Rates and processes of bedrock incision by the Upper Ukak River since the 1912 Novarupta ash flow in the Valley of Ten Thousand Smokes, Alaska

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ABSTRACT

The rates and patterns of bedrock channel incision significantly influence landscape evolution and long-term interactions among climate, tectonics, and erosion. Unfortunately, only sparse field data are available to quantify the controls on river incision rates. We exploit the diversion of the upper Ukak River by an ash flow in 1912 to measure rates of incision along a newly formed bedrock channel. Minimum estimates of the rate of incision into intact rock vary from 0.01 to 0.10 $m \cdot yr^{-1}$. This variation reflects differences in channel slope, channel width, lithologic facies, and intensity of jointing as well as the effects of upstream knickpoint migration. A stream-power–type incision model adequately explains the incision-rate data, provided (1) variations in channel width are prescribed on the basis of field measurements, (2) the slope exponent is significantly less than unity ($n = 0.4 \pm 0.2$), and (3) observed downstream changes in lithologic facies and the intensity of jointing account for the apparent twofold downstream decrease in the coefficient of erosion. Despite the very rapid rate of incision, calibrated stream-power erosion coefficients for the Ukak River ($K = 2.4 \times 10^{-4}\ m^{0.2} \cdot yr^{-1}$ to $9.0 \times 10^{-4}\ m^{0.2} \cdot yr^{-1}$) are within the range of previously published estimates. Two plausible explanations for the low values of the slope exponent *n* are that incision rate is limited by either (1) a combination of physical weathering and hydrodynamic joint-block extraction or (2) block fracture due to bedload impacts modulated on steeper channel segments by suspension of a significant fraction of the sediment load.

Keywords: geomorphology, fluvial erosion, erosion rates, Katmai National Park.

INTRODUCTION

Bedrock channels set the lower boundary condition on hillslopes such that channel-incision rates ultimately set the rate of landscape denudation even where landsliding is the dominant denudation process. In addition, bedrock channels set much of the relief structure of tectonically active landscapes and dictate relationships among relief, elevation, and denudation rate (e.g., Howard et al., 1994; Whipple et al., 1999). Further, bedrock channels play the critical role of communicating changes in boundary conditions (e.g., rock-uplift rate, sea-level fluctuation) across the landscape, thus controlling landscape response time (Whipple and Tucker, 1999). Because of their importance to a range of geomorphic and geodynamic problems, much research has recently concentrated on the quantitative description of these linkages between bedrock channels, climate, tectonics, and denudation rates (e.g., Howard et al., 1994; Tinkler and Wohl, 1998; Whipple and Tucker, 1999). A limitation, however, to recent theoretical developments is the sparse field data available to calibrate model parameters that describe the efficiency of bedrock erosion (Howard and Kerby, 1983; Stock and Montgomery, 1999).

In this paper we exploit a natural experiment in river incision into bedrock produced by the 1912 eruption that inundated the Valley of Ten Thousand Smokes, Katmai National Park, Alaska, with up to 200 m of volcanic ash (Hildreth, 1987; Kienle, 1991). The valley-filling ash flow displaced the upper part of the Ukak River (300 km^2 drainage area, annual flood discharge $\geq 100\ m^3 \cdot s^{-1}$), causing ~1.5 km of the length of the river to drape over an 80-m-high bedrock knob that had been covered by only a thin layer of ash (Fig. 1). As a consequence of this deflection, the upper Ukak River has carved a new bedrock channel into the underlying sandstones and siltstones of the Jurassic Naknek Formation (Riehle et al., 1993). Our survey of the site in June 1997 gave us an unprecedented opportunity to precisely measure the rate of bedrock-channel incision over an 85-yr period—free of the usual geologic uncertainties about boundary conditions, climate change, and exact timing of events (e.g., Stock and Montgomery, 1999) and similarly free of many of the uncertainties that accompany short-term (annual or seasonal) process-rate measurements (e.g., Hancock et al., 1998).

METHODS

Standard techniques with a transit, stadia rod, and tape were used to survey a precise channel plan-view map, a longitudinal profile, and 15 cross sections[1] along the ~1.5 km stretch of the river that is incised into bedrock (Fig. 2). Observed cross-sectional morphologies typically consisted of a broad outer channel and a deep, narrow inner channel. In some strongly joint controlled sections, the inner channel is very narrow (1–1.5 m)

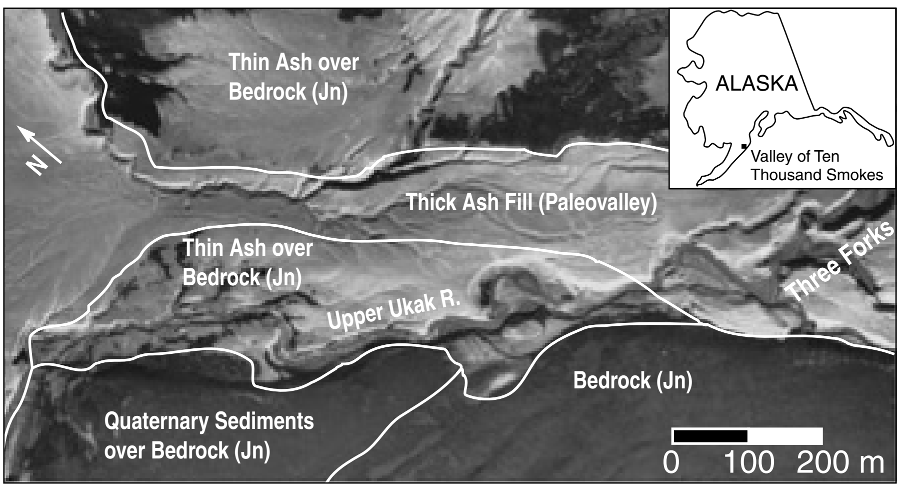

Figure 1. Aerial photograph of study reach showing ~200 m southwest deflection of upper Ukak River from paleovalley bottom. Darker tones are due to vegetative growth in areas either unaffected by ash flow or only thinly covered by ash. Jn is Jurassic Naknek Formation.

[1]GSA Data Repository item 200089, Cross-section data and modeling results, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

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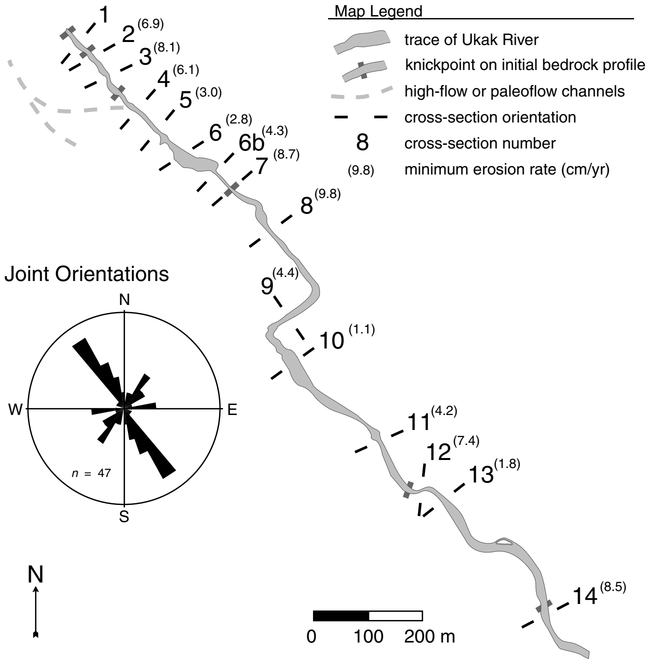

Figure 2. Plan-view survey of study reach indicating cross-section locations, minimum incision rates determined at each cross section (in parentheses), and locations of knickpoints in initial, unweathered bedrock surface. Rose diagram shows measured orientations on prominent joints.

and deep. Channel depth was measured with a 6-m-long pole graduated in decimeters. Despite the length of this probe, in a few cases (cross sections 2, 3, 7, 8) we were unable to reach the channel floor, yielding only minimum estimates of the total depth of incision.

In addition to these surveys, we made detailed observations and measurements of spatial variations in lithologic facies, bedding style and attitude, intrinsic rock strength, joint spacing and orientation, degree of weathering along joint surfaces, and erosional forms indicative of active erosion process(es). Following Whipple et al. (2000), we infer that plucking processes are dominant where channel bed and banks are primarily exhumed joint surfaces and where recently displaced, but intact, joint blocks are present. By this definition, "plucking" thus encompasses the combined effects of physical weathering, bedload impacts, and hydrodynamic lift in the fracture and extraction of joint blocks. Conversely, where exhumed joint surfaces are not prominently developed and channel bed and banks are dominated by smooth, polished surfaces adorned with flutes and potholes, we infer that abrasive processes are dominant.

We use the derived incision-rate data to place constraints on the well-known stream-power (or similar shear-stress) incision model (Howard and Kerby, 1983):

$$\varepsilon = KA^m S^n, \tag{1a}$$

$$\varepsilon = K'(S/W)^n, \tag{1b}$$

where ε is the bedrock incision rate (in meters per year), K and K' are dimensional coefficients, S is river gradient (in meters per meter), drainage area (A) appears in equation 1a as a proxy for discharge per unit channel width (W), and m and n are positive constants. As there are no lateral inflows along the short study reach of the ungauged Ukak river, we primarily utilize a simplified form of the stream-power incision model (equation 1b) in which discharge is held constant and absorbed into the coefficient of erosion (K'). We employ the standard form (equation 1a) only to compare our results with published estimates of K.

LITHOLOGY AND JOINTING

Along the incised reach of the Ukak River, the Jurassic Naknek Formation is tilted into a gentle southwest-dipping homocline (strike N25°–60°W, dip 3°–14°SW). The rocks are cut by an orthogonal set of subvertical joints trending predominantly N40°W and N45°E (Fig. 2). Joint spacing and continuity is locally variable, but a spacing of 0.5–2 m is typical of both sets of joints.

Two lithologic facies dominate the studied reach. Facies A is exposed predominantly in the inner channels of cross sections 1–8 and 14 (Figs. 2 and 3). Facies A is characterized by moderately thick (20–50 cm), locally convoluted beds of fine- to medium-grained sandstone. Facies A is well indurated and yields average Schmidt hammer readings of 59 ±3 (1 σ, 24 measurements) (see Selby, 1980). Rocks of facies A are in places intensely jointed (cross sections 7, 8, and 14). Facies B is exposed in cross sections 9–13 (Fig. 2). Locally very fossiliferous, facies B is characterized by thin sandstone (1–6 cm) beds intercalated with thin silt beds. These thinly bedded units are more susceptible to chemical and physical weathering (e.g., frost shattering) and have lower intrinsic rock strength than facies A. Schmidt hammer readings average 46 ±6 (1 σ, 35 measurements). The thinly bedded facies B also tends to be jointed at a finer scale—joint spacing locally is in the 0.2–0.5 m range.

EROSION PROCESSES

Field evidence suggests that both joint spacing and the degree of weathering influence local incision rates. Broad outer channels are typically cut into well-weathered and fractured rocks. These weathered sections are characterized by closely spaced (0.2–0.5 m) open joints (1–5 mm), such that the rock exposed in outer channel walls apparently has negligible cohesive strength (Fig. 3A). We surmise that erosion through this carapace of weathered rock was probably transport limited and rapid. Only inner-channel incision is representative of river incision into solid, cohesive bedrock.

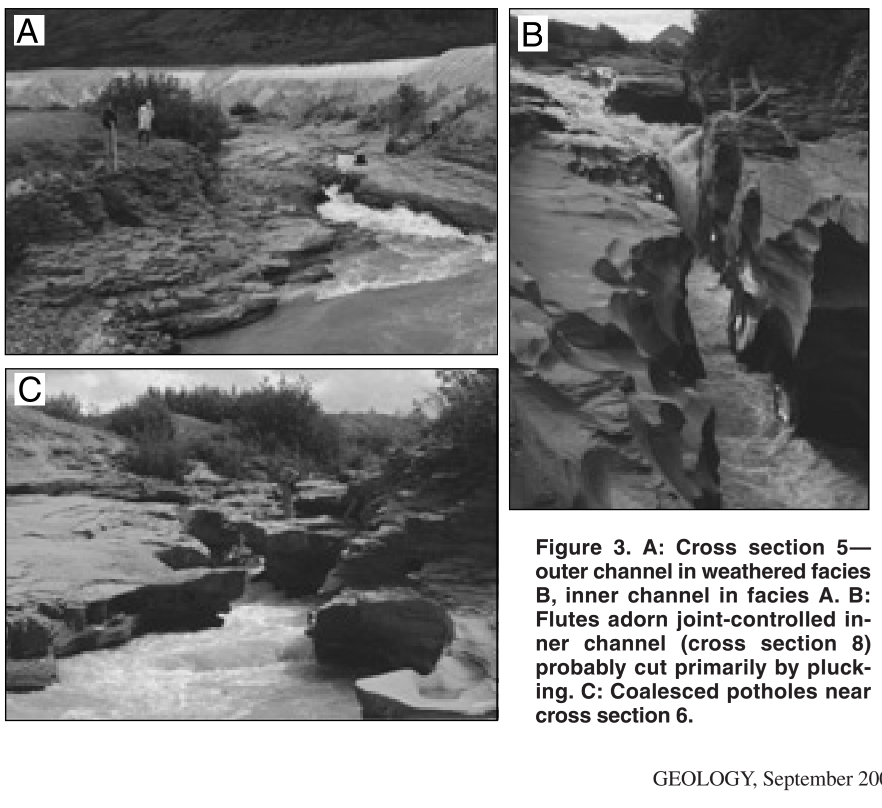

Figure 3. A: Cross section 5—outer channel in weathered facies B, inner channel in facies A. B: Flutes adorn joint-controlled inner channel (cross section 8) probably cut primarily by plucking. C: Coalesced potholes near cross section 6.

Inner channel walls and exposure of joint surfaces in them, as well as on the beds of abandoned paleochannels (Fig. 2), reveal fresh surfaces and tight, unweathered joint planes (Fig. 3B). This evidence indicates that deep weathering along major joints is probably not an important factor in inner-channel incision, although we cannot completely rule out this possibility. Both overall channel morphology and observations of erosion features along channel bed and banks indicate that plucking is probably the dominant process of inner-channel incision. The channel course is clearly joint controlled (Fig. 2). Inner channel walls are typically exhumed and relatively uneroded joint planes (Fig. 3B shows the most deeply fluted example). Similarly, the beds of dry high-flow and abandoned paleochannels are characterized by exhumed joint planes and loosened joint blocks with only minor indications of abrasive wear. In addition, numerous examples of recently plucked but otherwise uneroded joint blocks were observed (see Fig. 1 in Whipple et al., 2000).

Abrasion, probably by suspended sand and pumice, also occurs at geologically important rates on the Ukak River. Evidence for abrasion includes the development of polished and streamlined erosion forms such as flutes and potholes. Given that maximum observed flute depths are 0.5 m (Fig. 3B), assuming the full 85-yr interval available to carve flutes yields a *minimum* estimated rate of flute abrasion of $0.006\ \mathrm{m \cdot yr^{-1}}$ (see footnote 1). The most notable potholes are along the poorly jointed section of channel between cross sections 5 and 6b where the channel crosses over from one prominent joint set to another (Fig. 2). This relatively weakly eroded section is characterized by a series of coalesced potholes measuring 4–6 m in diameter and 2–3 m deep (Fig. 3C). Although these observations suggest a potentially important role of abrasive processes, it is impossible to judge the extent to which plucking of joint blocks may have contributed to the excavation of potholes in these well-jointed rocks.

INCISION RATES

All data used to derive incision rate estimates are available (see footnote 1). We assume that the carapace of weathered bedrock (see Figs. 3A and 4) was swept away instantly, so that our erosion-rate estimates are conservative. Derived incision rates show considerable local variability, ranging from 0.01 to $0.10\ \mathrm{m \cdot yr^{-1}}$ (Fig. 2). Local variations in lithologic facies, the spacing and continuity of joints, and upstream migration of knickpoints all significantly influenced the observed incision rates (see Fig. 2).

In an effort to test the applicability of a stream-power-type incision model and to provide field constraints on model parameters, we performed two analyses: (1) regression of observed local incision rates against channel slope and width (equation 1b) and (2) a search for best-fit (least-squares) parameters (K', n) via one-dimensional numerical simulation of channel-profile evolution, following Stock and Montgomery (1999). Because locally steep segments of the channel profile (knickpoints) erode more rapidly than their surroundings, they migrate upstream. Except perhaps in the case of actual waterfalls, no unique processes need be associated with knickpoint migration. However, knickpoint migration will cause temporal changes in local channel gradient. Therefore, the initial slope of the intact bedrock surface immediately downstream of each cross section (see footnote 1) was used in the regression analysis. Knickpoint migration and temporal evolution of channel-bed slope are captured more fully in the numerical simulations.

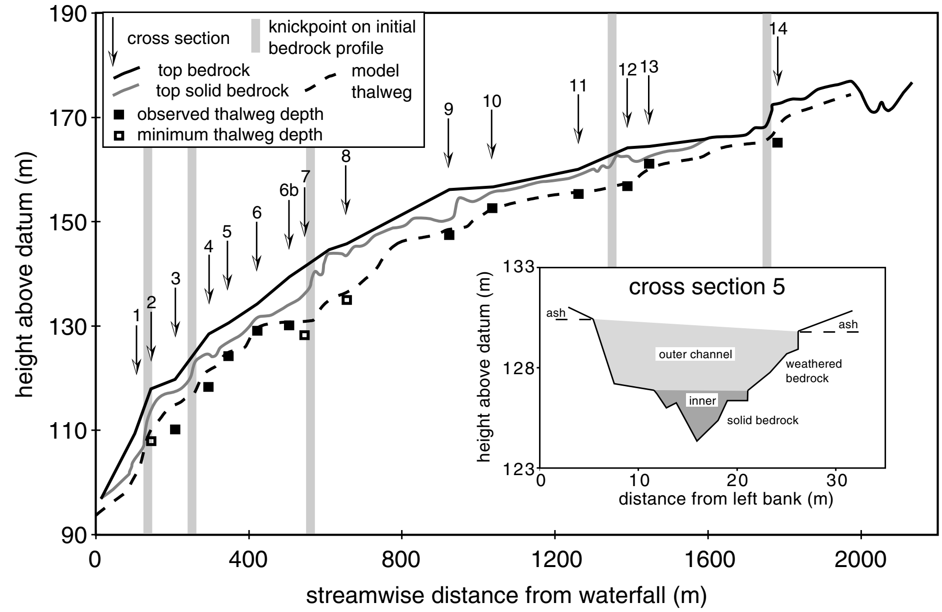

Figure 4. Longitudinal profile of surveyed channel, including cross sections, knickpoints, original bedrock-surface profile, top of solid-bedrock profile, measured channel-thalweg positions, and best-fit modeled thalweg profile. Inset of cross section 5 (see Fig. 3A) illustrates typical outer and inner channel morphology.

Regression of local incision rate against the slope-width ratio (S/W) supports the general form of the stream-power model (equation 1b) and indicates that slope exponent n is notably less than unity in this field setting (Fig. 5). Scatter in a regression including all field data appears to be largely due to variations in rock properties (Fig. 5). Variations in rock-mass strength are difficult to quantify in the field, but it is clear that erosion has been markedly more efficient where the channel is cut into either the weaker facies B (cross sections 9–13) or into locally intensely jointed sections of facies A (cross sections 7, 8, 14). With the sole exception of cross section 3, field classification of rock substrate into two groups (weak and/or heavily jointed vs. resistant rocks) separates the data into two statistically distinct groups (Fig. 5). The resistant rock units are being eroded at approximately half the rate of the weaker facies.

Numerical simulations of channel-profile evolution based on equation 1b were run for a period of 85 yr; the observed variations in channel width and the profile of the intact (unweathered) bedrock surface served as the initial conditions (solid gray line, Fig. 4). As suggested by the regression analysis, no simulations using spatially constant K' values yielded satisfying fits to the 14 observed thalweg depths. Accordingly, optimal values of K' and n were first fit to only the upper part of the channel profile, where weak and highly jointed rock types predominate (cross sections 7–14); then, by using these values, a best-fit fractional decrease in K' for cross sections 2–6b was found. The resulting best-fit model thalweg is plotted in Figure 4 (dashed line). Broad minima defined by the sum of the squares of differences between observed and model thalweg elevations yield best-fit values of K' and n that are closely in accord with the results of the regression analysis: $K'_{weak} = 10^{-0.36 \pm 0.45}$, $n = 0.4 \pm 0.2$, $K'_{resist} = 1.2–2.0\ K'_{weak}$ (for details, see footnote 1). Although this finding indicates that knickpoint migration introduced no significant bias into the regression analysis for this short interval of erosion, the results of the numerical simulation should be considered more accurate.

DISCUSSION AND CONCLUSIONS

To allow comparison with published estimates in a range of geologic, climatic, and tectonic settings, we use the local incision-rate data to calculate values of K in equation 1a. For the purpose of comparison, we use $m = 0.4$, $n = 1$, the best-fit values from Stock and Montgomery (1999) (for details, see footnote 1). The resulting estimates of K average $9.0 \times 10^{-4}\ \mathrm{m^{0.2} \cdot yr^{-1}}$ for weak and/or highly jointed rock units (sections 7–14) and $2.4 \times 10^{-4}\ \mathrm{m^{0.2} \cdot yr^{-1}}$ for the more resistant units (sections 2, 4–6b). Thus, rates of incision by the Ukak River are high but not exceptional, considering the high channel gradient, high precipitation in the region, relatively erodible lithology, and narrowness of the inner channel (averaging ~6 m). Stock and

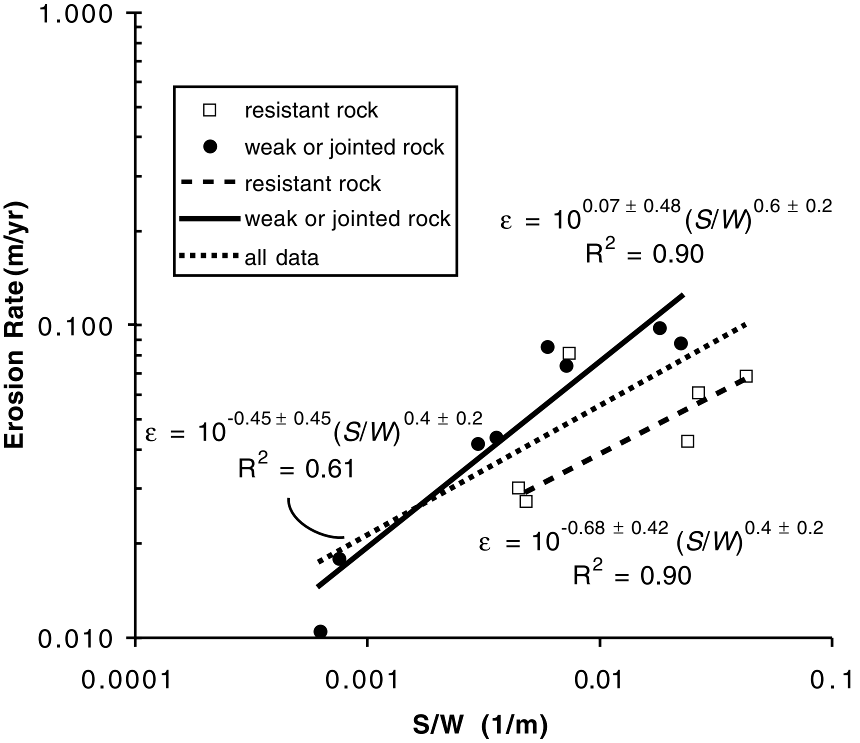

Figure 5. Erosion rate as function of slope-width ratio (local cross section values, equation 1b). Rock units are classified as weak or highly jointed (sections 7–14) or resistant (sections 2–6b) according to field observations. Single outlier in resistant facies group (section 3) was omitted from regression. Some error is introduced by use of channel-bed slope as proxy for energy slope and because there is no accounting of sidewall friction in deep, narrow inner channels of sections 4, 6b, 7, and 8.

Montgomery reported K values that range from 4×10^{-7} to 7×10^{-3} $m^{0.2} \cdot yr^{-1}$ and included values that equal or exceed those reported here for rivers incising erodible mudstones in Japan. However, these high values of K cannot be simply associated with rock type, because coastal streams incised into similar lithologies in California's King Range (Snyder et al., 2000) and in Santa Cruz (Rosenbloom and Anderson, 1994) yield estimates of K as much as two orders of magnitude lower (K = 1.3×10^{-5} to 8.4×10^{-5} $m^{0.2} \cdot yr^{-1}$ and $K = 1.1 \times 10^{-5}$ to 7.9×10^{-6} $m^{0.2} \cdot yr^{-1}$, respectively).

Observations of the channel bed (in dry high-flow and abandoned paleochannels) and banks indicate that erosion has occurred primarily by the extraction and transport of joint blocks. As discussed in greater depth by Whipple et al. (2000), this finding implies that the rate-limiting process is some combination of joint-block loosening by physical weathering (frost shattering, in this environment), fracture and loosening of joint blocks by bedload impacts, and hydrodynamic extraction and transport of blocks. Abrasive wear by either bedload or suspended load appears to play a secondary role in this field setting. We have at present little data with which to evaluate the potential influence of bedload flux on the observed erosion rates (discussed by Sklar and Dietrich, 1998).

The slope exponent (n) is thought to range between 2/3 and 5/2, depending on the dominant erosion process (Whipple et al., 2000). Our incision-rate data, however, clearly demonstrate a weaker dependence on channel gradient ($n \leq 0.6$). Several plausible explanations for low n values may be entertained: (1) hydrodynamic block extraction is rate limiting ($n = 2/3$; Whipple et al., 2000), but sidewall friction in narrow, deep channels reduces basal shear stress in the steepest reaches; (2) block fracture due to bedload impacts is rate limiting, but a significant fraction of the bedload is in suspension or incipient suspension though the steeper reaches (see Sklar and Dietrich, 1998); and (3) physical weathering ($n = 0$) influences, but does not entirely *control*, erosion rates. At present it is impossible to discriminate between competing hypotheses of erosion limited by hydrodynamic extraction aided by physical weathering and block fracture due to bedload impacts modulated by incipient suspension of tools in the steeper channel segments.

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