Substrate controls on the longitudinal profile of bedrock channels: Implications for reach-scale roughness

Jaime R. Goode[1,2] and Ellen Wohl[1]

[1] In this paper we examine the relationships among bedrock properties and hydraulics in shaping bedrock channel morphology at the reach scale. The Ocoee River and four other bedrock streams in the Blue Ridge province of the southeastern United States, which have reach-scale differences in bedrock erodibility controlled by lithologic and structural variation, are the focus of this study. We describe a simple conceptual model for concentrated erosion in bedrock channels and test three hypotheses in order to investigate the interactions among rock erodibility, characteristics of undulating rib-like bed forms, reach-scale gradient, and hydraulic roughness and energy dissipation. Substrate differences correlate with variation in reach morphology (i.e., gradient, bed form orientation, and amplitude), such that less erodible substrates are associated with steeper reach gradient and with transversely oriented ribs of greater amplitude. One-dimensional modeling in HEC-RAS indicated that in the reach with the least erodible substrate and greatest bed slope and rib amplitude, the reach-averaged hydraulic roughness was the greatest. Increased hydraulic roughness in steeper reaches points to the importance of positive and negative feedbacks in these systems: Greater substrate erosional resistance limits profile lowering, which likely creates steeper bed slopes and greater stream power, creating a self-enhancing feedback. This local increase in stream power is balanced by increased roughness resulting from the erosional processes that produce bedrock ribs, which represents a self-regulating feedback. The overall result reflects quantifiable adjustments between substrate resistance and hydraulic driving forces in bedrock channels.

1. Introduction

[2] The morphology of bedrock channels typically displays high spatial variability. Bedrock channel morphology reflects hydraulic driving forces acting across different time scales [*Baker*, 1977; *O'Connor et al.*, 1986] and substrate properties such as local lithologic and structural heterogeneity [*Wohl and Achyuthan*, 2002; *Kobor and Roering*, 2004; *Frankel et al.*, 2007; *Yanites et al.*, 2010], jointing [*Miller*, 1991; *Ehlen and Wohl*, 2002], bedding, and base level history [*Wohl et al.*, 1994; *Lavé and Avouac*, 2001; *Duvall et al.*, 2004]. The starting assumption for self-adjusted alluvial channels is that discharge exerts the dominant influence on channel form [*Leopold and Maddock*, 1953]. Despite the high erosional thresholds and substrate heterogeneity in bedrock channels, some evidence exists that bedrock channel dimensions also scale with flow [*Montgomery and Gran*, 2001; *Wohl and David*, 2008]. However, local bedrock properties also influence channel morphology [*Montgomery and Gran*, 2001]. Therefore, feedbacks between hydraulic parameters and bedrock characteristics likely govern the balance between spatial variability of channel form and scaling of channel dimensions by flow.

[3] In this paper, we examine the effects of bedrock properties on the Ocoee River and other bedrock channels in the southeastern United States. These channels have downstream variations in lithology and structure that appear to correlate with variations in channel morphology. Based on these observations, we develop a conceptual model for reach-scale variations in erosion along bedrock channels with high spatial variability in rock erodibility. We frame our conceptual model in the context of hydraulic driving forces relative to rock erodibility and explore how interactions among these two components govern reach-scale variations in channel geometry and hydraulics. Although not explicitly quantified as a component of these feedbacks in this study, we recognize that sediment transport dynamics are an important control on the bedrock channel morphology in question.

[4] One end-member of the conceptual model occurs when the substrate is homogenous and readily erodible by available energy. Under these conditions, the bed lowers uniformly, producing a relatively low gradient and an even bed with

[1]Department of Geosciences, Colorado State University, Fort Collins, Colorado, USA.
[2]Now at Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture, Boise, Idaho, USA.
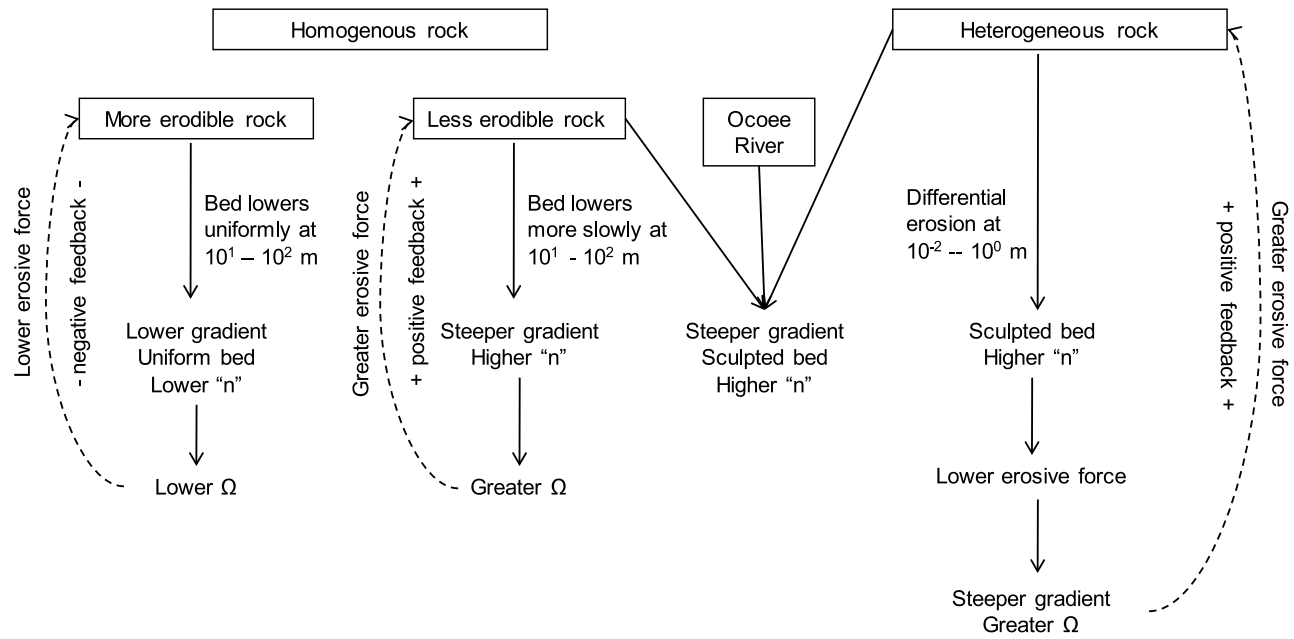
Figure 1. Conceptual model end-members. Assuming constant discharge and channel width, the only change in stream power ($\Omega = \gamma QS$) corresponds to a change in bed slope. Spatial scales of erosion are represented for each end-member.

lower hydraulic roughness (Figure 1). In order to maintain simplicity, this model is considered at the reach scale for a channel of constant width and discharge. The only degrees of freedom are slope and boundary roughness. Rock erodibility is considered as an independent control. Alternative end-members occur under conditions of less erodible rock, when the channel bed lowers less rapidly and reach-scale gradient steepens, or under conditions of heterogeneous substrate, when differential erosion can create a sculpted bed. Higher hydraulic roughness in each of these alternative end-members is assumed: In the former, steeper reach gradient must be compensated by an increase in hydraulic roughness, and in the later, sculpted bed forms produce topographic variability that can enhance hydraulic roughness. In harder, more massive rock, sculpting is typical because wide joint spacing precludes plucking as an erosional process. In heterogeneous rock, structural and lithologic variation may influence the location of this sculpting such that weaker substrate is preferentially eroded or eroded more uniformly, whereas less erodible rock remains as topographically higher (meter scale) or steeper portions (reach scale) of the bed or has predominantly localized erosion. Localized erosion can result in knickpoints or knickzones along the profile [*Gardner*, 1983; *Frankel et al.*, 2007], inner channels within the cross section [*Baker*, 1977; *Shepherd and Schumm*, 1974; *Wohl and Ikeda*, 1997; *Johnson and Whipple*, 2007], or sculpted abrasional forms such as potholes, flutes, and grooves [*Richardson and Carling*, 2005]. Another expression of focused erosion, which we explore for the first time in this paper, is the formation of undulating, structurally controlled bedrock ribs that are intermediate in scale between sculpted forms and either knickpoints or inner channels. When substrate is less erodible or more heterogeneous, steeper gradient and differential erosion increase hydraulic roughness (Figure 1).

[5] Three sets of hypotheses arise from this conceptual model when applied to the Ocoee River and associated study reaches: (1) Rock erodibility varies with the dominant lithology at the reach scale. (2) Differences in substrate properties correlate with differences in channel morphology, as reflected in gradient and bed form configuration. (3) Differences in substrate properties and channel morphology correspond to differences in hydraulic roughness. We test these hypotheses with the goal of better understanding the relative influence of different controls and processes shaping bedrock channel morphology.

2. Study Area

[6] Substrate resistance, channel gradient, and bed form configuration were studied on two sections of the Ocoee River, TN and four reaches along three other streams flowing through the Blue Ridge province of the southern Appalachians: Tellico River, TN; Little River, TN; and Cheoah River, NC (Figure 2 and Table 1). These streams were selected for the presence of consistently oriented ribs, range of bed slopes, and proximity to the main study site on the Ocoee River. The channels are incised into deep gorges with steep valley walls, but bedrock exposure is low and hillslopes are densely vegetated and mantled with thick soils typical of humid temperate landscapes. The region is tectonically quiescent, with homogenous denudation rates (25 ± 5 m/Myr) over 10^4–10^5 year time scales [*Matmon et al.*, 2003].

[7] The bedrock of all the study streams is composed of metasedimentary rocks (slates and metasandstones) that are a part of the Precambrian Ocoee Supergroup. Bedrock exposures in the main study area of the Ocoee River gorge are the Precambrian age Sandsuck Formation in the western gorge, which is composed of phyllites thinly interbedded with arkosic and calcareous quartzites; the Dean Formation,
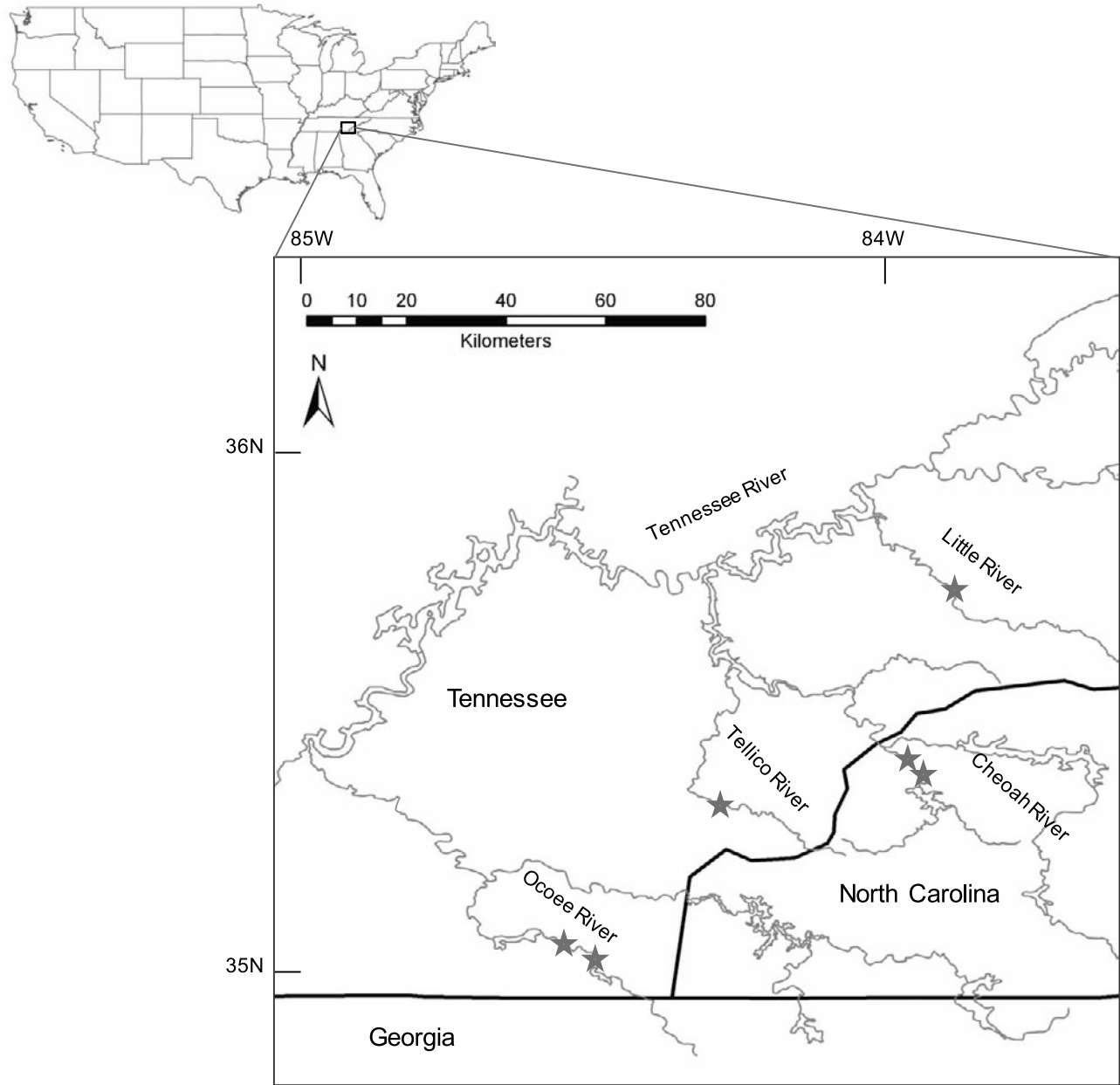
Figure 2. Study area site map. Study streams are labeled, and site locations are indicated by stars. All streams are tributary to the Tennessee River. Only the major tributaries contributing to the study streams are shown.

composed of thinly bedded quartzites and phyllites; and the Hothouse Formation, composed of metagreywacke and mica schist in the eastern gorge [*Sutton*, 1991]. Metamorphic grade decreases in the downstream direction from garnet to below biotite. Through the gorge the rock units form a sequence of alternating resistant ledges of metagreywacke and quartzite and softer phyllite. All other Blue Ridge streams show

Table 1. Blue Ridge Streams

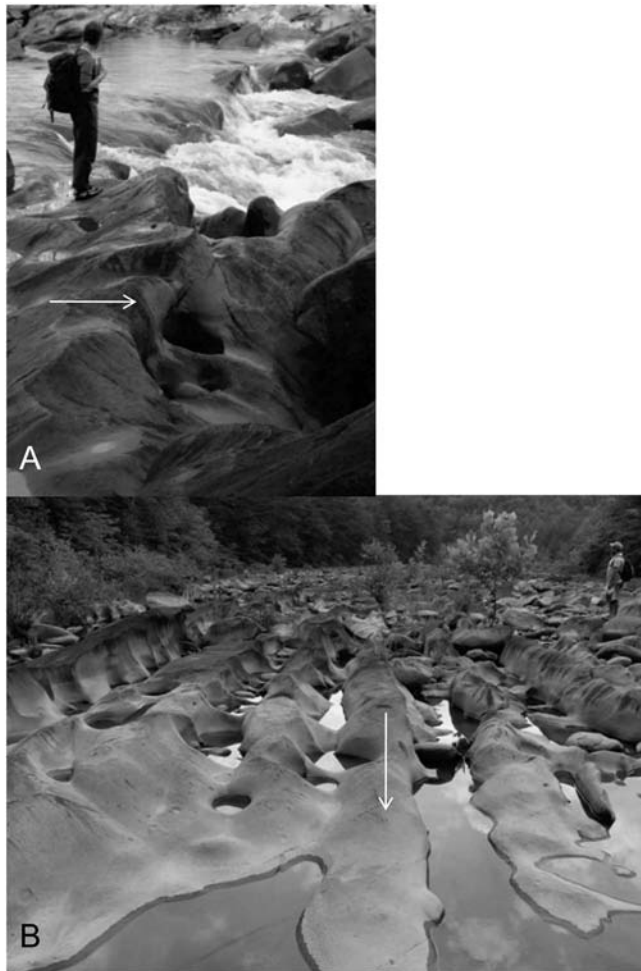| Stream Name (Reach)	Drainage Area (km^2)	Annual Peak Discharge (m^2/s)	Reach Length (m)	Channel Width (m)	Reach Gradient	Schmidt Hammer	Selby	Rib Orientation
Cheoah 1	460	141	170	47	0.0197	50 (5)	87	transverse
Cheoah 2	460	141	144	55	0.0093	46 (5)	81	transverse
Little	275	212	145	28	0.0446	51 (6)	89	transverse
Tellico	300	234	192	59	0.0418	48 (4)	85	oblique

Figure 3. Photographs of bedrock ribs along the upper Ocoee section. Arrows indicate the mean flow direction. (a) Ribs are transverse to flow with apparent sculpting. (b) Ribs are longitudinal to flow. The troughs between the ribs consist of coalesced potholes. Person in top right for scale.

exposures of metasandstones of the Ocoee Supergroup (e.g., Thunderhead Sandstone).

[8] The two sections of the Ocoee River are impounded at the upstream boundaries by dams Ocoee No. 3 and Ocoee No. 2. The corresponding drainage areas for these study sections are 1200 km^2 and 1300 km^2. These dams and their hydroelectric power facilities are operated by the Tennessee Valley Authority (TVA). The section below Ocoee No. 3 was chosen for detailed reach-scale measurements of hydraulic roughness. After the closure of the Ocoee No. 3 dam in 1942, the reach extending 8 km downstream to the No. 3 power station was completely dewatered, with the exception of winter stormflows that exceeded the hydropower capacity. Since the 1996 Olympics, the TVA has guaranteed flow on scheduled release days for the river section below the Ocoee No. 3 dam. The channel remains dry during much of the year except for scheduled releases. The scheduled releases of roughly 45 m^3/s occur for 6 h on both Saturday and Sunday from the last weekend in May through the first weekend in September. Winter and spring storms produce flows for which the daily average releases from the dam are typically in

the range of 40 to 60 m^3/s, and peak flows can reach 800 m^3/s. In addition to this altered flow regime, the dam has also perturbed the sediment supply and capacity. Woody vegetation exists at many locations within the channel bed as a result of infrequent flow releases and dewatering of the channel under regulation by the TVA.

[9] The features that we designate bedrock ribs are not unique to the Ocoee and other streams in the study area, but have not received much attention in the literature. *Richardson and Carling* [2005] describe structurally influenced concave sculpted features called joint furrows and bedding plane furrows. Bedrock ribs are long, narrow portions of bedrock that protrude above the surrounding bed and are the opposing topographic expression of joint and bedding plane furrows [*Richardson and Carling*, 2005]. Whether oriented transverse or parallel to flow, ribs are asymmetrical in cross section (Figure 3). Ribs are always oriented parallel to the metamorphic foliation in the rock (Figure 4), but in some cases the ribs also follow dominant joints. The orientation of the long axis of the ribs changes as the trend of the sinuous channel changes downstream, suggesting that rib orientation is controlled by structural features in the underlying folded metasedimentary units. Bedrock ribs appear to act as hydraulic controls when oriented at an angle that opposes the main flow direction. The occurrence of sculpted forms such as potholes and flutes along the boundaries of the ribs (e.g., along the upstream and downstream faces of transverse ribs, and in the troughs between longitudinal ribs) suggests that abrasion is the dominant mechanism of fluvial incision in this system.

[10] Sediment in these streams consists of sand- to boulder-sized material that occurs in discontinuous patches, between ribs and within potholes (Figure 4). Isolated locations of this alluvial fill are armored by large cobbles and boulders. High concentrations of well sorted, gravel-sized material occur in the wake zones of the bedrock ribs. These deposits are loose and bed sediment tracer data from these patches in the Ocoee River subreaches indicate a high rate of exchange and flux within the deposit as a result of turbulent flow [*Goode and Wohl*, 2007]. Results from this tracer study show that transport distances are greatest where ribs are of lowest amplitude, and are oriented parallel to flow. The angularity of the material ranges from very well rounded particles within potholes to more sub angular particles across the channel bed. This angularity difference appears to reflect not only the local hydraulic environment, but also the lithologic origin: phyllite produces more angular particles, whereas the metagreywacke corresponds to well-rounded particles. Also, sculpted features such as potholes tend to be larger and more numerous within reaches dominated by the metagreywacke.

3. Methods

3.1. Longitudinal Variation in Substrate and Channel Morphology

[11] Longitudinal profiles were surveyed with a laser total station along two different sections of the Ocoee River and along three other streams in the region. The upper Ocoee section (UO) extends 4.5 km downstream of the Ocoee No. 3 dam to the 1996 Olympic whitewater course and includes four subreaches. The UO section is the primary field site for which we collected the most spatially detailed field data. To supplement the data from this site, and to demonstrate that

Figure 4. Photograph of longitudinal ribs in upper Ocoee R2 showing alluvial patches in sculpted forms and between ribs. Flow is toward the viewer, and there is a small tape for scale indicated in the circle.

this reach of the Ocoee is not regionally unique in having bedrock ribs, we added the middle Ocoee section (MO), which extends 3.5 km downstream from the Ocoee No.2 dam, as well as four reaches along the Tellico, Little, and Cheoah (2 reaches) Rivers.

[12] The longitudinal profile for the UO site had points spaced at 1 m intervals and was primarily designed to detect changes in bed gradient at the scale of tens to hundreds of meters. Rib geometry (amplitude and spacing) was measured via detailed transects parallel and transverse to flow within the four UO subreaches; transects documented the locations of rib crests and troughs as well as substrate type (alluvium or bedrock). Within these transects, rib orientation was characterized as either longitudinal, oblique, or transverse to the downstream flow direction. These orientations were categorized according to the following criteria: longitudinal ribs varied $0°\pm10°$ with respect to the main flow direction, transverse ribs were oriented $180°\pm10°$ with respect to flow, and oblique ribs occurred at all other angles to flow.

[13] At the other five sites, profile points were surveyed at ~3 m intervals or less in order to document undulations in the bedrock streambed. We noted transitions in the orientation of bedrock ribs along each profile. We also noted rib crests, troughs between ribs, and presence of either alluvium or bedrock. We visually identified rib crests during the survey, but determined the troughs from the minimum bed elevations upstream and downstream of the crest from the survey data. Ribs adjacent to the thalweg were also surveyed at the crest and lowest upstream and downstream points to document rib amplitude. Rib crest spacing was computed from the displacement between rib crests along the thalweg profile survey [*Crickmore*, 1970] or along transects surveyed orthogonal to

the rib orientation when the ribs were longitudinal or oblique. Rib amplitude was calculated from the elevation difference between the average of the upstream and downstream trough elevations and the rib crest. We used two parameters to semiquantitatively constrain rock erodibility; Selby rock mass strength (RMS) classification [*Selby*, 1980] and Schmidt hammer measurements [*Duvall et al.*, 2004]. Selby RMS classifications are based on numerical ratings assigned to intact rock strength as measured using an N type Schmidt hammer; joint spacing, width, orientation and continuity; rock weathering; and groundwater outflow. The Selby RMS classification scheme, intended initially for rock hillslopes, provides a semiquantitative measure of bedrock strength over length scales that include heterogeneities such as joints and fractures. Schmidt hammer numbers scale empirically with compressive rock strength. In bedrock abrasion mill experiments *Sklar and Dietrich* [2001] demonstrated an inverse relation between abrasional resistance and tensile strength squared. Assuming that Schmidt hammer numbers are proportional to the tensile strength, greater Schmidt hammer numbers will indicate less erodible bedrock. Although the Selby RMS partially relies on the Schmidt hammer numbers, the Selby RMS incorporates the joint characteristics that may influence the rib orientation and spacing, whereas, the Schmidt measure is purely a measure of the intact strength as resistance against abrasional impacts. Selby RMSs were recorded at 21 evenly spaced locations within each subreach on the upper Ocoee. A total of 210 Schmidt hammer measurements were taken within each subreach; an average of 10 measurements was incorporated in each Selby RMS. Selby RMSs were recorded at 10 locations within each of the other five reaches.

Table 2. HEC-RAS One-Dimensional Modeling Results and Summary Data for Upper Ocoee Subreaches

Reach	UO1	UO2	UO3	UO4
Cross sections (n)	9	12	9	10
Rib orientation	longitudinal	longitudinal	oblique	transverse
Bed slope (m/m)	0.0075	0.0088	0.0106	0.0197
Reach length (m)	178	198	89	76
Reach average n	0.059	0.075	0.092	0.107
W/D	50.0	97.0	75.0	103
Stdev bed elev (m)	0.36	0.40	0.43	0.51
Energy slope (m/m)	0.011	0.013	0.007	0.022
Velocity (m/s)	1.43	1.10	0.89	0.93
Froude number	0.50	0.42	0.30	0.35
Total shear (N/m2)	76.3	80.3	54.7	128
Total stream power (W)	4850	5900	3280	9890
Unit stream power (W/m^2)	119	91.2	50.0	133
Schmidt reading	34 (7)	40 (6)	40 (5)	46 (6)
Selby score	65	72	75	77
Rib amplitude (m)	0.435	0.470	0.785	0.793
Rib spacing (m)	3.53	3.61	4.49	5.47
D50 (mm)	115	100	150	145
D84 (mm)	240	230	252	235

3.2. Hydraulic Modeling of Reach-Scale Roughness

[14] Direct measurement of flow hydraulics in high-energy bedrock streams is difficult for practical reasons. The Ocoee River is not measurable by either wading or boat at normal flows because flow is too fast and turbulent. Direct measurements are possible only along the margins. There are also no bridges along the study area from which hydraulic measurements can be obtained. In this study we used the U.S. Army Corps of Engineers (USACE) one-dimensional flow model HEC-RAS [*U.S. Army Corps of Engineers*, 2002] to examine differences in Manning's roughness, n, between the four subreaches of the UO. Based on a given discharge, n, and form energy losses (set to the default contraction and expansion coefficients), HEC-RAS uses the step backwater method to iteratively calculate energy-balanced water surface elevations between successive surveyed cross sections assuming steady gradually varied flow. The upstream and downstream boundary conditions were set to the known water surface elevations for the bounding cross sections and subcritical flow conditions were assumed in all modeling runs. The four UO subreaches were selected according to rib orientation. We selected unvegetated, straight reaches with consistent rib orientation to eliminate any other important sources of roughness such as woody bed vegetation or split channel flow. Roughly 10 cross sections (Table 2) were surveyed in each reach at a downstream spacing of approximately 15 m. Along each cross section, points were sampled at 1 m intervals to capture the highly variable bed topography. Figure 5 shows the three-dimensional topography of the four modeled subreaches.

[15] Water surface elevations at each cross section within the subreach were surveyed during one known recreational flow discharge of 45 m^3/s. HEC-RAS was used to iteratively determine n for each cross section; values for n were varied until the computed and observed maximum flow depth in the cross section converged to ±5 cm. In other words, these iterations were performed until the surveyed water surface profile along the channel margin matched the modeled water
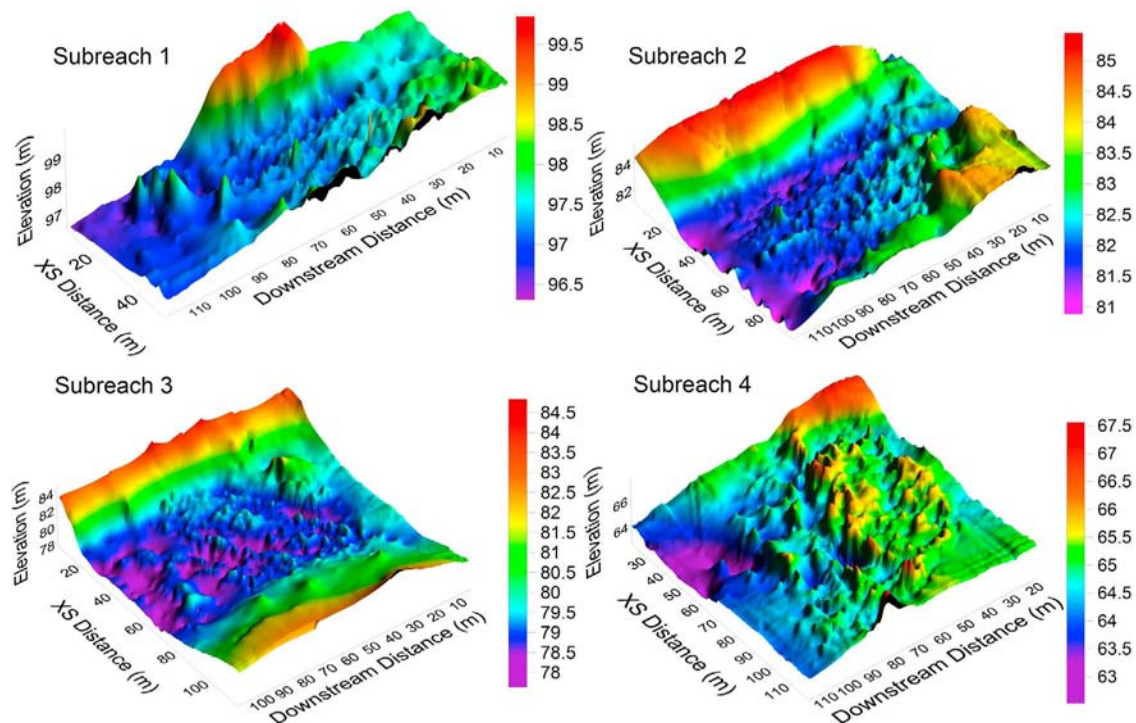

Figure 5. Three-dimensional plots of the four upper Ocoee subreaches. The surfaces were created in Surfer from detailed topographic hand-surveyed data that were collected for other study components. These data were collected at roughly 1 m resolution.
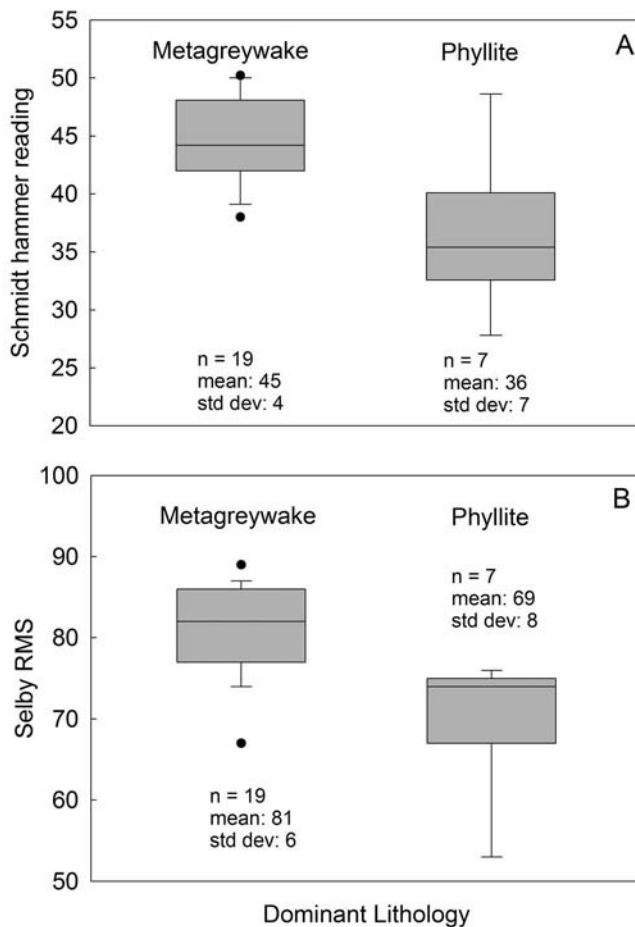
Figure 6. Comparison of substrate resistance among reaches along the upper and middle Ocoee sections: (a) Schmidt hammer reading and (b) Selby score. Reaches were distinguished based on rib orientation to flow. Within the box plots, the solid line represents median. The box ends indicate the upper and lower quartiles, and whiskers are the 10th and 90th percentiles. The solid dots represent outliers.

surface profile. The initial n for the downstream bounding cross section in each reach was set at the average n of all cross sections from the subsequent model run. We did not vary n across the cross section to maintain simplicity. The Ocoee does not have a pronounced thalweg, and the relatively minor variation in bed topography across each cross section justifies the use of cross-sectional average values of roughness.

[16] To assess uncertainty in the actual discharge in the downstream subreaches (2, 3 and 4) as a result of discharge input from one small tributary draining roughly 15 km^2 and several small groundwater seeps between subreaches 1 and 2, we examined the sensitivity of the computed water surface elevation by varying discharge at a constant n. In all three subreaches, we varied the discharge by 3 m^3/s, which we estimated as the maximum input from the tributary and groundwater sources between the dam and these subreaches. In subreach 4, an increase in discharge of 3 m^3/s led to a difference in the computed water surface of only 1–3 cm, which was within the level of detection. Computed water

surface elevations in upstream cross sections were not sensitive to the assumed n for the downstream boundary.

4. Results

4.1. Reach-Scale Differences in Erodibility

[17] Interreach differences in rock erodibility occur in the study streams. This was assessed by both Schmidt hammer readings and Selby rock mass strength classifications, which vary along the profiles of both sections of the Ocoee River. Of the 26 different reaches, differentiated along the profile according to rib orientation to flow, 19 were dominated by metagreywacke and 7 were dominated by softer and more densely foliated phyllite. Because the lithology is mixed within each reach, it is worth noting that rock erodibility, both in reality and in our measurements of it, may primarily reflect the relative proportions of weak and resistant bedrock. Although there was some variation in lithology within each reach, all reaches showed a strong dominance in bed substrate lithology (>80%). The Schmidt hammer readings of the dominant lithology in all reaches (phyllite or metagreywacke) were significantly different (Figure 6a; p = 0.02). Significantly different Selby RMS values (Figure 6b; p < 0.01) between these substrates also indicated contrasting rock erodibility. Based on the previously explained assumption that Schmidt hammer and Selby RMS measures are inversely related to erosional resistance, these results support the first hypothesis by indicating that reach-scale differences in rock erodibility are present.

4.2. Substrate Properties in Relation to Channel Morphology

[18] Simple regression analyses indicated that reach gradient, when adjusted by drainage area, varied as a significant positive power function of rock erodibility (R^2 = 0.57 and 0.42, for Selby RMS and Schmidt reading, respectively) (Figure 7). In this relationship we multiplied reach gradient by drainage area to control for differences in channel scale. This new response variable is physically meaningful, as it represents a surrogate form of total stream power. The other Blue Ridge streams had the largest measures of rock strength because they exist farther to the east of the Ocoee River, where metamorphic grade is higher. Figure 7 also shows that in addition to reach gradient, both rock erodibility parameters tend to be larger in reaches with transverse ribs than in reaches with longitudinal ribs.

[19] Localized steep zones in the longitudinal profiles of both the upper and middle Ocoee correspond to bedrock ribs with a transverse orientation to flow, whereas longitudinally oriented ribs occur at lower-gradient sections of the longitudinal profile (Figure 8). These profile plots also illustrate that steeper zones occur where the substrate resistance is greater. Comparison to the other three streams in the region corroborates these findings (Figure 9). Reach gradient was not adjusted by drainage area in this comparison because a large portion of the reaches correspond to the same drainage area, despite differences in rib orientation. It is worth noting that the four Blue Ridge streams had smaller drainage areas than the Ocoee reaches and greater reach gradients, which may reflect discharge as a first-order control on channel slope. However, transverse ribs dominated these reaches, suggesting a local substrate control on reach gradient. The
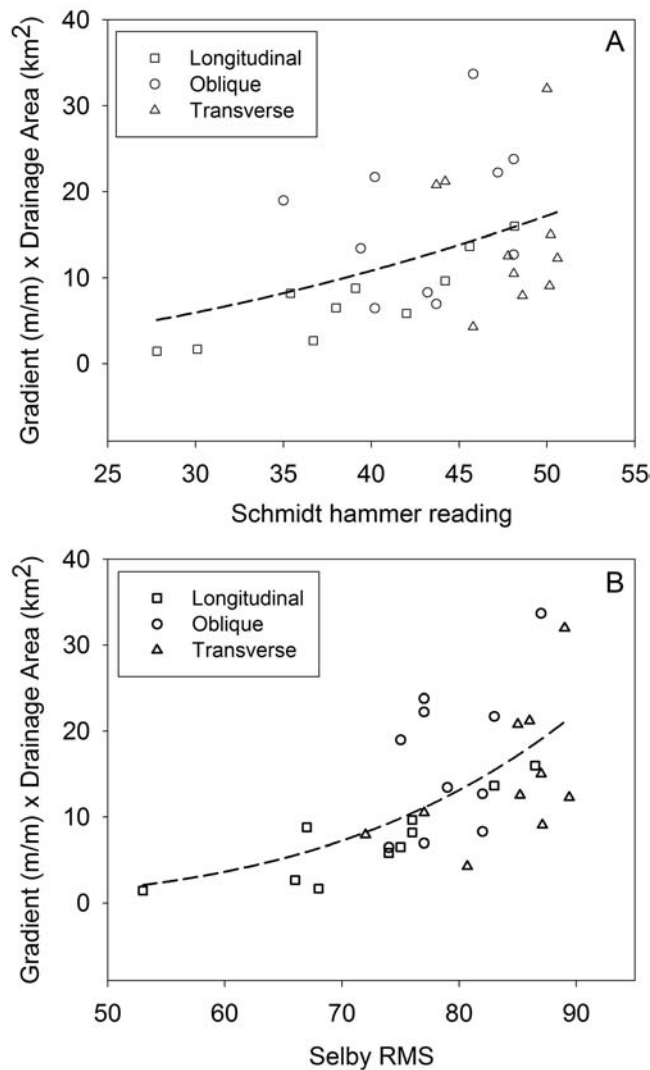
Figure 7. Reach gradient adjusted by drainage area as a function of rock erodibility. (a) Schmidt reading, $R^2 = 0.42$. (b) Selby score, $R2 = 0.57$. Both power functions are significant at $p < 0.05$. Data include reaches with varying rib orientation from all study streams (n = 30).

mean bed slope for reaches with bedrock ribs oriented transverse to flow is 0.020, compared to a bed gradient of 0.006 in reaches with longitudinally oriented bedrock ribs. A comparison of means with unequal variance indicated that the bed slopes for these different rib orientations were statistically different ($p < 0.01$). When the main flow direction is at an angle normal to the strike of the bedding and foliation of the substrate, the resulting bedrock ribs exert another level of resistance that correlates with an increase in channel slope.

[20] Profile plots from three other streams in the region (Figure 10) illustrate that localized steep zones (10^1 m scale) correspond to ribs of large amplitude. Rib amplitude data from these four reaches, in addition to the four subreaches on the UO, showed a significant logarithmic relationship between reach gradient and rib amplitude (Figure 11). Rib amplitude is also larger in reaches with higher substrate resistance (Figures 12a and 12b). These results support the second hypothesis that bedrock properties correlate with differences in channel morphology. Although rib amplitude and spacing are positively correlated ($R^2 = 0.63$), rib spacing was not correlated with either reach gradient or substrate resistance.

4.3. Substrate Controls on Reach-Scale Roughness

[21] One-dimensional flow modeling results from HEC-RAS are summarized in Table 2. These results indicate that reach-scale roughness associated with ribs longitudinally oriented to flow is different from reach-scale roughness for ribs oriented transverse to flow (Figure 13). This result is consistent when UO1 and UO2 (longitudinal ribs) are compared separately to UO4 (transverse ribs) ($p < 0.01$). Comparison of mean Selby RMS between UO1 and UO4 shows that substrate resistance is significantly greater in the steeper reach with transverse ribs ($p < 0.01$). Selby scores in UO1 and UO2 were significantly different ($p < 0.01$), despite similar rib orientation, with UO1 showing lower Selby RMS than UO2. The substrate in UO1 is dominated by the more densely foliated phyllite, whereas UO2 shows a greater proportion of metagreywacke in the exposed bedrock. The metagreywacke and phyllite had significantly different Schmidt readings and Selby RMS ($p = 0.02$ and $p = 0.01$, respectively). These lithologic differences also produced ribs of different amplitude. Rib amplitude was greater in the steeper reaches, UO3 and UO4, with oblique and transverse ribs, respectively. These substrate characteristics also correlate with reach-scale hydraulic roughness (Figures 14a and 14b).

[22] Although the small sample size (n = 4) limits statistical conclusions, our finding that n is directly proportional to both Selby scores and rib amplitude suggests that the underlying bedrock substrate has an important influence on reach-scale hydraulics. These results support the third hypothesis that differences in substrate properties and morphology correspond to differences in hydraulic roughness. The results of our analyses indicate that bedrock bed forms correlate strongly with reach-scale hydraulic roughness and energy dissipation. Feedbacks among substrate characteristics and flow hydraulics are thus likely to be important in this system.

5. Discussion

[23] Interpreted in the context of the conceptual model described previously, the results of this study show that reach-scale differences in rock erodibility strongly correlate with channel geometry and hydraulics. We interpret these results to support the feedbacks illustrated in the conceptual model (Figure 1): lower rock erodibility limits bed incision, resulting in increased slope relative to segments of channel bed with less resistant substrate. Local steepening of the profile effectively increases total stream power, thus enhancing hydraulic driving forces. Although the Ocoee also widens in the steeper subreaches, the change is not sufficient to produce lower values of unit stream power (Table 2). The orientation of the bedrock ribs relative to flow direction in the study reaches appears to be an independent parameter that reflects the underlying bedrock structure. Steeper bed slopes also correlate with transversely oriented bedrock ribs of greater amplitude, which increase reach-scale hydraulic roughness. Increased hydraulic roughness presumably mediates the local increase in stream power along steeper reaches, providing a self-regulating feedback. In the steeper reaches,
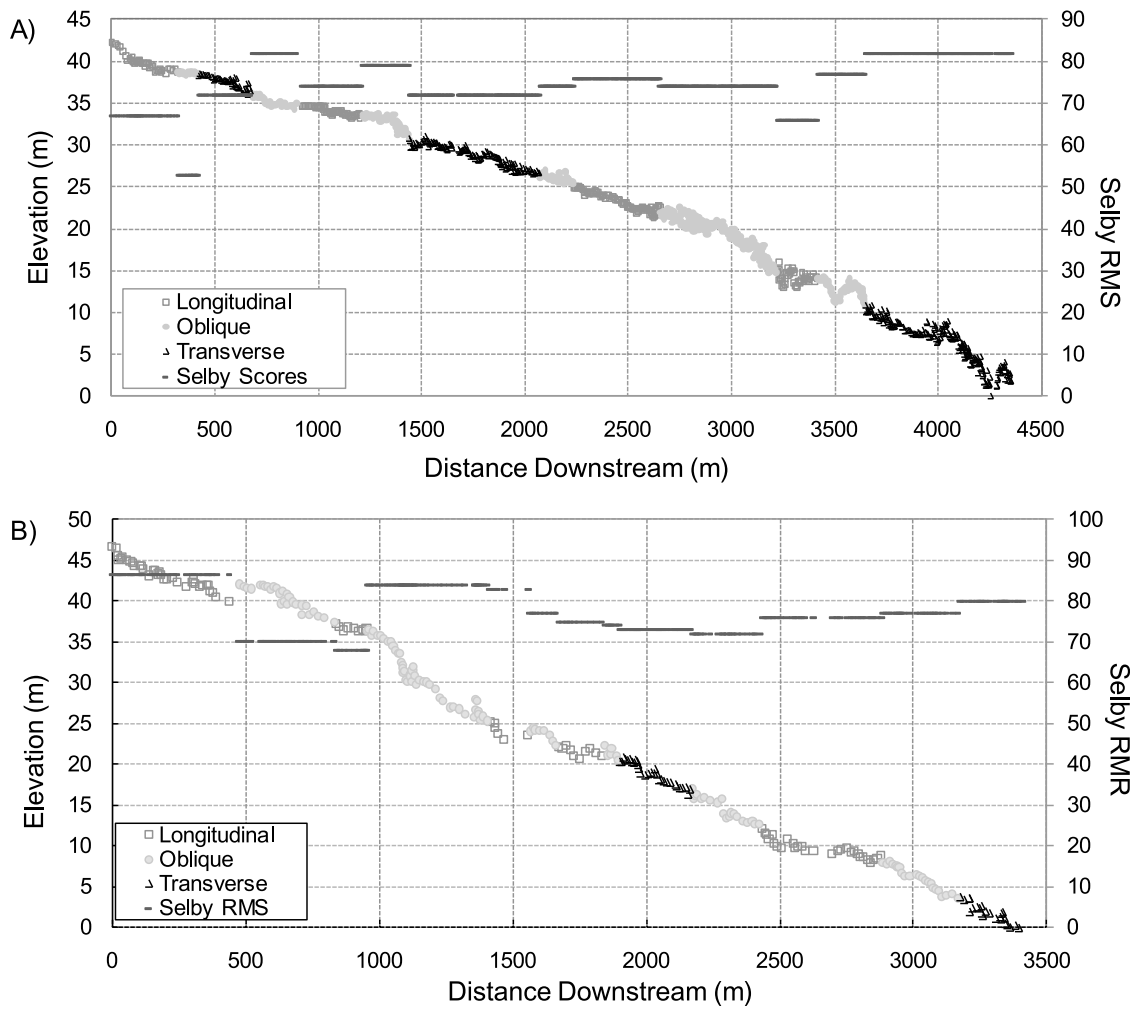
Figure 8. Longitudinal profile plots showing bed elevation variation according to rib orientation. Mean Selby scores are indicated by the solid lines for each reach. (a) Upper Ocoee and (b) middle Ocoee. Steep zones correspond to transverse ribs and greater Selby rock mass strength.
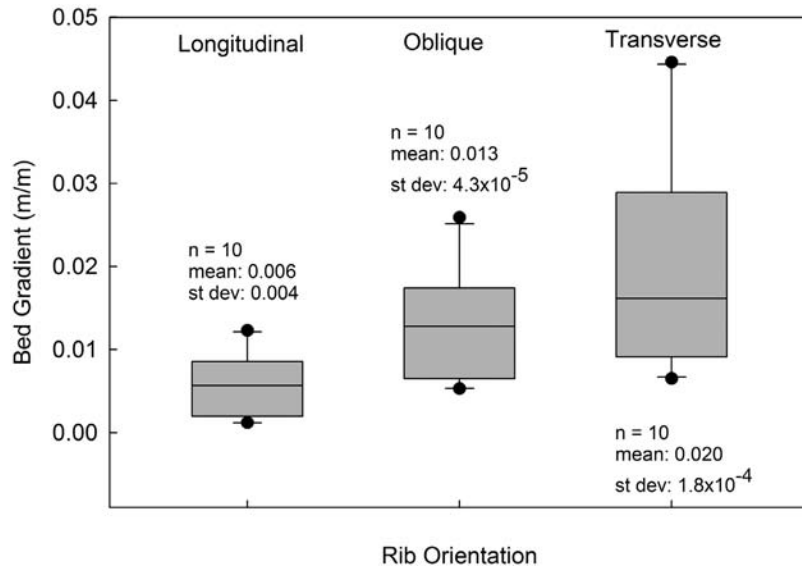
Figure 9. Comparison of bed slope among reaches with different rib orientations. Data include all surveyed reaches (upper Ocoee, n = 13; middle Ocoee, n = 13; Cheoah, n = 2; Tellico, n = 1; Little, n = 1). Within the box plots, the solid line represents median bed gradient. The box ends indicate the upper and lower quartiles, and whiskers are the 10th and 90th percentiles. The solid dots represent outliers.
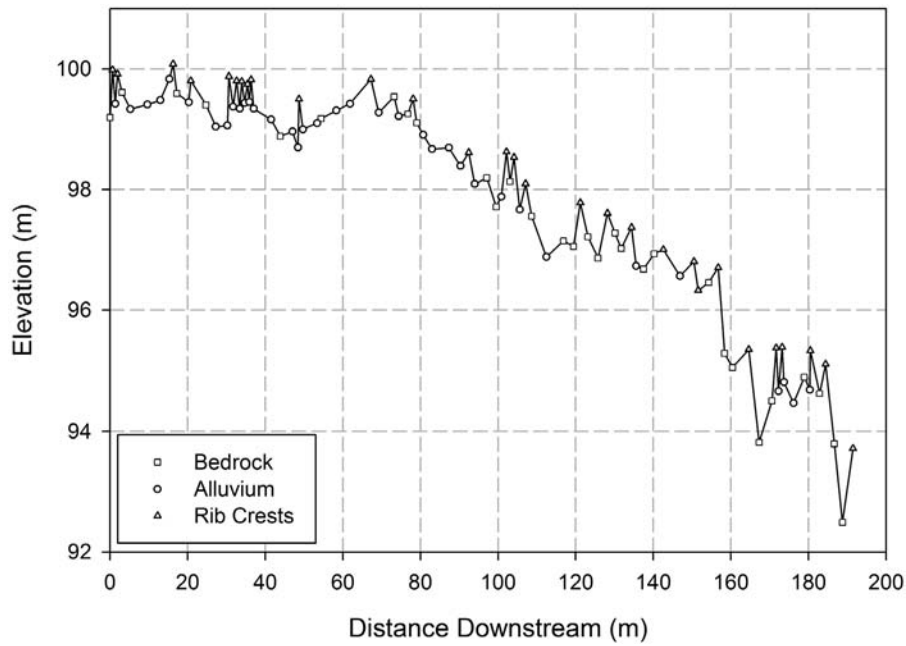

Figure 10. Longitudinal profile plot of the Little River study reach. Points along the profiles were identified as bedrock, alluvium, or rib crests. The detailed profile illustrates rib amplitude and spacing.
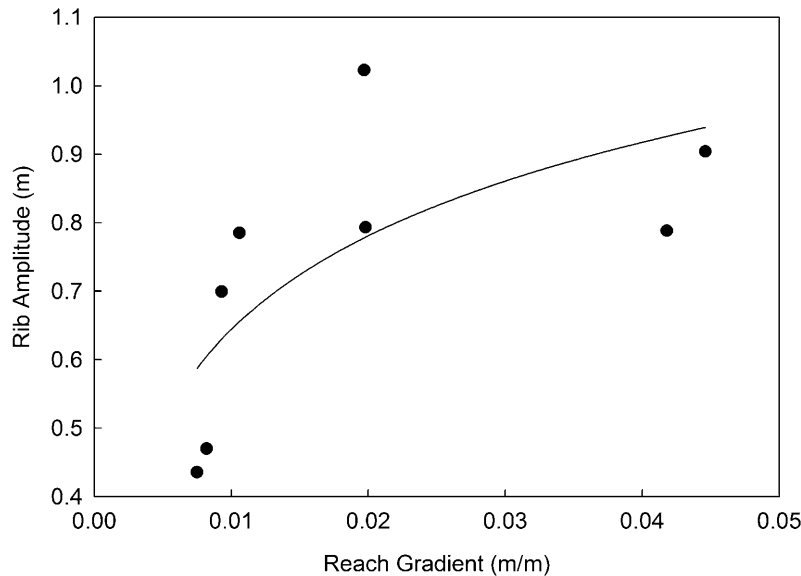
Figure 11. Positive logarithmic relationship between reach gradient and rib amplitude ($R^2 = 0.49$; $p = 0.05$). Data points represent the four upper Ocoee subreaches and the four reaches from other southeastern streams.

increased form roughness, produced by abrasional sculpting and rib geometry, reduces the erosional effectiveness of turbulent boundary shear stress, because more friction is expended as form drag as opposed to the strong near-wall turbulent shear that can drive abrasional impact wear. Correlations in rock erodibility and rib orientation that appear in the data limit separation of these two variables. This precludes determining which of the two is a more important independent control on reach-scale geometry and hydraulics.

[24] An interesting illustration of the adjustments among substrate resistance and channel geometry comes from one notable meander along the MO. The local strike and lithology of the ribs remains constant through the bend, but change in flow direction results in variation of rib orientation to flow; ribs transition from longitudinal to oblique and close to transverse. A corresponding transition in slope occurs through the bend and gradient increases as rib orientation changes from longitudinal to transverse. The relationships between rib orientation, the dominant joint and foliation orientation, and the channel gradient suggest that the channel bed morphology reflects the underlying substrate. Also, the orientation of the ribs exerts another level of flow resistance to which the channel must respond in order to maintain vertical incision. Increased stream power in these steeper reaches is likely distributed between increased roughness and greater abrasional wear on the more resistant rocks, but our data do not permit this distribution to be quantified. The amplitude of these ribs also appears to increase slightly as the ribs change in orientation. This potential correlation in rib amplitude and orientation suggests that the morphology adjusts in response to independent substrate controls. If the transversely oriented ribs of greater amplitude create greater hydraulic roughness, then greater reach gradient where the ribs are transverse suggests that the stream adjusts to locally increase reach-averaged stream power and localize erosion in response to this independent substrate characteristic.

[25] The interactions between hydraulics and substrate that we infer for the Ocoee River can be compared to those pro-

posed to act along alluvial channels. Bed forms in alluvial systems range from dunes and ripples in sand bed streams to steps and pools in gravel bed streams. The geometry and characteristics of alluvial bed forms are often interpreted in the context of extremal hypotheses [*Davies and Southerland*, 1980; *Richards*, 1976; *Grant*, 1997; *Wohl and Merritt*, 2008]. The fundamental assumption behind extremal hypotheses which posit minimization of variance in hydraulic variables, such as stream power, along a channel is that sites of greater energy expenditure, such as lateral constrictions or local steepening, will erode to a channel configuration with lower energy expenditure [e.g., *Kieffer*, 1989]. This assumption only holds if the boundary is readily deformable such that channel cross-sectional geometry can change substantially in response to increased energy expenditure. As boundary erodibility decreases, other mechanisms such as increased boundary roughness become more important. In coarse alluvial systems, for example, the geometry of step pool sequences adjusts in a manner that enhances flow resistance when the channel is supply limited [*Davies and Southerland*, 1980; *Abrahams et al.*, 1995]. The presence of bedrock bed forms [*Wohl and Grodek*, 1994; *Duckson and Duckson*, 2001] suggests that interactions between hydraulic energy and bed forms in bedrock streams might also regulate energy dissipation in these systems.

[26] *Wohl and Merritt* [2001] discriminated bedrock channel geometry according to gradient, substrate heterogeneity, and Selby rock mass strength. They interpreted correlations between channel morphology and substrate characteristics to indicate that, similar to alluvial streams, bedrock channel morphology reflects adjustments between hydraulic driving forces and substrate erodibility. The presence of spatial variations in substrate erodibility presumably creates spatial differences in these adjustments along bedrock channels that may limit the minimization of variance. *Hartshorn et al.* [2002] found greater variability and more irregular erosion in the quartzites. They attributed differences in channel morphology to differences in the intact rock
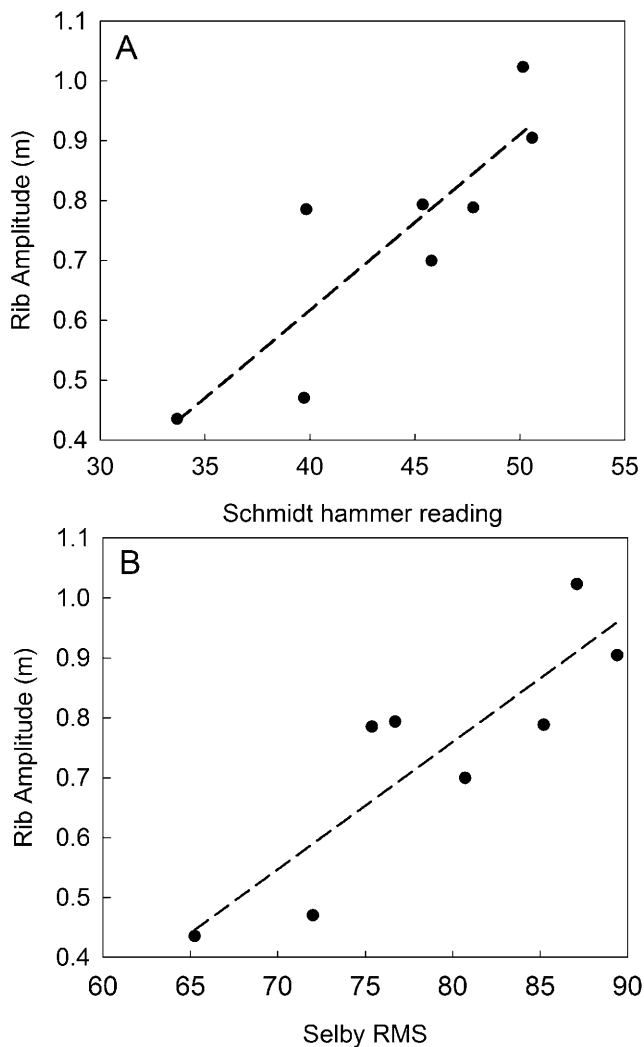
Figure 12. Bedrock rib amplitude as a function of substrate resistance, showing a positive correlation: (a) Schmidt hammer reading, $R^2 = 0.74$, and (b) Selby score, $R^2 = 0.76$. Data points represent the four upper Ocoee subreaches and the four reaches from other southeastern streams.

strength and joint spacing. Similarly, intact rock strength, Selby RMS, and orientation of bedrock structures that can be differentially sculpted to produce bedrock ribs vary significantly among the four subreaches of the upper Ocoee and strongly influence reach-scale geometry and hydraulics.

[27] The longitudinal variation in substrate characteristics along the rivers described here likely limits the degree to which these channels develop uniform energy expenditure toward either eroding the bed or generating heat in the flow. This is reflected in reach average values of stream power that vary by a factor of ~3. However, the heterogeneities in resistance may also set up mechanisms to locally enhance energy dissipation, resulting in feedbacks between hydraulics and substrate that tend to reduce longitudinal variation in energy expenditure in a manner similar that hypothesized for to alluvial streams.

[28] *Wohl et al.* [1999] showed that periodicity in the flow structure, created by bed or bank forms, perpetuates bedrock bed forms in the downstream direction, which leads to a

feedback between forms and hydraulics such that flow conditions oscillate around critical flow, as explained for alluvial channels by *Grant* [1997]. If flow oscillates around critical, then the effect is to minimize downstream variation in energy expenditure. Both alluvial and bedrock channels adjust roughness, albeit in different ways, to minimize interreach variability in energy expenditure.

[29] We have neglected bed load effects in this discussion, in part because upstream sediment supply to the Ocoee study reaches is altered by the presence of a dam. Sediment transport likely plays an important role, however, in the adjustments between hydraulics, boundary configuration, and incision of bedrock channels. Recent flume studies document how bedrock roughness influences incision patterns through its effect on local bed sediment transport [*Johnson and Whipple*, 2007; *Finnegan et al.*, 2007]. Also, *Chatanantavet and Parker* [2008] experimentally showed that the hydraulic roughness provided by the bedrock surface is an important factor in controlling the degree of alluviation. Their results agreed with those of *Demeter et al.* [2005], who showed that bedrock beds with greater roughness required a lower sediment supply rate before alluvial patches formed. All four of these studies point to the influence of bedrock roughness on localized bed sediment transport, which ultimately controls the incision rate [*Sklar and Dietrich*, 1998, 2004; *Johnson et al.*, 2009]. Although we did not examine bed sediment transport in this study, our results indicate that hydraulic roughness is enhanced through the development of larger bedrock bed forms in reaches of steeper gradient and greater substrate resistance. This not only illustrates focused erosion as predicted by our conceptual model, but also points to the importance of positive and negative feedbacks in development of bedrock channel morphology. In a subsequent study of the Ocoee River we investigate how bedrock channel morphology influences bed sediment transport. Overall, our results here provide another example where, as in alluvial streams, bedrock channel morphology reflects a quantifiable balance between hydraulic driving forces and substrate resistance [*Wohl and Merritt*, 2001], which is regulated though variations in hydraulic roughness and turbulence generation.

6. Conclusions

[30] Lithologic and structural variation along the profiles of the streams examined in this study creates differences in the substrate erodibility. These substrate heterogeneities lead to localized concentration of hydraulic energy, which is reflected by the positive correlation between rock erodibility and reach gradient. Bedrock ribs of greater amplitude are also consistent with steeper reach gradients. In reaches with transverse ribs, the gradient is steeper than segments with longitudinal ribs. These results suggest that reach gradient is largely a function of independent lithologic and structural controls. First-order assessment of reach-scale roughness in this bedrock channel indicates that the orientation of bedrock ribs also controls roughness and energy dissipation. Comparison of Manning's *n* between the reaches suggests that roughness increases with rib amplitude and as the orientation of bedrock ribs changes from longitudinal to transverse. Although increased reach gradient occurs where rock erodibility is lower, which suggests locally greater potential for erosion through increased stream power, these steeper
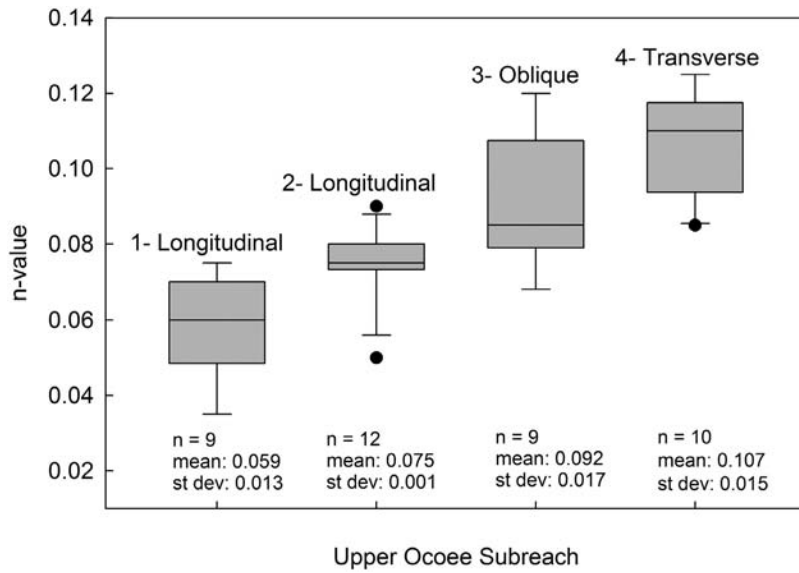
Figure 13. Comparison of calculated n values from the upper Ocoee subreaches. Rib orientations are indicated above each plot. Samples represent each cross section from the HEC-RAS modeling. Within the box plots, the solid line represents median n value from all cross sections. The box ends indicate the upper and lower quartiles, and whiskers are the 10th and 90th percentiles.
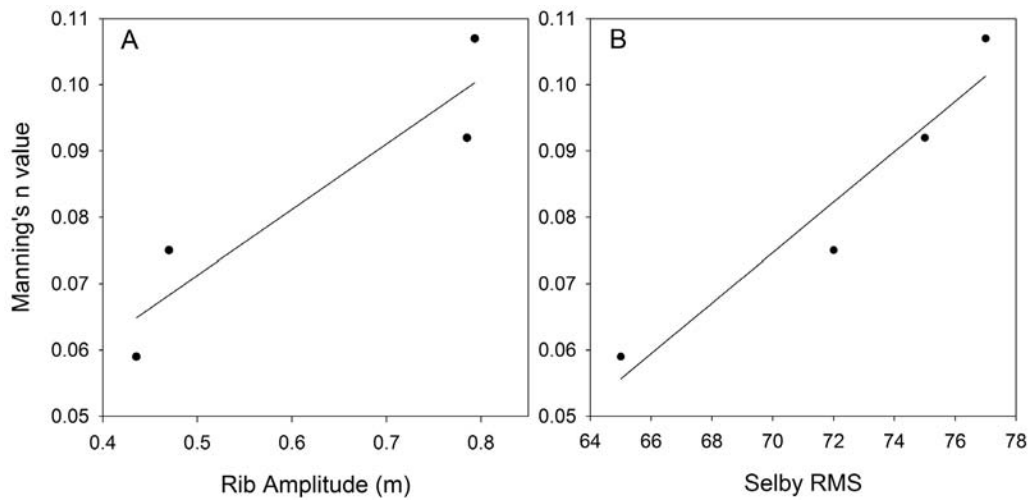

Figure 14. Substrate controls on reach-scale roughness. (a) $R^2 = 0.86$ and (b) $R^2 = 0.87$. Selby scores for each of the four upper Ocoee reaches represent an average of 21 points in each reach. Average n value in each reach is from all cross sections. Rib amplitudes are averaged from each reach (R1, n = 58; R2, n = 99; R3, n = 68; and R4, n = 70).

reaches are also associated with greater bed form amplitude and increased hydraulic roughness and energy dissipation, and this may counteract increases in stream power. These linkages demonstrate that there are complex feedbacks that operate between the underlying substrate, channel morphology and hydraulics, which reflect a balance between the hydraulic driving forces and substrate erodibility of bedrock streams.

References

Abrahams, A. D., G. Li, and J. F. Atkinson (1995), Step-pool streams: Adjustment to maximum flow resistance, *Water Resour. Res.*, 31(10), 2593–2602, doi:10.1029/95WR01957.

Baker, V. R. (1977), Stream-channel response to floods, with examples from central Texas, *Geol. Soc. Am. Bull.*, 88, 1057–1071, doi:10.1130/0016-7606(1977)88<1057:SRTFWE>2.0.CO;2.

Chatanantavet, P., and G. Parker (2008), Experimental study of bedrock channel alleviation under varied sediment supply and hydraulic conditions, *Water Resour. Res.*, 44, W12446, doi:10.1029/2007WR006581.

Crickmore, M. J. (1970), Effect of flume width on bedform characteristics, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, 96(HY2), 473–496.

Davies, T. R., and A. J. Southerland (1980), Resistance to flow past deformable boundaries, *Earth Surf. Processes*, 5, 175–179, doi:10.1002/esp.3760050207.

Demeter, G. I., L. S. Sklar, and J. R. Davis (2005), The influence of variable sediment supply and bed roughness on the spatial distribution of incision in a laboratory bedrock channel, *Eos Trans AGU*, 88(52), Fall Meet Suppl., Abstract H53D-0519.

Duckson, D. W., and L. J. Duckson (2001), Channel bed steps and pool shapes along Soda Creek, Three Sisters Wilderness, Oregon, *Geomorphology*, 38, 267–279, doi:10.1016/S0169-555X(00)00098-2.

Duvall, A., E. Kirby, and D. Burbank (2004), Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California, *J. Geophys. Res.*, 109, F03002, doi:10.1029/2003JF000086.

Ehlen, J., and E. E. Wohl (2002), Joints and landform evolution in bedrock canyons, *Trans. Jpn. Geomorphol. Union*, 23(2), 237–255.

Finnegan, N. J., L. S. Sklar, and T. K. Fuller (2007), Interplay of sediment supply, river incision, and channel morphology revealed by the transient evolution of an experimental bedrock channel, *J. Geophys. Res.*, 112, F03S11, doi:10.1029/2006JF000569.

Frankel, K. L., F. J. Pazzaglia, and J. D. Vaughn (2007), Knickpoint evolution in a vertically bedded substrate, upstream-dipping terraces, and Atlantic slope bedrock channels, *Geol. Soc. Am. Bull.*, 119(3), 476–486, doi:10.1130/B25965.1.

Gardner, T. W. (1983), Experimental study of knickpoint and longitudinal profile evolution in cohesive, homogeneous material, *Geol. Soc. Am. Bull.*, 94, 664–672, doi:10.1130/0016-7606(1983)94<664:ESOKAL>2.0.CO;2.

Goode, J. R., and E. Wohl (2007), Coarse sediment transport dynamics at three spatial scales of bedrock channel bed complexity, *Eos Trans AGU*, 88(52), Fall Meet. Suppl., Abstract H51E-0794.

Grant, G. E. (1997), Critical flow constrains flow hydraulics in mobile-bed streams: A new hypothesis, *Water Resour. Res.*, 33, 349–358, doi:10.1029/96WR03134.

Hartshorn, K., N. Hovius, W. B. Dade, and R. L. Slingerland (2002), Climate-driven bedrock incision in an active mountain belt, *Science*, 297, 2036–2038, doi:10.1126/science.1075078.

Johnson, J. P., and K. X. Whipple (2007), Feedbacks between erosion and sediment transport in experimental bedrock channels, *Earth Surf. Processes Landforms*, 32, 1048–1062, doi:10.1002/esp.1471.

Johnson, J. P. L., K. X. Whipple, L. S. Sklar, and T. C. Hanks (2009), Transport slopes, sediment cover, and bedrock channel incision in the Henry Mountains, Utah, *J. Geophys. Res.*, 114, F02014, doi:10.1029/2007JF000862.

Kieffer, S. W. (1989), Geologic nozzles, *Rev. Geophys.*, 27, 3–38, doi:10.1029/RG027i001p00003.

Kobor, J. S., and J. R. Roering (2004), Systematic variation of bedrock channel gradients in the central Oregon Coast Range: Implications for rock uplift and shallow landsliding, *Geomorphology*, 62, 239–256, doi:10.1016/j.geomorph.2004.02.013.

Lavé, L., and J. P. Avouac (2001), Fluvial incision and tectonic uplift across the Himalayas of central Nepal, *J. Geophys. Res.*, 106, 26,561–26,591, doi:10.1029/2001JB000359.

Leopold, L. B., and T. Maddock (1953), The hydraulic geometry of stream channels and physiographic implications, *U.S. Geol. Surv. Prof. Pap.*, 252, 57 pp.

Matmon, A., P. R. Bierman, J. Larsen, S. Southworth, M. Pavich, and M. Caffee (2003), Temporally and spatially uniform rates of erosion in the southern Appalachian Great Smoky Mountains, *Geology*, 31, 155–158, doi:10.1130/0091-7613(2003)031<0155:TASURO>2.0.CO;2.

Miller, J. R. (1991), The influence of bedrock geology on knickpoint development and channel bed configuration along downcutting streams in south-central India, *J. Geol.*, 99, 591–605.

Montgomery, D. R., and K. B. Gran (2001), Downstream variations in the width of bedrock channels, *Water Resour. Res.*, 37(6), 1841–1846, doi:10.1029/2000WR900393.

O'Connor, J. E., R. H. Webb, and V. R. Baker (1986), Paleohydrology of pool-riffle pattern development: Boulder Creek, Utah, *Geol. Soc. Am. Bull.*, 97, 410–420, doi:10.1130/0016-7606(1986)97<410:POPPDB>2.0.CO;2.

Richards, K. S. (1976), The morphology of riffle-pool sequences, *Earth Surf. Processes*, 1, 71–88, doi:10.1002/esp.3290010108.

Richardson, K., and P. A. Carling (2005), A typology of sculpted forms in open bedrock channels, *Spec. Pap. Geol. Soc. Am.*, 392, 108 pp.

Selby, M. J. (1980), A rock mass strength classification for geomorphic purposes: With tests from Antarctica and New Zealand, *Z. Geomorphol.*, 24, 31–51.

Shepherd, R. G., and S. A. Schumm (1974), Experimental study of river incision, *Geol. Soc. Am. Bull.*, 85, 257–268, doi:10.1130/0016-7606(1974)85<257:ESORI>2.0.CO;2.

Sklar, L. S., and W. E. Dietrich (1998), River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, in *Rivers Over Rock: Fluvial Processes in Bedrock Channels*, *Geophys. Monogr. Ser.*, vol. 107, edited by K. Tinkler and E. E. Wohl, pp. 237–260, AGU, Washington, D. C.

Sklar, L., and W. E. Dietrich (2001), Sediment and rock strength controls on river incision into bedrock, *Geology*, 29, 1087–1090, doi:10.1130/00917613.

Sklar, L. S., and W. E. Dietrich (2004), A mechanistic model for river incision into bedrock by saltating bed load, *Water Resour. Res.*, 40, W06301, doi:10.1029/2003WR002496.

Sutton, S. J. (1991), Development of domainal slaty cleavage fabric at Ocoee Gorge, Tennessee, *J. Geol.*, 99(6), 789–800, doi:10.1086/629552.

U.S. Army Corps of Engineers (2002), HEC-RAS river analysis system user's manual, version 3.1, Hydrol. Eng. Cent., Inst. for Water Resour., Davis, Calif.

Wohl, E., and H. Achyuthan (2002), Substrate influences in incised-channel morphology, *J. Geol.*, 110, 115–120, doi:10.1086/324207.

Wohl, E., and G. C. L. David (2008), Consistency of scaling relations among bedrock and alluvial channels, *J. Geophys. Res.*, 113, F04013, doi:10.1029/2008JF000989.

Wohl, E. E., and T. Grodek (1994), Channel bed-steps along Nahal Yael, Negev desert, Isreal, *Geomorphology*, 9, 117–126, doi:10.1016/0169-555X(94)90070-1.

Wohl, E. E., and H. Ikeda (1997), Experimental simulation of channel incision into a cohesive substrate at varying gradients, *Geology*, 25, 295–298, doi:10.1130/0091-7613(1997)025<0295:ESOCII>2.3.CO;2.

Wohl, E. E., and D. M. Merritt (2001), Bedrock channel morphology, *Geol. Soc. Am. Bull.*, 113, 1205–1212, doi:10.1130/0016-7606(2001)113<1205:BCM>2.0.CO;2.

Wohl, E., and D. M. Merritt (2008), Reach-scale geometry of mountain streams, *Geomorphology*, 93, 168–185, doi:10.1016/j.geomorph.2007.02.014.

Wohl, E. E., N. Greenbaum, A. P. Schick, and V. R. Baker (1994), Controls on bedrock channel incision along Nahal Paran, Israel, *Earth Surf. Processes Landforms*, 19, 1–13, doi:10.1002/esp.3290190102.

Wohl, E. E., D. M. Thompson, and A. J. Miller (1999), Canyons with undulating walls, *Geol. Soc. Am. Bull.*, 111(7), 949–959, doi:10.1130/0016-7606(1999)111<0949:CWUW>2.3.CO;2.

Yanites, B. J., G. E. Tucker, K. J. Mueller, Y. G. Chen, T. Wilcox, S. Y. Huang, and K. W. Shi (2010), Incision and channel morphology across active structures along the Peikang River, central Taiwan: Implications for the importance of channel width, *Geol. Soc. Am. Bull.*, 122(7–8), 1192–1208, doi:10.1130/B30035.1.

J. R. Goode, Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture, 322 E. Front St., Ste. 401, Boise, ID 83702, USA. (jaimegoode@fs.fed.us)

E. Wohl, Department of Geosciences, Colorado State University, 1482 Campus Delivery, Fort Collins, CO 80523-1482, USA.