0.099 | −0.323 |
|                 | Mean   | 0.171  | 0.016  | 0.113  | 0.014  |
|                 | Standard dev. | 0.024  | 0.007  | 0.033  | 0.02   |
| Combined wall erosion rate (cm/h) | 5 cm | 0.405  | 0.033  | 0.194  | −0.012 |
|                 | 50 cm | 0.445  | 0.093  | 0.209  | 0.007  |
|                 | 150 cm| 0.546  | 0.067  | 0.219  | 0.047  |
|                 | 250 cm| 1.776  | 0.05   | 0.238  | 0.064  |
|                 | 350 cm| 1.196  | 0.078  | 0.245  | 0.071  |
| Width/Depth erosion rate ratio | 5 cm | 0.622  | 0.069  | 0.25   | −0.034 |
|                 | 50 cm | 2.471  | 0.501  | 0.829  | 0.015  |
|                 | 150 cm| 4.174  | 0.328  | 1.267  | 0.189  |
|                 | 250 cm| 5.098  | 0.339  | 2.647  | 0.454  |
|                 | 350 cm| 7.549  | 1.034  | 1.826  | 0.438  |
did so infrequently and not at a constant rate. The sediment, therefore, is unlikely to be responsible for all of the erosion in the channels. Arguably, the sediment eroded off the head of the channel was employed to abrade the tail of the slot. Fluid stressing likely caused the erosion of sediment off of the head of the slot. We are confident that the slots were abrading and not dissolving because, in the trial substrate tests, the mixtures containing calcium carbonate that did dissolve displayed distinctly different morphologies than the erosional features seen in the final experiment. However, in all likelihood, the substrate probably did erode through dissolution to some extent in these longer duration flows; we have no way to quantify this. In addition, the Mississippi River water we used contained no significant size fraction of suspended sediment that could detach from the flow. We hypothesize that the mechanisms for erosion in the experiment were likely the mechanical impact of water turbulence loosening the sand in the substrate, fluid stressing, and abrasion farther downstream by particles that were freed from the upstream bed and walls of the channel.

7.3. Channel bed profiles and water surface profiles

Each channel in our experiment started with an initially flat bottom slope. This setup created a hydraulic gradient in each channel. While this setup does not properly mimic the situation in Wire Pass or other natural channels, it does allow us to compare varying width/depth ratios within each channel. We acknowledge that if we had imparted a gradient in the channels from the start, our results and observations, especially on a reach scale, may have been different. On a local scale, we think our setup still produced relevant results, as many of the small-scale features and erosional
patterns and bedforms in our experiment are also documented in the field.

8. Discussion of experimental slot evolution

8.1. Comparison of channel discharge, velocity, and incision rates

The velocity and bed incision rates in all of the channels are similar. Specifically, slots A and D are almost identical in terms of discharge, velocity, and vertical incision rate. We hypothesize that the pinch and swell undulating wallforms in slot A are directly responsible for this relationship. Apparently, the center core of slot A, the straight section defined by the dimensions of the pinches and excluding the swells, was the rate-limiting or effective cross-sectional area of the channel. The wallforms modulated the flow velocity and minimized energy expenditure in the channel.

Slots B and C accommodated about twice the discharge as slots A and D (Fig. 16). The in-phase undulations of slot B allowed the flow to use effectively the entire channel, as compared to the pinch and swell undulations of slot A. In slot B, discharges calculated from channel geometry at each of the locations and measured velocities yield values within 0.01 L/s of each

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Fig. 10. Wall erosion rates in slot D. The overall mean wall erosion rate is 0.05 cm/h.
Fig. 11. Canyon depths at 0, 10, and 25 h. Slots A, B, and C appear to incise gradually upstream, and slot D appears to propagate a knickpoint upchannel.

Fig. 12. Bed erosion rates for each slot from slot end to slot head.
other. Although we know they must be equal, because no water is being stored in the channel, it is reassuring that the independently calculated values give nearly the same result (Fig. 16). Slot C had a larger hydraulic radius and a larger width/depth ratio than slot D; it experienced less wall shear stress and displayed a higher mean velocity.

Because each slot started with a flat, nonsloping bottom, slope was set by the head difference between the top and bottom of each channel. At channel heads, the width/depth ratio of the flow was \( \ll 1 \), whereas at channel tails it was \( \gg 1 \) (Fig. 17). The flow thickness at the tail of the experimental slots declined through the experiment. The early deeper flow allowed shear and erosion on the channel walls. When the tail began to incise in a pattern that propagated upchannel, driven by the steep slope into the tailbox, the flow thinned as the velocity increased. The flow eventually lost contact with the upper portions of the walls as it incised downward.

8.2. Pattern of channel bed incision

In each experimental slot, a steady base level held significantly below the bottom of all of the channels drove channel bed incision. Incision rates were highest at the channel tails and evolved such that this incision propagated gradually upchannel (Fig. 12). The exception to this pattern is slot D; here, the incision was interrupted by a small crack that formed in the center of the channel bottom. Upstream from this, a

Fig. 13. Channel bottom topography after 25 h. Entire channel for all slots (A) shows gradual incision propagating upchannel in slots A, B, and C, and knickpoint in slot D. Close up section (B) shows that topography is affected by walls.
knickpoint propagated at a different rate upchannel than the gradual incision of other channels. In addition, each channel bed also incised at the channel head. This is likely the result of a boundary effect from the water entering the channel; water forced through the entrance of the headgate created a scour hole in the bed. These incision patterns are probably influenced by the initial flat slope of the channel, and
are not an exact proxy for the situation in Wire Pass and other natural slot canyons.

8.2.1. Velocity versus bed incision rate

A relationship between mean flow velocity and bed incision rate is evident in slots A and B. As expected in slot A, the mean flow velocity (measured across channel at 6/10 flow depth) is higher in the pinch than in the swell. The incision rate (measured at approximately the same location as the velocity in the center of the channel) was comparably higher in the pinch as well. We expect the velocities to differ, because discharge needs to be conserved within the channel. Sensibly, the flow is deeper and has a higher velocity in the pinch; it imparts more shear stress on the bed and increases the incision rate there. In slot B, the left and right bend velocities were slightly slower than the crossover velocity. Incidentally, the width of the crossover was slightly smaller than the width of the bends, and required the velocity be slightly higher in order to conserve discharge.

8.2.2. Channel wall erosion versus bed incision

The width/depth ratio of the flow affected channel wall erosion and bed incision. When the flow was deeper than it was wide, the bed incision (lowering) rates were lowest and wall erosion (widening) rates were highest; while when the flow was wider than it was deep, channels incised more rapidly and widened more.
slowly (Fig. 15). Deep, narrow flows tended to widen the channel in slots A, B, and C, while wide, shallow flows tended to incise the channel.

Taking into consideration what we know about slot canyons in the field, that flash floods with low width/depth ratios maintain narrow channels that do not appear to widen, our widening/deepening observations may not make sense intuitively. However, when the flow width/depth ratio is low, proportionally more of the wetted perimeter, and therefore shear stress, is focused on the channel walls than the bed, suggesting that preferential widening over deepening in those flow situations is not unreasonable. The two major features present in the field but lacking in our experimental slots are sediment

Fig. 16. Velocity, incision rate, and discharge comparisons. Velocities represent the mean surface velocity measured at a channel cross section. Incision rates are those at a single point in the center of the channel near the same location as the velocity measurements. Discharges are calculated from channel geometry and velocity. Maximum/minimum uncertainties are indicated.

Fig. 17. Variation in the width/depth ratio of flow at different points in the experimental slots. When width/depth < 1, channels preferentially widened. When width/depth > 1, channels preferentially incised. At some width/depth ratio ∼1, channel shape is at steady state and channels incised and widened at the same rates.

Fig. 18. Local scale erosion features in slots A and B show that high erosion rates in the back eddies on the lee side of wall bumps (A) create low-angle sharp cuspate edges out of the initial rounded sinusoidal wallforms (dashed) (B).
and an initial channel slope. Lack of a significant amount of mobilized bed sediment that we know exists in the field may explain why we are able to discern the wall widening in our experiments. We hypothesize that flows in the field, if devoid of bed sediment, might respond similarly to our experimental slots, but with the added factor of sediment that mantles the bed, downward incision is greatly enhanced. In addition, in our experiment, we varied channel width/depth while keeping discharge constant. In a natural system with a bed gradient, the lowest width/depth flows have higher discharges, and maybe velocities than high width/depth flows. The low width/depth flows in the field may simply impart more shear stress on their beds than in our experiment because of our initially flat bed setup.

In each experimental slot, canyon widening rates were higher at the channel head than at the channel tail (Fig. 15). These rates declined in the downchannel direction. The straight slot C had the highest mean flow velocity, but the slowest bed incision rate, and the largest wall erosion rate of any channel. Instead of a simple velocity/incision rate relationship, this suggests that the flow width/depth ratio played a significant role in the evolution of slot C.

The widening-deepening erosion rate ratios for slots A and B were strikingly different (Fig. 15). While the overall pattern of reach and local scale erosion was similar, slot A preferentially eroded its walls over its bed for at least the top 150 cm of the channel, whereas slot B preferentially eroded its bed for much of the reach. This suggests that the walls in slot A were more susceptible to lateral erosion. The wall collapse at the head of slot A made it difficult to get an accurate rate of widening.

8.2.3. Implications of channel wall shapes

Incision rates for all four slots are quite similar, despite wall morphology differences, and therefore differences in discharge. A major factor modulating the discharge in our experimental slots is wall shape. Out-of-phase undulations, like those in slot A, can accommodate a lower discharge flow down a channel at

![Fig. 19. Photograph of sharp cuspate edge wall evolution in Wire Pass (A); simplified, corresponding sketch showing hypothetical flow paths (B).](image-url)
velocities similar to those in a high discharge flow and can accomplish a comparable amount of incision.

The situation in Wire Pass is more complicated, as wall shapes are mixed in the field (Fig. 2). Possibly, the specific combination of wall shapes allows modulation of a range of flow velocity fields in response to varying discharges to accomplish similar incision rates and minimize energy expenditure.

8.3. Local scale wallform evolution

In the undulating slots, A and B, erosion was localized at specific sites among the wallforms. In both slots, the walls preferentially eroded on the lee side of wall bumps and not at the channel constrictions in slot A or the slightly narrower section between wallforms in slot B (Figs. 15 and 16). We presume that the flow was streamlined in these sections, and that the suspended abrading particles were moving parallel to the walls. We know that suspended particles with sufficient mass can detach from the flow as they move around bumps in the wall because the curvature of flow lines along the lee side of bumps is greater than the constrictions or connecting sections. In slot A, there is a symmetrical wall divergence. The flow expansion ratio is approximately 2, and the divergence angle is about 30° on each side. In slot B, there is an asymmetrical wall divergence. The flow expansion ratio is approximately 1.25, and the
The divergence angle is about 6.5°. Although we can not be sure that the flow was fully recirculating in the divergent zones of slot A and we are confident that it was not fully recirculating in slot B, we do know that these geometries caused a zone of preferentially high erosion in the lee of the wallforms, probably from a combination of particles impacting the walls and direct fluid stresses (Carling, 1989).

The processes of active, low-to high-angle sharp cuspat edge formation is described by Richardson and Carling (2005). The development of this phenomenon is clearly seen in the experimental slots. The initial smooth shape of the wallforms evolved toward a cusped edge with an asymmetry that highlights the importance of abrasion by suspended sediment (Fig. 18). Low-angle sharp cuspat edges are seen clearly in the field as well (Fig. 19). Even if wallforms are formed from potholes as suggested by Wohl (1993, 1998), and Richardson and Carling (2005) and discussed below, their long-term evolution is still unknown. Our results suggest that the wallforms may propagate upchannel, but longer duration experiments are necessary to test this hypothesis. In the straight channels, no distinct style of wallform developed over the limited duration of the experiment. In longer experiments, wallforms might form eventually.

8.3.1. The relationship of the wallforms to erosional bedforms

In the laboratory experiments, each slot produced unique erosional bedforms. This suggests that the wall shape directly influenced erosion on the beds. In slots A and B, the most common style of bedform was flutes. The shape of the flutes, especially in slot B, asymmetric parabolas with a deeper section near the walls that shallowed in the downflow direction, suggests that they formed from a large-scale vorticity in the flow set by the spacing of wallforms and the geometry of the flow.

We know that a zone of enhanced erosion occurred on the lee side of wall bumps. The back-eddy spinning around the edge of the wallform likely translates to the bed. The difference between the bedforms in slots A and B is their distribution on the bed. In slot A, the flutes are clustered in the channel swells, directly upflow of the pinches. In slot B, the flutes originate on the left side of the channel in the left bends and on the right side of the channel in the right bends. They decline in depth with distance toward the center of the flow, and the tips sometimes meet in the center of the channel.

We hypothesize that the vortices initiated by these wallforms generated the erosional bedforms. From observations of flow surface morphology (Fig. 5), we know that water in the pinches in slot A was super-elevated compared to the swells. This flow superelevation may also terminate, hinder, or raise the spinning of the vortices produced in the back eddies (Fig. 20A). In slot B, the largest flutes appear to originate on the wall with the back eddy (Fig. 20B).

In slot C, rounder flutes also form in the bed. However, the deepest point in the flute is often near the center of the channel and declines in depth toward the walls. As the experiment progressed, the flutes enlarged until many spanned the entire channel floor. The bed of slot C incised neither uniformly nor steadily. In a given cross section, the erosion of the canyon floor alternated,
preferentially eroding more on one side of the channel than on the other and then back to the other side.

The bedforms in slot C must have evolved from the complex turbulence in the flow, as there were no macro-wallforms in the initial slot. The straight walls likely allowed a high-speed core in the channel center, in which minor perturbations in the bed were self-enhanced from vortices on the bottom of the flow (Fig. 20C). The bedforms in slot D are small, rounded flutes. They resemble the forms in slot C, but at a much smaller scale.

Potholes formed in all of the channels when sand-pebble-size sediment was added to the flows and began to swirl around in vortices at the bed. In slots A and B, potholes formed in the back-eddy areas, while in slots C and D they were not confined to any part of the channel. In the field, the remnants of potholes are seen on the canyon walls (Fig. 21). While potholes and the coalescence of potholes are known to nucleate wallforms (Wohl, 1993, 1998; Richardson and Carling, 2005), we see that the converse is also likely true: vorticity created by preexisting wallforms created favorable areas on the bed of a channel to nucleate potholes.

9. Conclusions

9.1. Channel flows

Because many slot canyons only fill with water during flash floods, studying flow mechanics in the field is not trivial. Debris wedged as much as 5 m overhead between the channel walls serves as a reminder that large floods have occurred, but for much of the year the bed is dry. The flow through the laboratory models offered insight into possible processes active in the field. Because the experimental slots were molded with flat slope channel bottoms, flow was driven by a hydraulic gradient. This caused the width/depth ratio of flow to be <1 at the channel heads and >1 at the channel tails.

The resulting general erosion pattern from this varying flow width/depth ratio was similar in every channel: at the channel heads, the slots preferentially widened; while at the tails, they preferentially incised. Accordingly, most of the wetted perimeter at the channel head is wall rather than bed, while at the channel tail the bed comprises more of the wetted perimeter. Applying these results to field observations is challenging. Wohl et al. (1999) points out overhead silt lines as evidence of past flood depths, but the discharge and velocity of every flow that comes through the slots in our field study is not known or recorded. We assume that slot canyons in the field generally flood with low width/depth ratio flows. These are the floods that mobilize the 1+ m of bed sediment and access the bedrock. Based on our laboratory results and field observations, we believe that this sediment must be a major component of vertical bed incision in the field. Without sediment, natural slot canyons may preferentially widen their walls in low width/depth flows. Additionally, low width/depth flows in the field may impart more shear stress on the bed than our experimental channels suggest because they begin with a channel slope, have higher velocity, and can impart higher shear stress on the bed during high discharge.

9.2. Wallforms

Walls in real slot canyons undulated in two styles: pinch-swell and meander-like. Styles were intermixed, motivating our end-member laboratory model geometries. The style of wallform in the experimental channels strongly controlled the discharge in each channel. In the pinch and swell slot, the effective and active area of flow was set by the width of the pinches and maintained through the swells because of flow separation eddies created downstream of each pinch (Carling, 1989).

The force responsible for creating wallforms in the field is unclear. Individual wallforms may nucleate either from turbulence in the flow resulting in continued focused erosion on a single portion of canyon wall, or as an extension of a bedform or pothole. In the field, some wallforms clearly originated from potholes; it was possible to trace the carved out form of the pothole up the side of the canyon wall. In most cases, the bed was inaccessible, and the initiation mechanism was difficult to infer. In the laboratory, we created the straight channels in part to determine if wallforms would evolve spontaneously. While we found that small-scale features did arise, the experiments were not run long enough to allow macroform evolution. Potholes did form readily in all slots when sediment was provided, but we failed to find a connection between the potholes and wallform formation. Again, longer runs may have helped illuminate this relationship.

Finally, a clear connection exists between the local-scale abrasional pattern on the undulating wallforms in the laboratory and in the field. In the laboratory, both styles of undulations displayed the highest erosion rates on the lee side of wall bumps. This produces an upflow-propagating, low-angle cuspate edge shape similar to that seen in the field.
9.3. Bedforms

Bedforms were impossible to measure in the field, as the bed was mantled everywhere with 1+ m of sediment. The only bed-related features found in the field were two ∼3 m steps in the bed, but if these steps reflected the underlying bedrock or simply resulted from the jamming of large boulders and debris in the slot was unclear. In contrast, erosional bedforms in the laboratory were ubiquitous but unique to every channel. The style of wallform influenced the style and location of bedforms. Based on the morphology of erosional bedforms, we believe that the interaction of the walls with the flow created turbulent vortices that sculpted the bed flutes with abrasion by suspended sediment.

The clear interaction of the flow with the bed in the laboratory slots suggests that similar processes may be active in the field. However, in order for the flow to access the bed, it must first mobilize the thick sediment mantle. Determining the frequency and extent to which the flow accesses and erodes the channel bed remains a key element of the bedrock incision process that must be addressed in real field settings.

9.4. Sediment

More than a meter of sand and larger cobbles and boulders is readily available to erode Wire Pass and Buckskin Gulch. We know that suspended sediment is bombarding and abrading the walls of these field slots, and based on our widening/deepening observations in the lab, we presume that a fraction of bedload sediment contributes to channel evolution as well. Sklar and Dietrich (2004) highlight the importance and intricacies of incision by saltating bedload, noting that grain size, sediment supply and shear stress thresholds are both critical in determining whether a channel will incise through saltating bedload abrasion.

In the laboratory experiments, we attempted to set up a steady rate of sediment inflow to the slots, but lack of equipment made sediment input sporadic. We did not have bedload sediment in our experiments. We suspect that both fluid stressing and abrasion of freed particles eroded the channels; some unknown fraction of the erosion also could have occurred by dissolution, although our choice of substrate was designed to minimize this process. A steady supply of suspended sediment likely would have only enhanced the rate of formation of the features we have described. We believe bedload sediment would have increased bed incision.

9.5. Suggestions for further experimentation

By building on previous studies of bedrock incision in both the laboratory and field, we created a new substrate for physical modeling of bedrock incision through abrasion. Our experimental setup allowed for simultaneous monitoring of channels with a variety of wall shapes, and observation of varying width/depth flow ratios within each slot. Our channels did not have an initial imparted bed gradient, and they did not have a steady supply of suspended and bedload sediment. We believe future experiments should employ both of the above in order to most accurately simulate natural slot canyons and further the understanding of bedrock incision through abrasion.

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