An Examination of the effects of Joint Geometry on the Inferred Erosion Rate of Bedrock Channels in the Austrian Alps

By Daniel Scott

Abstract

River incision into bedrock drives landscape change and often must be understood for effective design of engineered structures. I hypothesize that joint geometry (the orientation and spacing of joints) may play a strong role in controlled erosion rates in jointed bedrock channels. During a 3 month research stay in Innsbruck, Austria, I collected field data on a reach-scale describing channel slope, drainage area, joint orientation, and joint spacing in channels in the northern Austrian Alps. I use multiple linear regression techniques to build a model that uses these data to predict an inferred erosion rate index. Results from this modeling show that erosion rate index is highly correlated with average joint spacing in limestone channels. However, there is significant variation between channels in limestone and those in shale. I also observed significant abrasive erosion in channels that may obscure the effects of joint orientation. From this, I conclude that more data from a wide range of lithologies and erosional regimes will be necessary to fully constrain the relationship between joint geometry and erosion rate. This work provides an important first step in developing a more robust model of bedrock river evolution in the context of jointed channels.

Introduction

Bedrock incision is the critical erosive mechanism controlling large-scale landscape erosion and tectonic response (Howard et al., 1994). As rivers erode, they transport sediment downstream, thus moving rock material from the land to the oceans. However, sediment transport is limited by the amount of sediment produced from bedrock. Bedrock rivers are a primary source of bedrock sediment, and set the base level of erosion in a river network, in that the lowering of the land surface is limited by the rate of erosion of bedrock rivers. Thus, in order to understand and predict the evolution of landscapes, we must first be able to understand bedrock river incision.

My work in Austria has helped to develop a parameterization of bedrock river incision. My investigation has worked towards determining the effects of joint geometry (the spacing between joints and orientation of joints relative to the bed surface and direction of flow) on plucking, the dominant mechanism of bedrock channel incision in streams with jointed beds (Whipple et al., 2000a). During plucking, flow entrains and transports individual blocks of bedrock (Whipple et al., 2000a). These blocks must first be produced for transport by processes of block detachment. Although these processes are poorly understood, they generally consist of a mechanism for widening or completely cracking preexisting joints in the bed surface. For instance, it has been proposed that the hydraulic or impact wedging of individual clasts into a joint may act to widen or extend the joint (Hancock et al., 1998). Once a block has been detached or nearly detached, it may be transported and/or broken down into smaller sediment. This mode of erosion is generally more episodic than abrasion-type erosion, which removes bed material more slowly but consistently. Because the plucking process so heavily depends on the jointing of the bed surface, it is suspected that the orientation and spacing of joints relative to the direction of flow and slope of the bed surface may be an important control on the hydraulic force necessary to pluck blocks from the bed.

Previous work focusing specifically on the processes of block plucking has dominantly used flume experiments to investigate the relationship between hydraulic forces and block entrainment. This work has focused on plucking blocks of a characteristic size (Chatanantavet and Parker, 2009) and horizontally plucking blocks by sliding (Coleman et al., 2003; Dubinski and Wohl, 2013). These investigations support a relationship between shear stress and the rate at which blocks are plucked from the bed, as well as a relationship between the geometry and protrusion of blocks relative to the bed and the hydraulic force necessary for plucking to occur (Lamb et al., 2015). This indicates that joint geometry and spacing, by controlling block geometry and protrusion, could control the shear stress necessary to pluck blocks and the rate at which a bedrock river incises into its bed.

Field investigations of bedrock river incision by plucking have focused on observations of erosion rates, either measured or inferred, and the spatial correlation between higher erosion rates and factors such as closely spaced joints (Whipple et al., 2000b). Wohl (2008) observed that river valley constrictions correlated with joint spacing on the Poudre River, CO, interpreting reaches of greater bedrock width to be caused by more densely spaced joints and correspondingly greater erosion rates. Spotila et al. (2015) similarly found that wide, highly eroded valley segments on the New River, in the Northeast U.S., were associated with closely spaced joints in bedrock. On a smaller scale, potholes in bedrock rivers have been observed to correlate and orient with joints (Ortega et al., 2014). However, this trend is not observed across all lithologies (Lima and Binda, 2015).

On the broad scale, it is also possible to draw analogs between glacial erosion into bedrock valleys and fluvial erosion into bedrock channels. Although glacial processes are markedly different than fluvial erosive processes, they may provide some insight into how lithologic characteristics such as joint geometry affect the resistance of bedrock to erosion. Glacial erosion tends to be controlled by joint orientation (Hooyer et al., 2012) as well as spacing

(Dühnforth et al., 2010; Anderson, 2014). Kelly et al. (2014) found that the dip of bedding relative to the flow of the glacier influences the erosional landforms produced by the glacier as well as the relative dominance of plucking versus abrasion processes. Becker et al. (2014) proposes that the landscape of Tuolumne Meadows, California, USA is the result of variations in glacial erosion caused by the distribution of preexisting bedrock fractures, and suggest that fracturing may be a more important control than lithology in terms of controlling landscape evolution.

Bedrock river incision has been modeled as the combination of abrasion-type erosive mechanisms in conjunction with plucking (Chatanantavet and Parker, 2009). However, previous models parameterize potentially plucked blocks by their size alone. This ignores previous findings indicating that the orientation of joints and their spacing have strong influences on the efficiency of erosion. This research aims to better parameterize joint systems in bedrock channels such that the complex parameters of joint orientation and spacing can be added to existing erosion models. This will allow for a more accurate model of bedrock incision, leading to better characterizations of landscape evolution.

Hypotheses and Objectives

The efficiency of plucking depends on the orientation of blocks relative to flow. Limited experimental and modeling evidence points to block sliding and toppling at the face of knickpoints in the channel dominates erosion in jointed channels (Dubinski and Wohl, 2013; Lamb et al., 2015). A block that has a joint face more exposed to the flow is more likely to be able to be entrained by a given flow than one with joint faces that are less exposed to the flow

(Coleman et al., 2003). Similarly, the normal force acting on a block will likely be more efficient at moving that block downstream if the full force of the flow is directed on the block in a downstream direction.

I hypothesize that channels with joint sets that produce block faces that are oriented more perpendicularly to the flow, allowing more of the hydraulic force to be directed in a downstream direction, will result in a greater erosion rate than joint sets producing block faces oriented more parallel to flow. Similarly, I hypothesize that more closely spaced joints will result in higher rates of erosion.

I seek to use field data to develop a statistical model describing the effects of joint geometry on erosion rate. Because flume experiments, such as those conducted by Dubinski and Wohl (2013), are difficult to execute and cannot feasibly explore all potential joint geometries, I hope to use field data to narrow down the potential joint geometry parameters that are most important in controlling erosion rate. These parameters can then be feasibly tested in a flume, which could lead to a numerical model describing the process of plucking. Here, I will present analysis of preliminary data from channels in the Austrian Alps that will serve as a first order test of the aforementioned hypotheses. However, this preliminary analysis is only a small part of the planned dataset I seek to collect to test my hypotheses. This preliminary analysis will serve as a test of my field methods and analysis procedures and hopefully provide insight into the sample size necessary to rigorously test my hypotheses.

Methods

To test my hypotheses, I sought to predict erosion rate using measured joint geometry parameters. To do this, I needed to measure joint geometry in the channel and flow direction. Measuring erosion rate directly in the field on a large scale, however, is unfeasible considering the high costs and time required to do so. Therefore, I infer an erosion rate based on an erosion rate index for each study reach.

Measuring Joint Geometry

For the purposes of modeling the effects of joint geometry on erosion rate, I designate channel reaches in the field whose joint characteristics, channel geometry, lithology, and flow were relatively constant throughout the reach. These reaches serve as individual samples in my model. Within each reach, I take multiple opportunistic samples of joint geometry by measuring the strike (the azimuth orientation of a line oriented horizontally along the plane of the joint) and the dip (the angle from horizontal of a line oriented perpendicular to the line of strike along the plane of the joint) of each joint set with a compass and clinometer (Figure 1). Along with each measurement of joint orientation, I measure the spacing between individual joints in a joint set by counting the number of each joints per meter (Figure 2). For joint sets dipping over 45°, I measure joint spacing along a horizontal line. For joint sets with a dip below 45°, I measure joint spacing along a vertical line. This better approximates spacing along the channel bed, as the channel bed generally does not intersect joints along a straight line. Finally, I measure flow direction using a compass in order to relate joint geometry to flow direction.

Figure 1: The author measuring the strike and dip of joints formed by bedding in limestone.

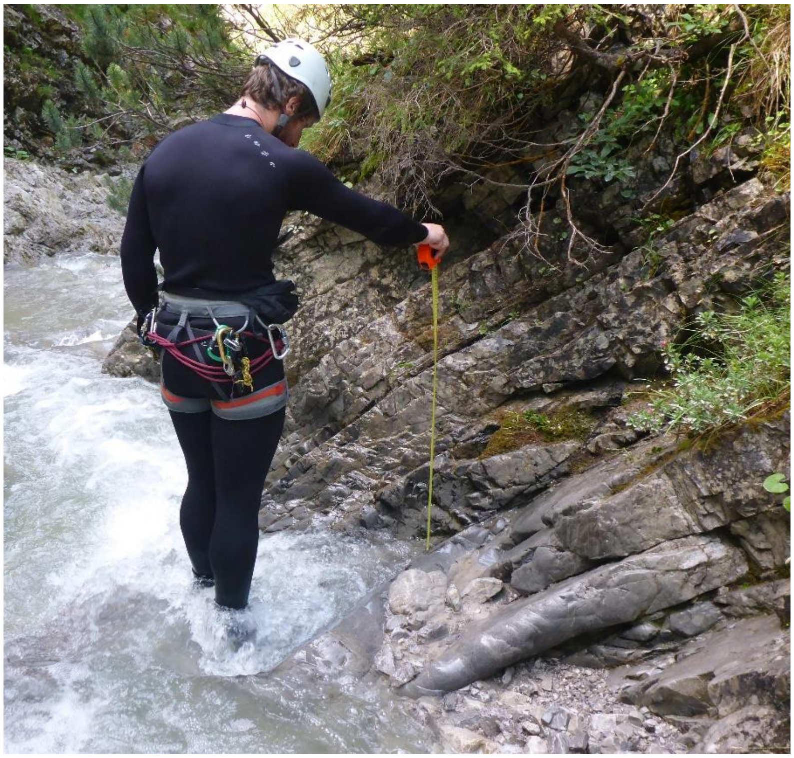

Figure 2: The author measuring the spacing of joints formed by bedding in limestone. Because the joints are dipping at an angle of less than 45°, the spacing of the joints was measured vertically.

Many reaches exhibit multiple joint sets, making identification of all joint sets difficult (Figure 3). In some cases, reaches were excluded from measurement when identification of all dominant joint sets was deemed too difficult to be done accurately. Some reaches exhibited very complex joint sets that were only exposed in small sections of the reach. These joint sets were assumed to be insignificant due to their confined spatial extent and were therefore ignored.

Figure 3: An example of complex jointing that was deemed too difficult to accurately identify and measure. Note tape measure for scale.

Measuring Erosion Rate Index

It has been proposed that a power law relating long term erosion rate to a function of drainage area and slope (Howard and Kerby, 1983; Howard et al., 1994) may serve as a way of modeling the long term evolution of bedrock channels. This power law is based on the idea that stream power is directly correlated to erosion rate, and that drainage area is a proxy for discharge. In lieu of directly measuring erosion rate, I use an erosion rate index (E_i) given by Equation 1:

$$E_i = AS$$

This erosion rate index effectively relates a drainage-area-normalized slope to erosion rate, whereby steeper channels are inferred to be eroding faster for a given drainage area, and channels of the same erosion rate but different drainage area will exhibit a difference in slope inversely proportional to their difference in drainage area.

To determine E_i for each study reach, I needed to measure slope and drainage area. I took the latitude and longitude of the upstream-most point of each reach using a handheld GPS unit. I then used a 10 m resolution DEM to extract a drainage area to the coordinates of the GPS point. To measure slope, I conduct a survey of the channel bed using a laser rangefinder. Because of the difficulties of accessing some of the study channels, I use a low-resolution survey method consisting of measuring the slope between each step crest in the channel. This slope is an approximation of the true water surface slope, but is likely a good approximation of the reach-average slope during a high flow event when steps may be submerged and hydraulic forces are large enough to cause block movement.

Parameterizing Joint Geometry

Because of the complexity of joint geometry in a stream channel (e.g., multiple joint sets, highly variable geometry between joint sets), there are many potential parameterizations of joint geometry for the purpose of defining predictor variables for a model to predict erosion rate index. I chose to define my parameters both on the scale of individual joints (each parameter representing an individual joint set in the reach) and on the scale of all joint sets averaged together (each parameter representing the average effect of all joint sets).

Because reaches contained anywhere between 1 and 3 joint sets, it became necessary to prioritize joint sets when testing their individual effect on erosion rate index. Thus, I use the following individual joint set parameters: 1) the deviation in strike (horizontal axis) from the flow direction of the joint set most perpendicular to flow, 2) the deviation in strike from the flow direction of the joint set most parallel to flow, 3) the deviation in dip (vertical axis) from the slope of the flow of the joint set most perpendicular to flow, and 4) the deviation in dip from the slope of the flow of the joint set most parallel to flow. I chose to use only the most perpendicular to flow direction or slope and the most parallel to flow direction or slope because I suspected that the most perpendicular joint set should experience the most normal force from the imposing flow, and the most parallel joint set should experience the least normal force from the imposing flow. If those parameters were found to be significant in my model, I would then attempt to include any other joint sets. However, if none of those parameters were found to be significant, it would be more likely that the effects of the orientation individual joint sets are insignificant in terms of prediction erosion rate index.

I chose to use the following parameters averaged over all joint sets: 5) the average spacing of all joint sets, 6) the average total deviation from flow of all joint sets. The average total deviation is simply the average of the sum of the strike deviation from flow direction and the dip deviation from flow slope for each joint set. It represents the average total deviation of the joint planes from the plane normal to the flow (the plane on which normal force from the flow is maximized).

Statistical Analysis

I utilize the R statistical package for all analyses (R Core Team, 2014). I use all subsets multiple linear regression analysis to test every potential model relating the aforementioned predictor variables that describe joint geometry to the aforementioned erosion rate index. I also tested the fit of a nonlinear model, after selecting significant variables. Because of the small sample size, I chose to rank models by the corrected Akaike Information Criterion (Wagenmakers and Farrell, 2004). Before testing all models, I performed log transformations to normalize non-normal variables. After reducing the number of potential predictors, I tested for the possibility of lithology playing a role in predicting erosion rate by removing the reaches with a shale lithology. After selecting a model, I performed model diagnostics to evaluate whether the model met the assumptions inherent in multiple linear regression. Unless otherwise noted, all reported models met multiple linear regression assumptions.

Field Sites

Data presented here was collected in the Northern Alps of Austria, mainly in the vicinity of the city of Innsbruck (Figure 4). The data presented here are from streams with dominantly small drainage area (0.05 to 5.98 km^2), running through dominantly massive or bedded limestone, with one channel (comprising 4 individual reaches) flowing over exposures of shale. Most of the channels presented here are quite steep (3.17 to 39.23 degrees). Because of the difficulties of accessing larger rivers to perform the aforementioned field measurements, this study is limited to small rivers with at least some period of low flow that allows access to the channel bed.

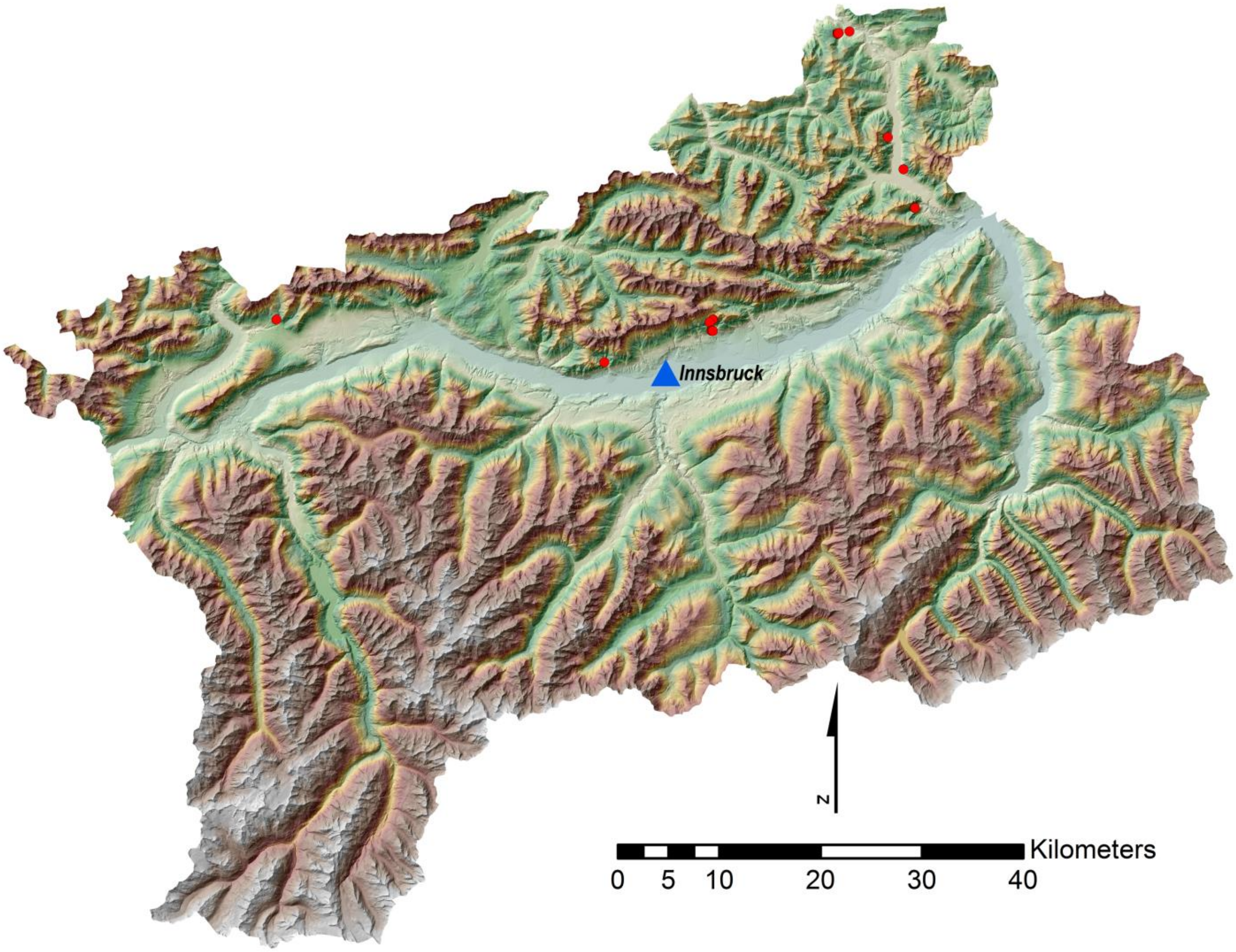

Figure 4: Hillshade map of the Austrian Alps in the vicinity of the city of Innsbruck (blue triangle). Red dots mark study reaches.

The climate in the study region is humid continental. The average yearly precipitation in Innsbruck is 895.6 mm, with mean annual daily temperature of 8.5° C (Zentralanstalt für Meteorologie und Geodynamik, 2002). Precipitation in summer months is often in the form of high intensity thundershowers, which produce highly episodic flooding in small channels. There is also a significant snowmelt peak early in the summer.

The channels in this region are heavily modified by humans, with many of the study reaches being downstream of check dams. Check dams may have been introduced around the 14th century, and were likely quite common by the 19th century (Jaeggi and Pellandini, 1997). Thus, the sediment and water regimes in these channels have been altered for significant periods of time prior to this study. It is very difficult to understand the effects of this type of engineering due to the lack of detailed records or monitoring on these channels. However, because bedrock erosion is a long term process, the impact of human engineering is probably insignificant on the scale of long term bedrock incision and development of these channels. Therefore, this analysis ignores the potential impacts of these check dams and other river basin engineering structures.

Results

Sample size for models including the reaches with shale lithology is 19. Sample size for models excluding shale reaches is 15. All individual joint set parameters (1-4) were found to be insignificant in predicting erosion rate index. A linear model using average joint spacing and average joint deviation was only significant at a 10% confidence level ($p = 0.08$), and displayed a low adjusted R^2 ($R^2_a = 0.18$). However, after removing reaches with a shale lithology, that same model became significant ($p = 0.04$, $R^2_a = 0.32$). Nonlinear models tended to perform better than linear models, with the model for all reaches (shale included) being significant at a 5% confidence level ($p = 0.05$, $R^2_a = 0.22$), and the model for only limestone reaches being highly significant and explaining the majority of the variance in the dataset ($p < 0.001$, $R^2_a = 0.67$). Thus, I conclude that the most appropriate model is a nonlinear (power law) model relating erosion rate index to average joint spacing and average total deviation of joint sets for only limestone reaches. This model predicts that the erosion rate index decreases with increased average spacing and increased average total deviation. However, analyzing the marginal importance of each of the two predictor variables reveals that the average total deviation of joint sets is not marginally significant ($p = 0.92$) in predicting erosion rate index. Thus, I conclude that the best model is one that uses only average joint spacing to predict erosion rate index. This model is highly significant and explains the majority of the variance in the dataset ($p < 0.0001$, $R^2_a = 0.70$). This model takes the form of a power law,

$$E_i = a(\ln S)^b$$

where S is the average spacing of all joint sets in a reach.

Discussion

The model results indicate that the erosion rate index is nonlinearly related to joint spacing. As joints become spaced further apart, the erosion rate index decreases. This is expected: wider spaced joints will tend to produce larger individual blocks that require more force to transport downstream and cause erosion. The nonlinearity of this relationship is notable in the sense that previous work (e.g., Dubinski and Wohl, 2013) has found a linear relationship between driving forces (shear stress) and block erosion in flume settings. Unfortunately, the limited scope of this dataset prevents significant interpretation of the nonlinearity of this relationship. Data from larger channels and a greater diversity of lithologies may elucidate the relationship between joint spacing and erosion rate.

What is unexpected is that the orientation of joint planes did not appear to control the erosion rate index. This implies that the rate of block detachment and transport downstream (assumed to be represented by the erosion rate index) is likely not controlled by the deflection of force applied to the upstream face of the block in these systems. Because the erosion rate index correlates only with joint spacing (an effective measure of the size of a block), it is possible that vertical forces (lift) play a more dominant role than horizontal (shear) forces, as shear forces on a block would likely depend on the orientation and protrusion of the upstream-facing part of the block. This may imply that blocks in these systems erode dominantly by being lifted from the channel bed, as opposed to toppling off steps. Both of these mechanisms have been observed experimentally as mechanisms of bedrock erosion by plucking (Dubinski and Wohl, 2013). However, it is very difficult to infer from this limited data the nature of erosive processes in these channels.

It is possible that abrasion and/or dissolution has caused a weathering of joint faces where they are exposed at the stream bed. The channels presented here did not generally exhibit jointed blocks that protrude from the channel bed more than approximately 10 cm (e.g., Figure 5). Rounded block edges indicate that abrasion is an active erosive mechanisms in these channels (e.g., Figure 6). Abrasion was observed on many exposed joint faces. Such abrasion could act to round the face of the joint plane as it is exposed to flow above the channel bed. Because of the low exposure height of block above the channel bed, abrasion could round off the entire exposed joint face. This could result in hydraulic force from the flow not impacting the joint plane on a face oriented along the joint plane itself, but instead one that is shaped by abrasion. This would invalidate the assumption that the orientation of the joint plane controls the magnitude of force impacting a block, as the joint plane may not define the part of the block being impacted by the flow.

The observation of significant rounding of the edges of joint planes indicates that abrasion plays a dominant role in eroding these channels, and that the ratio of abrasion-related erosion to plucking-related erosion is likely high. From this, I hypothesize that in systems with high rates of abrasion (acting to round joint planes) relative to rates of erosion by plucking (acting to expose fresh, unrounded joint planes) may exhibit erosion rates independent of joint orientation due to the rounding of joint faces exposed to flow. Because this study did not include other lithologies that may have a lower ratio of abrasion to plucking erosion, I cannot test this hypothesis.

Figure 5: Channel bed showing multiple small bedrock steps and dense jointing. Like many other channels in the limestone Alps, blocks showed relatively little protrusion from the channel bed. Notice the helmet and backpack in the center left of the picture for scale.

Figure 6: Channel bed showing bedding joints that have been significantly rounded at their edges by abrasive erosion. Notice that joint planes exposed above the bed are often abraded such that the part of the plane exposed to flow is not at the same orientation as the rest of the joint plane.

Because of the drastic improvement in the model after the removal of shale reaches, I conclude that the joint controls on erosion rate index are likely dependent on lithology. Unfortunately, there are too few samples from non-limestone lithologies to fully test for the presence of a robust model describing erosion rate index for the shale reaches. If there truly exists a dependence on lithology, this dependence is probably manifested in variations in tensile strength and the ration of abrasion/dissolution erosion to plucking erosion. Because the detachment of a block from the channel bed depends on the amount of force required to fully expand a joint until it separates the block from the channel bed, higher tensile strength should decrease the erosion rate between two reaches with similar joint geometries. Limestone is notably susceptible to dissolution, making the rounding of sharp edges more likely to occur over short timescales than in more chemically-resistant lithologies. As explained above, this could round joint faces exposed to flow and decrease the influence of joint planes on the orientation of exposed block surfaces.

Conclusions

This study serves as a starting point for the exploration of the effects of joint geometry on erosion rate in jointed bedrock channels and gives guidance for future work. From a limited dataset, I can conclude that joint spacing is a dominant control on erosion rate index in jointed limestone channels. The notable observation that joint orientation does not correlate with erosion rate index suggests a conceptual misunderstanding of the hydraulic forces acting on jointed blocks, or the invalidity of assumptions made about the erosion of blocks in bedrock rivers. That is, it may be the case that joint plane orientation does not determine the orientation of block faces exposed to flow. This would decouple joint plane orientation from erosion rate, as I have observed here. Further exploration of different lithologies or systems that are more obviously dominated by plucking would help to explore these possibilities. It may be that a classification of bedrock systems on a continuum of abrasion-dominated to plucking-dominated, as opposed to previously suggested pseudo-binary classifications (e.g., Whipple et al., 2000a), is more appropriate in terms of determining the mechanism of erosion. A channel that is heavily influenced by both abrasion and plucking may act more similarly to channels observed in this study. In contrast, a channel that shows very little evidence of abrasion may display a stronger relationship between joint orientation and erosion rate. I hypothesize that the influence of joint orientation on erosion rate depends highly on the mechanisms of erosion at play in a bedrock system and the lithology of that system.

Further field observations focusing on a broader range of lithologies would help to explore a greater range of erosional mechanisms and tensile strengths. It is difficult to conclude from this dataset alone whether tensile strength plays a role in the influence of joint geometry on erosion rate. However, it appears that the methods applied in this study worked well for limestone and shale lithologies, and are likely applicable to other lithologies. Because of the generality and simple nature of the measurements, it is easy to accommodate a wide variety of slope, joint geometry, and ease of access. Future work using these methods would allow for rapid characterization of many channels. Based on the results of this study, it appears that a rapid increase in the size of this dataset is more important than a more detailed examination of the effects of joint geometry on erosion rate index. Thus, continuation of the current methodology seems appropriate.

However, once a dataset has been established that includes a range of lithologies, more diversity in drainage area, and covers the spectrum of abrasion vs plucking dominated channels, it appears that it will be possible to parameterize and model the effects of joint geometry on erosion rate. This is a promising result because it can lead to eventual physical (e.g., flume) and numerical models of these processes, eventually increasing the predictive power of more comprehensive bedrock-channel-erosion models.

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