https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

Building a Bimodal Landscape with Varying Bed Thicknesses in Last Chance Canyon, New Mexico

Sam Anderson[1], Nicole Gasparini[1], Joel Johnson[2]

[1]Earth and Environmental Science, Tulane University, New Orleans, 70118, USA
[2]Jackson School of Geosciences, University of Texas at Austin, Austin, 78712, USA

Correspondence to: Sam Anderson (sanderson@tulane.edu)

Abstract. We explore how rock properties and channel morphology vary with rock type in Last Chance canyon, Guadalupe mountains, New Mexico, USA. The rocks here are composed of horizontally to near horizontally interbedded carbonate and sandstone. This study focuses on first and second order channel sections where the streams have a lower channel steepness index (ksn) upstream and transition to a higher ksn downstream. We hypothesize that differences in bed thickness and rock strength influence ksn values, both directly by influencing bulk bedrock strength but also indirectly through the production of coarse sediment. We collected discontinuity intensity data (the length of bedding planes and fractures per unit area), Schmidt hammer rebound measurements, and measured the largest boulder at every 40-foot elevation contour to test this hypothesis. Bedrock and boulder minerology was determined using a lab-based carbonate dissolution method. High resolution orthomosaics and DEMs were generated from drone photos. The orthomosaics were used to map channel sections with exposed bedrock. The high-resolution DEMs were used to measure channel slope and hillslope relief. We find that discontinuity intensity is negatively correlated with Schmidt hammer rebound values. Channel steepness is higher where reaches are primarily incising through more thickly bedded carbonate bedrock. Where there is more thinly bedded sandstone rock exposed, channel steepness tends to be lower. Furthermore, the effect that rock properties have on channel morphology is confounded by sediment input from hillslopes. Thickly bedded rock units on surrounding hillslopes contribute larger sized colluvial sediment to the channels, and these reaches have higher ksn. Larger and more competent carbonate sediment armors both the carbonate and the more erodible sandstone and dampens the negative effect sandstone bedrock has on channel steepness. We believe that in the relatively steep, high ksn downstream channel sections slope is primarily controlled by the coarse alluvial cover. We further posit that the upstream low ksn reaches have a baselevel that is essentially fixed by the steep downstream reaches, resulting in a stable configuration where channel slopes have adjusted to lithologic differences and/or sediment armor.

1 Introduction

There is little debate that rock properties impact bedrock river incision rates and channel morphology (Duvall et al., 2004; Johnson et al., 2009; Harel et al., 2016). For example, Wohl et al, (1994) found that knickpoints in the Nahal Paran River, Israel formed where relatively resistant chert layers were exposed. Flume experiments by Sklar and Dietrich, (2001) illustrated that, all else equal, bedrock incision rate scales with the inverse square of rock tensile strength. River channels may narrow in reaches with harder rocks (e.g., Bursztyn et al., 2015; Montgomery and Gran, 2001) and/or steepen (e.g., DiBiase et al, 2018;

Darling and Whipple, 2015). Bedrock properties can also have non-local impacts, further compounding the relationship between rock properties and channel morphology. Studies have found that the abundance and calibre of sediment delivered to a channel reach from upstream and/or surrounding hillslopes can steepen reaches beyond what might be predicted from channel bedrock properties alone (e.g., Johnson et al., 2009; Thaler and Covington, 2016; Chilton and Spotila, 2020; Lai et al., 2021). Theory suggests that in channels with the same incision rates (I) and climate, relatively less erodible rock will have a higher channel steepness index (ksn), or slope normalized by drainage area (Whipple and Tucker, 1999; Wobus et al., 2006). Put differently,

Eq. (1):

$$I = K_c K_r {k_{sn}}^n, \tag{1}$$

where Kc and Kr are the impacts of climate and bedrock properties on erodibility, respectively, and n is a positive constant. Channel steepness index can be calculated directly from a DEM, using widely available tools such as TopoToolBox (Schwanghart and Scherler, 2014). Bedrock that is more resistant to fluvial erosion has a lower erodibility. Setting aside challenges with estimating Kc, if there were measurable rock properties that were empirically related to Kr, we could estimate bedrock incision rates without geochemical techniques or long-term field campaigns.

However, our community has not yet reached an empirical definition of equation 1. One challenge is that we do not know if eq. 1 is universally valid. In landscapes with vertical variability in bedrock properties, numerical modelling suggests that there are cases in which this relationship is inverse; in other words, less erodible rocks have a lower channel steepness index than more erodible rocks (Perne et al, 2017). Even more fundamental is that there are many variables controlling rock erodibility. We have a simple tool, the Schmidt Hammer, to measure relative rock compressional strength in the field. Compressional strength scales directly with tensile strength (Murphy et al., 2016), which scales with incision rate (Sklar & Dietrich, 2001). Unfortunately, we do not have an empirical relationship to relate Schmidt Hammer measurements to Kr. There are also variables that must be measured across an area of a river reach. For example, fracture density impacts bedrock incision processes (e.g., Spotila et al., 2015; Dibiase et al., 2018), but we do not know if point measurements like those obtained from a Schmidt Hammer can fully quantify the impact of fracture density on erodibility. It is unlikely that a single measurement tool can parameterize every bedrock property that controls incision rates. Yet, an empirical equation for estimating Kr from field measurements and/or drone imagery and/or geologic maps would be extremely powerful for the tectonic geomorphology community.

In this study we measure bedrock and sediment properties in first order channels in the Guadalupe Mountains, New Mexico, USA. We use our measurements to inform the relationship between rock properties, erodibility, and channel morphology. Our field area has alternating layers of primarily sandstone and primarily carbonite rocks. We measure some variables directly in the field, such as Schmidt Hammer values of the bedrock and lengths of boulder axes. We also take advantage of imagery, to calculate fracture density, and rock samples collected in the field to find rock minerology. We cannot develop an empirical relationship for erodibility because we do not have incision rate measurements. However, we build a hypothesis for how the variability in rock properties has impacted the evolution of this landscape. Our interpretation of the landscape agrees in concept

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

with numerical findings that suggest that more erodible rocks stratigraphically underlain by less erodible rocks can create a scenario in which the upstream reaches of a channel have an effectively pinned baselevel even though the downstream reaches are relatively steeper (Forte et al., 2016). This leads to a bimodal landscape in morphology and erodibility: higher elevation topography has lower channel steepness, gentler hillslopes, and hypothesized higher erodibility; and lower elevation topography has relatively high channel steepness, steeper hillslopes, and hypothesized lower erodibility.

2 Field Area

This study focuses on channels with intermittent flow in Last Chance canyon (Figure 1). During Permian time, a shallow lagoon existed behind a reef complex to the south and deposited what would become interbedded carbonate and siliciclastic bedrock of Last Chance Canyon (Hill, 2000; Phelps et al., 2008; Kerans et al., 2017). The Guadalupe mountains were uplifted during basin and range extension beginning 27 million years ago, exposing the previously buried bedrock (Chapin and Cather, 1994; Ricketts et al., 2014, Hoffman, 2014; Decker et al., 2018).

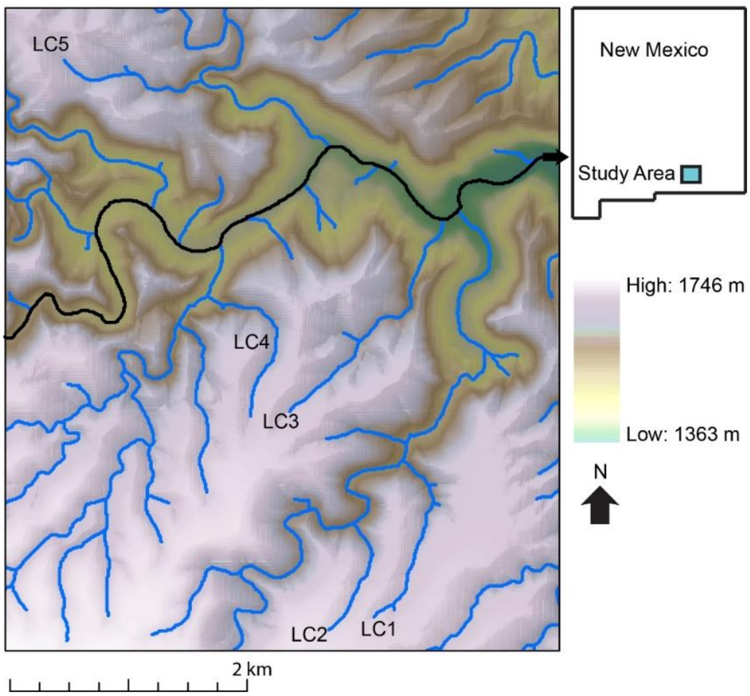
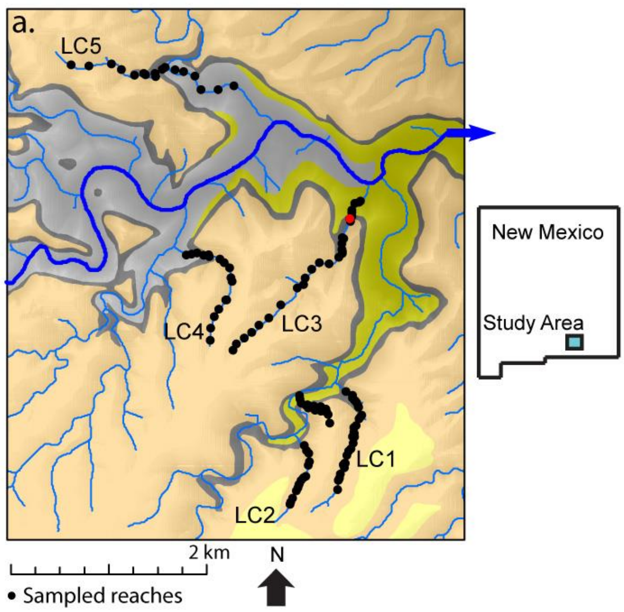


Figure 1: Topographic map with elevations superimposed on a hillshade of Last Chance canyon with ephemeral stream channels. Main stem of channel colored black with arrow indicating the direction of stream flow. The five channels we surveyed channels are labeled.

Because of its morphology and accessibility, we use data gathered within Last Chance Canyon to identify how different lithologies affect stream channel and landscape morphology. Last Chance Canyon has horizontally to near horizontally bedded

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

bedrock and is currently tectonically inactive (Hill, 1987; Hill, 2006). Higher order channels further downstream in Last Chance Canyon are shallow, inundated with coarse alluvium, and have no exposed bedrock. Last Chance canyon is made up of primarily carbonate and sandstone bedrock (Scholle et al., 1992; Hill, 2000; Phelps et al., 2008). This simple variation in lithology makes Last Chance canyon an ideal location to explore the effect of varying bedrock properties on stream channel morphology. Mapped descriptions of stratigraphic units in Last Chance canyon includes both sandstone and carbonate bedrock, with thicknesses on the order of centimetres to meters (figure 2). Properties relevant to geomorphic processes at the high-resolution spatial scale required by our investigation are not included in the rock unit descriptions from published maps (NPS, 2007).



b.

Approximate thickness (m)	Rock Unit	Description	Approximate Elevation (m)
	Queen Formation	Predominently sandstone with some dolomite near the base of the unit.	1700 up
150 m	Greyburg Formation	Mostly 2.5 to 15 cm thick sandstone bedswith few 2.5 cm to 3 m thick dolomite beds	1540 - 1560
30 m	Upper San Andres Formation	0.5 cm to 1 m thick dolomite beds with one to three sections of thinly bedded sandstone.	1440 - 1510
0 - 130 m	Lower San Andres Formation	0.3 to 1.5 m thick dolomite beds with some medium to very grained sandstone beds.	Varies
0 -150 m	Sandstone tongue of the Cherry Canyon Formation	Very fine grained, well sorted quartz sandstone with scattered, irregular chert nodules.	1400

Figure 2: a. Geologic map of Last Chance canyon with b. a description of mapped lithologies (King, 1948; Boyd, 1958; Hayes, 1964; USGS, 2017). Approximate elevation and thicknesses apply only to the section of Last Chance canyon displayed here. Dots indicate

locations we took measurements at (in five tributaries and one hillslope). The main stem of the channel is colored dark blue and the arrow indicates the direction of stream flow. The five channels we surveyed are labeled LC1 through LC5.The reach marked with a red circle is LC3.2, is shown in figure 3, and has a Lat/Long of 32.252513, -104.701289.

3 Methods

3.1 DEM Analysis

We used a 10 m digital elevation model (DEM) of Last Chance canyon to determine channels of interest to survey and to ascertain the location and elevation of where a channel transitions from steep to shallow channel sections (USGS, 2019). We used TopoToolBox to generate longitudinal stream profiles, ksn maps, and χ (chi) plots of all surveyed channels (Schwanghart and Scherler, 2014). The channel steepness index, or ksn, is a measure of channel gradient normalized for drainage area and allows for the comparison of slope along a single channel or among multiple channels to isolate erosional and/or bedrock erodibility patterns (Kirby & Whipple, 2012). χ, like ksn, is a way of identifying changes in channel slope along a single channel or in multiple channels with varying drainage areas. Because channels can adjust to more resistant lithologic units by steepening across them (Duval et al., 2004; Jansen et al., 2010), we used χ plots and ksn maps to detect changes in slope that could be due to differences in bedrock erodibility and/or sediment size and cover.

We also used a DEM to measure channel slope and hillslope relief. Elevations were measured 75 m upstream and 75 m downstream each reach, the downstream elevation was then subtracted from the upstream elevation and the value was divided by the length, 150 m, to determine slope. Relief was measured in ArcGIS using a circular 500 m window around each reach. 500 m was chosen as the relief window because it has been shown to characterize hillslope relief (Dibiase et al., 2010).

3.2 Field Survey

In March and May of 2018, and in February of 2021, we surveyed five channels which we had preselected based on DEM analysis, mapped geology, and accessibility. Our investigation started in lower order channels at elevations above 1400 m in channels LC3, LC4, and LC5 and in elevations above 1500 in channels LC1 and LC2 (figure 1). We studied reaches of varying length in the five different channels. At every ~40 ft contour interval, used for convenience and to ensure unbiased sampling, we surveyed channel reaches for bedrock properties when exposed, measured the largest boulder in the reach, and took rock samples from each to confirm minerology.

3.3 Rock Properties

We used a Schmidt hammer to take a minimum of 30 rebound values in each reach we surveyed that had exposed bedrock (Niedzielski et al., 2009). We discarded Schmidt hammer values which were less than 10, which is the minimum value the device can read, as they represent multiple values and make statistical analysis of the data difficult (Duval et al., 2004). Schmidt hammer values were recorded at roughly evenly spaced intervals up the thalweg of each channel regardless of weathering or presence of fractures. All Schmidt hammer values were taken perpendicular to the bedrock surface. Schmidt hammer values

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

are affected by proximal discontinuities. Because we sampled at evenly spaced intervals in the exposed bedrock and did not avoid discontinuities, our Schmidt hammer values reflect a combination/distribution of local rock elastic properties modulated by discontinuities (Katz et al., 2000).

We used a GoPro5 attached to the end of a selfie stick to take wide-angle HD videos of the bottom of 18 different reaches of varying size. We used Agisoft Photoscan to generate high resolution orthomosaics of each reach using the GoPro videos and then manually traced all discontinuities with Adobe Illustrator (figure 3). We placed a rock hammer of known length on the bedrock surface when taking video to scale each orthomosaic to the correct length. All discontinuities by which bedrock could be plucked from the thalweg were traced, including bedding planes and fractures created by weathering (Spotila, 2015). We then used Fraqpac, a Matlab software suite, to determine the average discontinuity intensity, which is the average length of fractures and bedding planes, per square meter, of each reach (Healy, 2017).

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

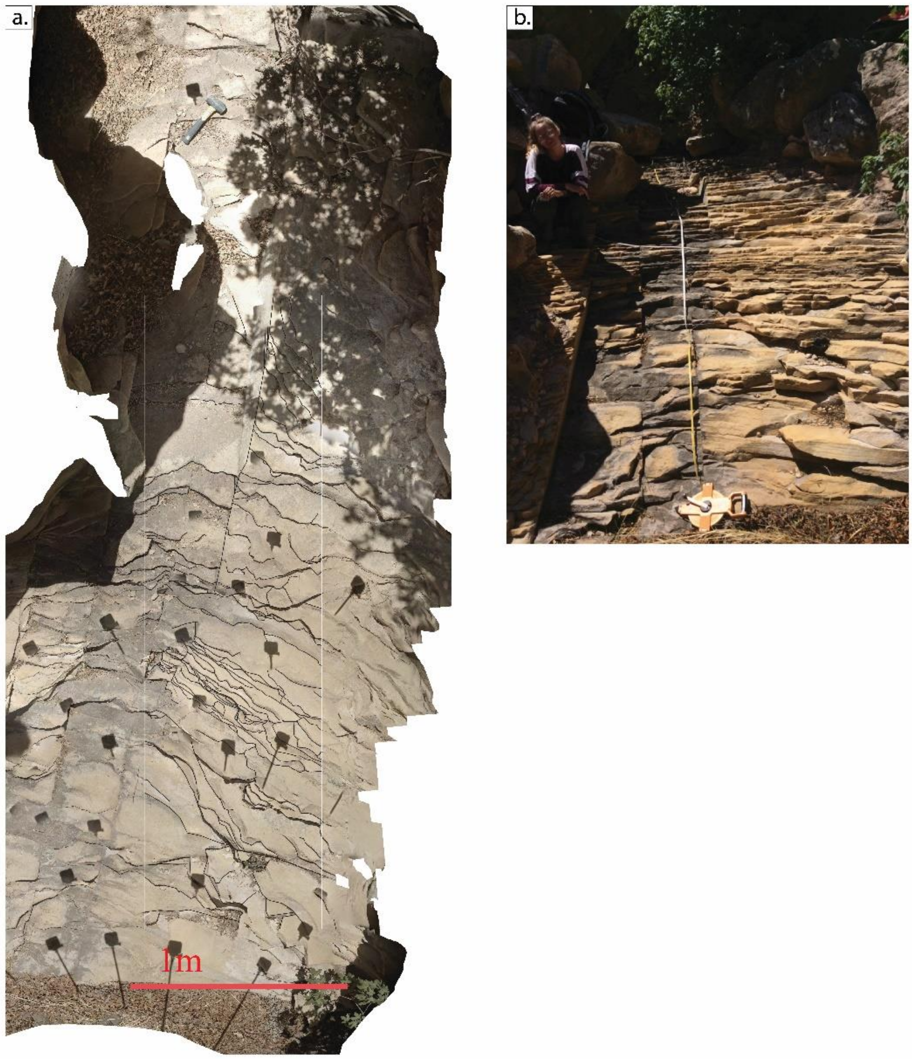


Figure 3: a) An orthomosaic and b) photo of sandstone reach, LC3.2, with a discontinuity intensity of 13.03 1/m in the steep channel section with traced discontinuities. The shadows in the orthomosaic are from the GoPro and selfie stick used to film the reach. Lat, Long: 32.252513, -104.701289

We used a drone, DJI Mavic 2 pro, to take photos of the five surveyed channels from elevations of approximately 20 meters above the five stream channels, and 120 meters above adjacent hillslopes for three of the five channels. We used Agisoft photoscan to generate high resolution DEMs (0.027 to 0.28 m posting) and orthomosaics of the five channels and three adjacent hillslopes. We used the DEMs to take relief and slope measurements, and the orthomosaic to quantify relative proportion of where stream channel beds were exposed bedrock or covered with sediment.

3.4 Lithology

At each 40 ft elevation contour interval we took rock samples from bedrock, when exposed, and from the largest boulder in the stream channel to ensure correct categorization of lithology. The minerology of each rock sample was assumed to be representative of the minerology of the reach or boulder it was taken from. Our efforts to determine end-member lithological classifications in the field were complicated because individual samples often contained carbonate, calcite, and quartz. To find a quantifiable ratio of the amount of carbonate in each sample, we ground each rock sample up using a jaw crusher and disk mill. The ground up sample was rinsed in water a minimum of five times, dried in an oven over night, and then weighed the following morning. We then dissolved the carbonate minerals by soaking each sample in Nitric acid for at least 24 hours. The sample was again rinsed in water a minimum of five times and dried overnight. We then reweighed each sample to determine the ratio amount of carbonate minerals which had dissolved. Samples were classified as carbonate if they were more than 50% carbonate minerals, and sandstone rock if they were less than 60% quartz (Bell, 2005). Samples which ranged from 50 – 59% of either quartz or carbonate minerals were eliminated from analysis. To ensure the validity of this methodology, we replicated this processes on six of the samples and used a microscope to check that all carbonate minerals dissolved. For one of the samples, we replicated this process five times. All replicate measurements demonstrated similar results (standard deviation of 0.62%, and variance of 0.39%), giving credence to our methodology.

4 Results

4.1 Last Chance Canyon Morphology

Last Chance canyon tributaries have upstream sections with relatively shallow channels and lower gradient hillslopes, and a knickzone downstream which has steep channels and hillslopes (figure 4). Based on χ plots (figure 4c and d) and field observations, we find that the stream channels transition from steep to shallow at approximately 1640 m for channels 1 and 2 and at approximately 1550 m for channels 3, 4 and 5. The transition from steep to shallow is more subtle in channels 1 and 2. A t test verifies a bimodal distribution of hillslopes, where slope gradients above 1550 m (channels 3, 4, 5) and from above 1640 m (channels 1, 2) are different from hillslopes from 1400 to 1550 m.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

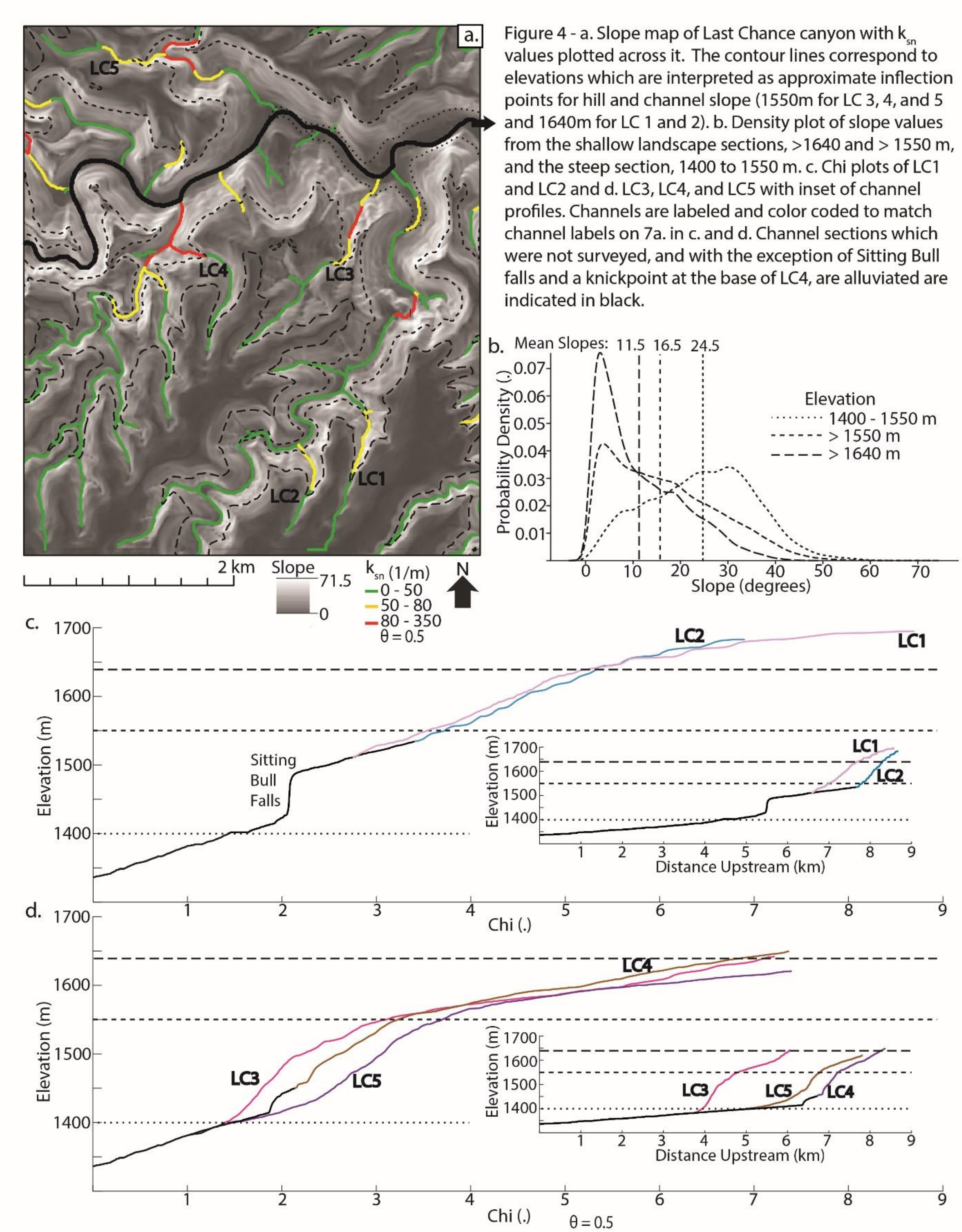


Figure 4 - a. Slope map of Last Chance canyon with k_{sn} values plotted across it. The contour lines correspond to elevations which are interpreted as approximate inflection points for hill and channel slope (1550m for LC 3, 4, and 5 and 1640m for LC 1 and 2). b. Density plot of slope values from the shallow landscape sections, >1640 and > 1550 m, and the steep section, 1400 to 1550 m. c. Chi plots of LC1 and LC2 and d. LC3, LC4, and LC5 with inset of channel profiles. Channels are labeled and color coded to match channel labels on 7a. in c. and d. Channel sections which were not surveyed, and with the exception of Sitting Bull falls and a knickpoint at the base of LC4, are alluviated are indicated in black.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

4.2 Bedrock Properties from Last Chance Canyon

In Last Chance canyon, discontinuity intensity and Schmidt Hammer values change with slope in the more thinly bedded sandstone rock, but not in carbonate rock (figure 5). Bedding planes are zones of weakness by which bedrock can be plucked, and both bedding planes and fractures were treated as discontinuities (Spotila, 2015). Because the units are horizontally to near horizontally bedded, thinly bedded sandstone rock with higher slopes have more exposed bedding planes. They also have lower Schmidt hammer values (Figure 5a). However, discontinuity intensity and rebound values are invariant with slope in the thickly bedded carbonate rock.

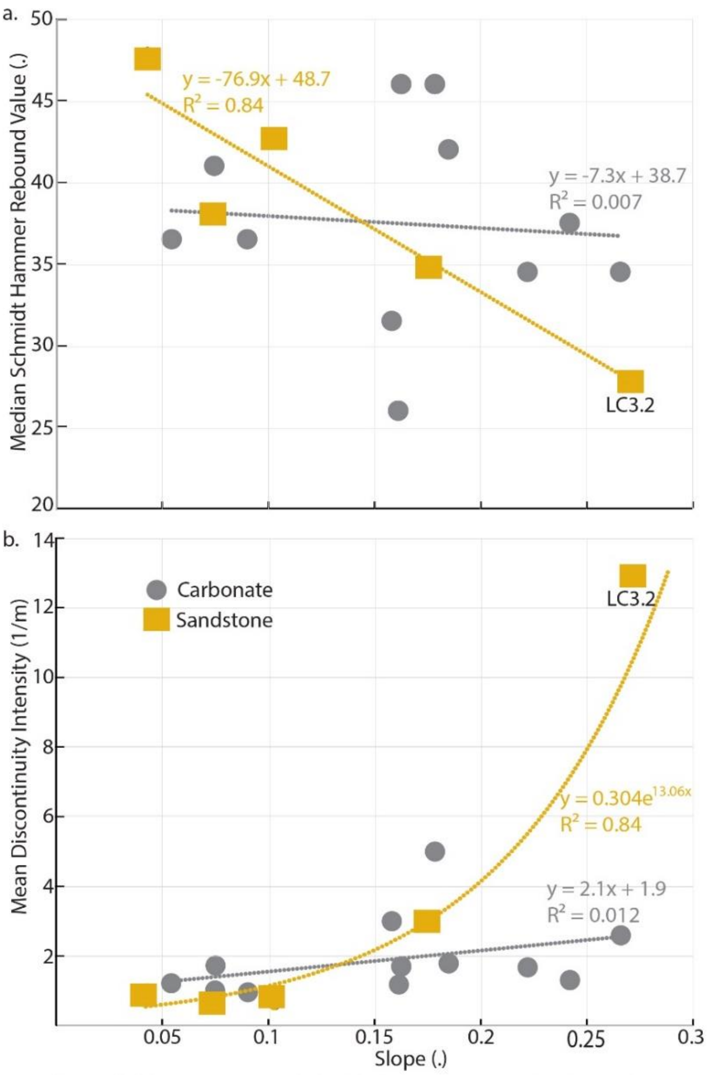


Figure 5: Slope vs. a. mean Schmidt Hammer rebound value and b. mean discontinuity intensity for 5 sandstone and 11 carbonate reaches. We calculated slope over a distance of 150 m downstream and 150 m upstream of each reach. LC3.2, which was highlighted in figure 2 and shown in figure 3, is labeled.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

The average discontinuity intensity and Schmidt Hammer value from the thinly bedded sandstone in the steep channel section, where more bedding planes are exposed, is 7.98 m-1 (n = 2 reaches, standard deviation σ = 5.04) and 31.6 (n = 61, σ = 9.5) respectively. The average discontinuity intensity of the more thickly bedded carbonate in the steep channel section is 2.34 m-1 (n = 6, σ = 0.56), and they have an average Schmidt Hammer value of 36.1 (n = 240, σ = 10.8). Within the upstream channel sections, the reaches have a shallower slope with fewer exposed bedding planes per channel distance. In the shallower sandstone reaches, measured discontinuity intensity is smaller, 0.77 m-1 (n = 3, σ = 0.16), but average Schmidt Hammer values are larger, 41.7 (n = 88, σ = 9.1), in comparison with the sandstone in the steeper section. Carbonate reaches in the shallow channel sections have a slightly higher discontinuity intensity of 1.51 m-1 (n = 6, σ = 0.32) and average Schmidt Hammer value of 37.1 (n = 90, σ = 9.3) in comparison with the shallow sandstone reaches.

We calculated four separate t-tests for on Schmidt hammer values from the different lithologies and channel sections in Last Chance Canyon. We compared Schmidt hammer values between carbonate and sandstone reaches in the shallow and steep parts of the channel and found them both to be of different populations. Schmidt hammer values for sandstone reaches in the steep section were statistically different from sandstone rock in the shallow section. Schmidt hammer values for carbonate reaches in steep and shallow sections were of the same statistical population. This the only test of the four in which the null hypothesis was accepted and further demonstrates the lack of strong correlation between channel slope and rock strength in carbonate reaches.

4.3 Boulder Data

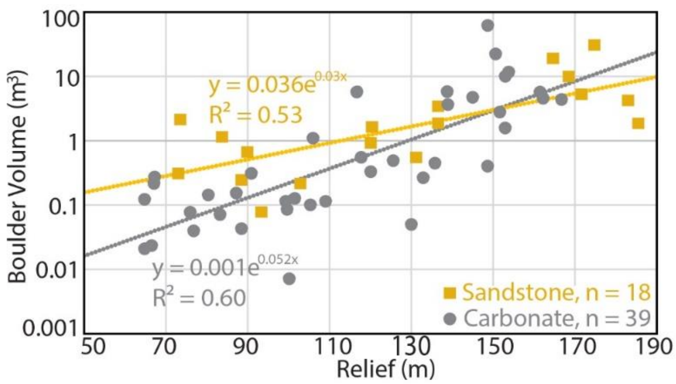


Figure 6: Relief (calculated using a 500 m window) vs. Boulder volume, calculated by multiplying the a, b, and c axis, for all boulders we measured in the field.

As relief increases the volume of the largest and most geomorphically relevant carbonate boulders increases exponentially (figure 6). Relief, calculated using a 500 m window around the reach, was used to show the influence the hillslopes have in contributing alluvial armor (DiBiase et al., 2010). Lower relief corresponds to the shallower upstream reaches, and the data show that boulders are smaller there. In the shallow upstream channel section, there is more exposed bedrock than in stream channels in the steep channel section and sediment found in the shallow reaches is generally smaller. In the steep channel

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

section, the stream channels are inundated with large sediment. The volume of sandstone boulders also increases, but less dramatically than the carbonate boulders. Of the boulders we measured, 70% of the boulders in the steep section and 64% of the boulders in the shallow channel section are carbonate.

As hillslope relief increases the length of all a, b, and c axes in carbonate boulders increases with similar slopes and with relatively high r squared values (figure 7). Conversely, in sandstone boulders, the c axis correlates best with hillslope relief (R2 = 0.54, m = 1.1). the length of the b axis demonstrates a slightly weaker relationship with relief (R2 = 0.46, m = 1.8) than the c axis. The length of the a axis (R2 = 0.11, m = 0.97) correlates poorly with relief. We choose to fit an exponential trendline to the carbonate because it was a better fit. We fit a linear trendline to the sandstone because there was minimal difference between the R2 values for exponential and linear fits for the a and b axis. An exponential fit had a slightly lower R2 value for the c axis of the sandstone boulders. Carbonate boulders were slightly more equidimensional than sandstone boulders; they had an average shape factor (dmin/dmax) of 0.36 (n = 39, σ = 0.17) while the more elongate sandstone boulders were 0.29 on average (n = 19, σ = 0.18).

5 Discussion

Bedrock properties vary between lithologies and etch their signal on landscape morphology (Jansen et al., 2010; Scharf et al., 2013; Bursztyn et al., 2015; Forte et al., 2016; Yanites et al., 2017). In Last Chance canyon, differences in rock properties correlate with changes in channel slope and hillslope relief. Here, we introduce five key interpretations from our study. (1) Discontinuity intensity affects rock strength, and channel steepness is higher where reaches are primarily within thickly bedded carbonate bedrock. (2) Where more thinly bedded sandstone rock is exposed, channel steepness tends to be lower. (3) Furthermore, the effect of exposed bedrock on landscape morphology is confounded by interplay with sediment input from hillslopes (Duval et al., 2004; Johnson et al., 2009; Finnegan et al., 2017, Keen-Zebert et al., 2017). Thickly bedded and steeper rock units on surrounding hillslopes contribute larger sized colluvial sediment to the channels, leading to steeper channel slopes (Thaler and Covington, 2016). (4) Larger and more competent carbonate sediment armors both the carbonate rock and the more thinly bedded sandstone and dampens the negative effect sandstone bedrock has on channel steepness. (5) We further hypothesize that the landscape has adjusted to a relatively stable configuration where the shallow channel section at the top of the range cuts through weaker rock and has a base level that is pinned by both the more thickly bedded rock and larger alluvium in the steep downstream section.

A combination of local slope and bedding plane amount and spacing controls discontinuity intensity at the reach scale in sandstone bedrock, but not in carbonate bedrock (figure 5). Steeper reaches cut across more horizontal bedding planes over a shorter distance than shallower reaches. Thus, slope affects discontinuity intensity and rock strength differently in units with less bedding planes than in more thinly bedded bedrock units. We find that thinly bedded sandstone bedrock is anisotropic, where they are weaker at higher slopes and become less weak as slopes become more parallel to bedding plane orientation (Weissel and Seidl, 1997). The lower slopes in sandstones develop because bulk rock properties are weaker (Bursztyn et al., 2015), but when sandstone bedrock is eroded down to slopes that are sub-parallel to bedding, then their rock strength effectively increases. The lack of exposed sandstone rock at higher slopes is illustrated by the single data point (LC3.2) in figure 5. We posit that this one data point is an outlier, because sandstone bedrock has a higher discontinuity intensity at steeper slopes, and generally is unable to sustain steep slopes in Last Chance canyon. At low slopes sandstone is more stable, as evidenced by their lower discontinuity intensities and higher Schmidt hammer values (figure 5). Because carbonate bedrock is more thickly bedded, its discontinuity intensity is more independent of reach scale slope than in sandstone bedrock, where discontinuity intensity is very dependent on slope. Carbonate bedrock strength is not anisotropic in the same way sandstone bedrock is.

The landscape seemingly reflects the tendency of sandstone rock to erode to low slopes: In the shallow upstream channel section, there are larger amounts of the less thickly bedded siliciclastic units exposed, while the steep channel section is mostly made up of thickly bedded carbonate rock or is inundated with sediment. Sandstone reaches with higher slopes have lower Schmidt hammer rebound values, because more bedding planes are exposed. Schmidt hammer values are similar between carbonate reaches in the steep and shallow channel section: Our statistical analysis of Schmidt hammer values from carbonate bedrock in the shallow upstream and steep downstream channel sections confirmed that they are of the same population. Because the thickly bedded carbonate rock units have low discontinuity intensities regardless of slope, carbonate bedrock in the shallower upstream and steeper downstream sections of Last Chance canyon have similar Schmidt hammer values, suggesting that rock strength is independent of slope in carbonate bedrock.

The more thickly bedded and higher relief hillslopes contribute larger-sized and more geomorphically relevant boulders from the hillslopes to the channel (Neely et al., 2020) (figure 6). Because siliciclastic bedrock tends to be more riddled with discontinuities in the steep channel sections, we expect local shallowing. However, there are no shallow sandstone reaches in the steep section. Hillslope derived sediment from the thicker bedrock armors the less thickly bedded units, dampening the effect an increase in discontinuity intensity has on local shallowing (Thaler and Covington, 2016; Chilton and Spotila, 2020). Within these channel sections which are inundated with sediment, we interpret that channel steepness tends to be independent of bedrock properties and instead depends on the amount, size, and competency of the sediment armor. Because sandstone bedrock tends to be armored by large sediment in the steep channel section there is less potential for erosion in these more thinly bedded units (DiBiase et al., 2018).

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

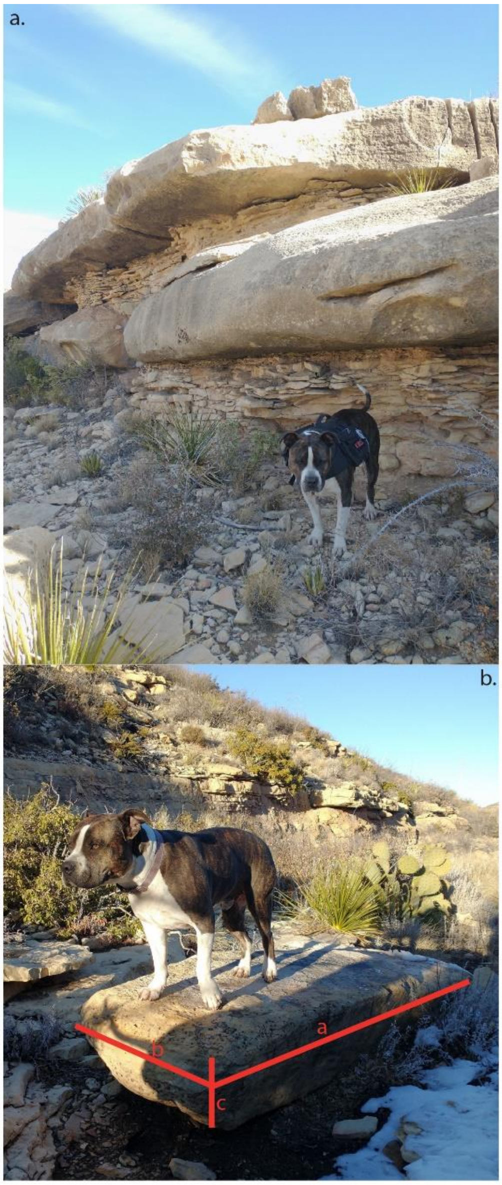


Figure 7: Relief (calculated using a 500 m window) vs. Boulder volume, calculated by multiplying the a, b, and c axis, for all boulders we measured in the field.

Bed thickness distributions affect the shape of the large sediment measured in the channels (figure 7). Bedrock fracture patterns control the initial size of sediment supplied by hillslopes (Verdian et al., 2020). Here, in Last Chance canyon, the maximum length of one axis of a boulder entering a channel from proximal hillslopes is controlled by the distance between bedding planes. In carbonate bedrock the distance between bedding planes tends to be longer than in sandstone bedrock. Where hillslope relief increases, bedrock units are thicker, and the length of the a, b, and c axes increases for the carbonate boulders (figure 8). In sandstone boulders, the c axis correlates with hillslope relief, the b axis length also correlates with relief, but to a lesser extent, and the a axis length does not demonstrate any relationship with relief. Because sandstone bedrock is more thinly bedded, the c axis will tend to reflect the distance between bedding planes from the source rock. The higher average shape factor, 0.36, of the more equidimensional shaped carbonate boulders relative to the more rectangular dimensional sandstone boulders (average shape factor, 0.29), although subtle, further speaks to the effect that the distance between bedding planes affects sediment shape. Because a sediment grain tends to break across its shortest axis, the more elongate sandstone boulders are generally less competent than carbonate boulders. Also, this could be why there were less sandstone than carbonate boulders. Of the 58 boulders we measured, 70% in the steep channel section and 64% in the shallow were carbonate. Because carbonate bedrock is thickly bedded, boulders sourced from this bedrock tend to be larger and because they are more equidimensional, they likely stay larger for longer than sandstone boulders.

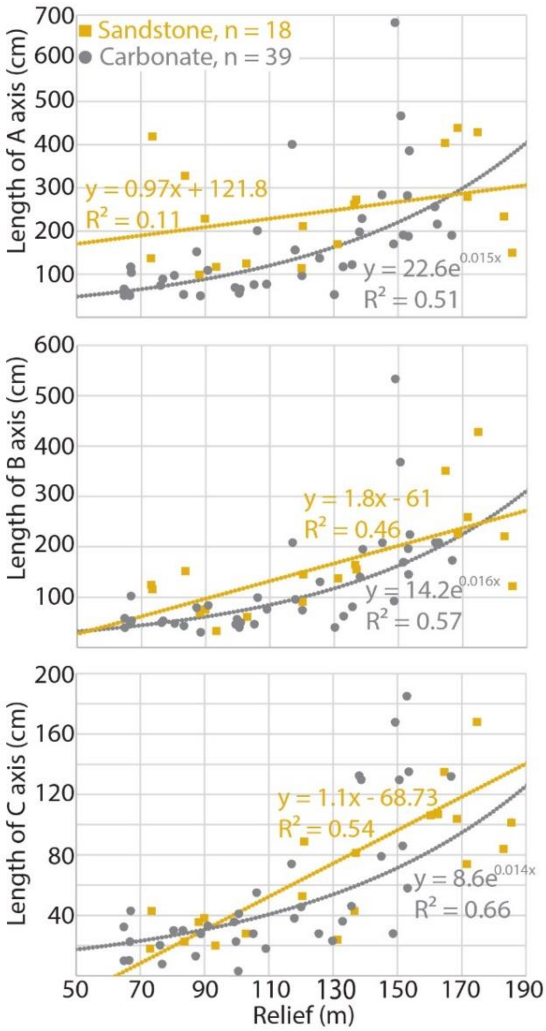


Figure 8: Relief (calculated using a 500 m window) vs. Boulder volume, calculated by multiplying the a, b, and c axis, for all boulders we measured in the field.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

The shallow channel section at the top of the range has a base level that is set by the steep, and boulder laden, channel section downstream. χ plots for channels LC 3, 4, and 5, demonstrate two well defined channel sections, where in the higher elevation, lower relief, and lower slope section above 1550 m there is more exposed bedrock, more exposed sandstone, less alluvium, and smaller boulders armoring the channel (figure 9). Conversely, LC 1 and 2 lack the conspicuous transition from downstream steep section to upstream shallow section, which is apparent in the other three channels. We hypothesize the less notable change in upstream steepness in LC 1 and 2 is due to the armoring of sandstone rock units and relative abundance of alluvium above 1550 m in elevation. Lithology measurements from proximal hillslopes in LC 1 and 2 indicate that just above elevation 1550 m there are sandstone units in the channel as in LC 3, 4, and 5 but they are buried by alluvium. By comparing LC 1 and 2 with 3, 4, and 5 we see how the signal from changes in rock properties is dampened by alluvium.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

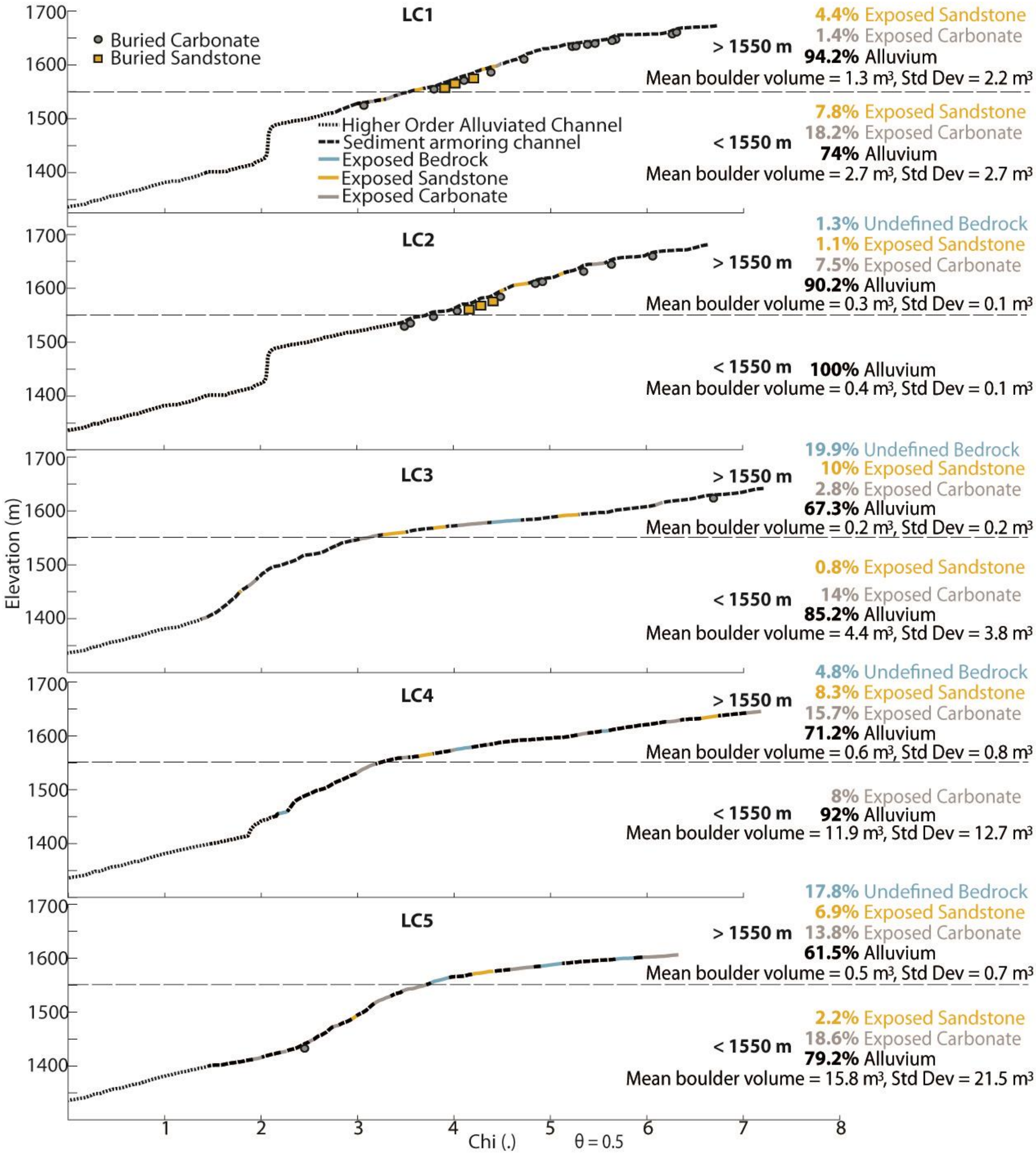


Figure 9: Chi plots of LC1 - LC5 with exposed bedrock or sediment armored sections mapped. Where known, rock type is shown. To the left of each channel, relevant statistics for each channel are displayed from 1400 - 1550m and above 1550 m. Average boulder volumes, which we measured in the field, above and below 1550 m elevation are shown along with corresponding standard deviations.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

We hypothesize that erosion in the steep reaches of our study channels is inhibited due to an abundance of thick and resistant bedrock and large immobile boulders in the steep channel section. This may seem counterintuitive, because the downstream portions of our study channels are both steeper and have higher steepness indices than the upstream channel lengths (figure 4) and high steepness indices are thought to correlate with high erosion rates and/or less erodible rocks (Hilley and Arrowsmith, 2008). Although we do not have measurements of erosion rate in Last Chance canyon, we make the link between channel steepness and erodibility by assuming all channel reaches have a similar, low, erosion rate. In other parts of the Guadalupe Mountains, west of Last Chance canyon, erosion rates do not depend on rock type, nor on slope (Tranel, 2020). We suggest that low erodibility controls channel steepness in our study channels, and not high erosion rates. Regardless of what triggered these channels to steepen or how these reaches steepened over time, given the current conditions, channel erosion is likely similar in the steep and shallow landscape sections.

In contrast, the upstream, predominantly sandstone, channel sections also likely have minimal erosion, but for different reasons. These channel reaches have lower slope and lower channel steepness indices (figure 4). Our observations of rock properties and alluvial cover suggest that these upstream reaches are likely more erodible, leading to lower channel steepness. Despite the lower rock strength, erosion rates may be extremely low in the upstream channel sections, because their baselevel is pinned by the steep, slowly eroding downstream reaches. Such a configuration of weak, more erodible rocks that have low erosion rates because of downstream, less erodible, and stable reaches has been illustrated numerically (Forte et al., 2016; Perne et al., 2017). Although we do not have erosion rate measurements in our study area, numerical model predictions suggest that our hypotheses are plausible. We think that any erosion in the steep portions of the channels is likely adjusted to similar erosion rates in the upstream more erodible portions of the channels, leading to a relatively stable geometry. In this way, the bimodal topography in Last Chance canyon has evolved to reflect the rock properties of the two dominant lithologies.

6 Conclusions

We present several observations about the effect of rock properties on bedrock channel steepness in Last Chance canyon. We suggest that discontinuity intensity influences channel geometries. Streams steepen across sedimentary units with thicker beds and lower discontinuity intensities. Conversely, channel steepness is lower in channel reaches incised into thinly bedded sandstone units with higher discontinuity intensity.

The extent of sediment cover and the size of boulders in the channel also impacts channel morphology. More thickly bedded carbonate bedrock on the hillslopes contributes larger sized, and more geomorphically relevant, alluvium to the channel. This coarse carbonate sediment armors both the more and less thickly bedded bedrock and smooths channel slope across reaches with different lithologies and discontinuity intensities. In Last Chance canyon, channel sections that contain larger carbonate alluvium are generally steeper even if the channel bed is siliciclastic with high discontinuity intensity.

Finally, we hypothesize that the upstream, low channel steepness reaches draining to downstream reaches with relatively higher channel steepness, create a relatively stable morphology. The more erodible shallow channel reaches at the top of the Last

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

Chance canyon have a base level that is pinned by the steep, and less erodible, channel downstream. Any erosion or lowering of the steep channels will likely result in rapid lowering and smoothing of the upstream, less resistant reaches, maintaining a similar channel profile through time.

References

Bell, F. G. (2005). ENGINEERING GEOLOGY| Problematic Rocks.

Bursztyn, N., Pederson, J. L., Tressler, C., Mackley, R. D., & Mitchell, K. J. (2015). Rock strength along a fluvial transect of the Colorado Plateau – quantifying a fundamental control on geomorphology. Earth and Planetary Science Letters, 429, 90–100. doi:10.1016/j.epsl.2015.07.042

Chapin, C. E., Cather, S. M., & Keller, G. R. (1994). Tectonic setting of the axial basins of the northern and central Rio Grande rift. Special Papers-Geological Society of America, 5–5.

Chilton, K. D., & Spotila, J. A. (2020). Preservation of Valley and Ridge topography via delivery of resistant, ridge-sourced boulders to hillslopes and channels, Southern Appalachian Mountains, U.S.A. Geomorphology, 365, 107263. doi:10.1016/j.geomorph.2020.107263

Darling, A., & Whipple, K. (08 2015). Geomorphic constraints on the age of the western Grand Canyon. Geosphere, 11(4), 958–976. doi:10.1130/GES01131.1

Decker, D. D., Polyak, V. J., Asmerom, Y., & Lachniet, M. S. (2018). U--Pb dating of cave spar: a new shallow crust landscape evolution tool. Tectonics, 37(1), 208–223.

DiBiase, R. A., Rossi, M. W., & Neely, A. B. (2018). Fracture density and grain size controls on the relief structure of bedrock landscapes. Geology, 46(5), 399–402. doi:10.1130/G40006.1

DiBiase, R. A., Whipple, K. X., Heimsath, A. M., & Ouimet, W. B. (2010). Landscape form and millennial erosion rates in the San Gabriel Mountains, CA. Earth and Planetary Science Letters, 289(1), 134–144. doi:10.1016/j.epsl.2009.10.03

Duvall, A., Kirby, E., & Burbank, D. (2004). Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California. Journal of Geophysical Research: Earth Surface, 109(F3). doi:10.1029/2003JF000086

Forte, A. M., Yanites, B. J., & Whipple, K. X. (2016). Complexities of landscape evolution during incision through layered stratigraphy with contrasts in rock strength. Earth Surface Processes and Landforms, 41(12), 1736–1757. doi:10.1002/esp.3947

Finnegan, N. J., Klier, R. A., Johnstone, S., Pfeiffer, A. M., & Johnson, K. (2017). Field evidence for the control of grain size and sediment supply on steady-state bedrock river channel slopes in a tectonically active setting. Earth Surface Processes and Landforms, 42(14), 2338–2349.

Harel, M.-A., Mudd, S. M., & Attal, M. (2016). Global analysis of the stream power law parameters based on worldwide 10Be denudation rates. Geomorphology, 268, 184–196. doi:10.1016/j.geomorph.2016.05.035

Healy, D., Rizzo, R. E., Cornwell, D. G., Farrell, N. J. C., Watkins, H., Timms, N. E., … Smith, M. (2017). FracPaQ: A MATLABTM toolbox for the quantification of fracture patterns. Journal of Structural Geology, 95, 1–16.

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

Hill, C. A. (1987). Geology of Carlsbad cavern and other caves in the Guadalupe Mountains, New Mexico and Texas. Bull. 117, New Mexico Bureau of Mines and Minerals Resources.

Hill, C. A., & Others. (2000). Overview of the geologic history of cave development in the Guadalupe Mountains, New Mexico. Journal of Cave and Karst Studies, 62(2), 60–71.

Hill, C. A. (2006). Geology of the Guadalupe Mountains: An overview of recent ideas. Caves and karst of southeastern New Mexico: Guidebook, 57th Field Conference, New Mexico Geological Society, Guidebook, 57th Field Conference, 145–150.

Hilley, G. E., & Arrowsmith, J. R. (2008). Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California. Geology, 36(5), 367–370.

Hoffman, L. L. (2014). Spatial variability of erosion patterns along the eastern margin of the Rio Grande Rift. Illinois State University.

Jansen, J. D., Codilean, A. T., Bishop, P., & Hoey, T. B. (2010). Scale dependence of lithological control on topography: Bedrock channel geometry and catchment morphometry in western Scotland. The Journal of geology, 118(3), 223–246.

Johnson, J. P. L., Whipple, K. X., Sklar, L. S., & Hanks, T. C. (2009). Transport slopes, sediment cover, and bedrock channel incision in the Henry Mountains, Utah. Journal of Geophysical Research: Earth Surface, 114(F2). doi:10.1029/2007JF000862

Katz, O., Reches, Z., & Roegiers, J.-C. (2000). Evaluation of mechanical rock properties using a Schmidt Hammer. International Journal of rock mechanics and mining sciences, 37(4), 723–728.

Keen-Zebert, A., Hudson, M. R., Shepherd, S. L., & Thaler, E. A. (2017). The effect of lithology on valley width, terrace distribution, and bedload provenance in a tectonically stable catchment with flat-lying stratigraphy. Earth Surface Processes and Landforms, 42(10), 1573–1587.

Kerans, C., Zahm, C., Garcia-Fresca, B., & Harris, P. M. (2017). Guadalupe Mountains, West Texas and New Mexico: Key excursions. AAPG Bulletin, 101(4), 465–474.

Kirby, E., & Whipple, K. X. (2012). Expression of active tectonics in erosional landscapes. Journal of structural geology, 44, 54–75.

Konare, A., Zakey, A. S., Solmon, F., Giorgi, F., Rauscher, S., Ibrah, S., & Bi, X. (2008). A regional climate modeling study of the effect of desert dust on the West African monsoon. Journal of Geophysical Research: Atmospheres, 113(D12).

Lai, L. S.-H., Roering, J. J., Finnegan, N. J., Dorsey, R. J., & Yen, J.-Y. (2021). Coarse sediment supply sets the slope of bedrock channels in rapidly uplifting terrain: Field and topographic evidence from eastern Taiwan. Earth Surface Processes and Landforms, 46(13), 2671–2689. doi:10.1002/esp.5200

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

Murphy, B., Johnson, J., Gasparini, N., & Sklar, L. (04 2016). Chemical weathering as a mechanism for the climatic control of bedrock river incision. Nature, 532, 223–227. doi:10.1038/nature17449

National Park Service Resources Inventory Program Lakewood Colorado, (2007). Digital geologic map of Guadalupe Mountains National Park and vicinity, Texas (NPS, GRD, GRE, GUMO).

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

Niedzielski, T., Migoń, P., & Placek, A. (2009). A minimum sample size required from Schmidt hammer measurements. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 34(13), 1713–1725.

Perne, M., Covington, M. D., Thaler, E. A., & Myre, J. M. (2017). Steady state, erosional continuity, and the topography of landscapes developed in layered rocks. Earth Surface Dynamics, 5(1), 85–100. doi:10.5194/esurf-5-85-2017

Phelps, R. M., Kerans, C., Scott, S. Z., Janson, X., & Bellian, J. A. (2008). Three-dimensional modelling and sequence stratigraphy of a carbonate ramp-to-shelf transition, Permian Upper San Andres Formation. Sedimentology, 55(6), 1777–1813.

Ricketts, J. W., Karlstrom, K. E., Priewisch, A., Crossey, L. J., Polyak, V. J., & Asmerom, Y. (2014). Quaternary extension in the Rio Grande rift at elevated strain rates recorded in travertine deposits, central New Mexico. Lithosphere, 6(1), 3–16.

Scharf, T. E., Codilean, A. T., De Wit, M., Jansen, J. D., & Kubik, P. W. (2013). Strong rocks sustain ancient postorogenic topography in southern Africa. Geology, 41(3), 331–334.

Scholle, P. A., Ulmer, D. S., & Melim, L. A. (1992). Late-stage calcites in the Permian Capitan Formation and its equivalents, Delaware Basin margin, west Texas and New Mexico: evidence for replacement of precursor evaporites. Sedimentology, 39(2), 207–234.

Schwanghart, W., & Scherler, D. (2014). Short Communication: TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences. Earth Surface Dynamics, 2(1), 1–7. doi:10.5194/esurf-2-1-2014

Sklar, L. S., & Dietrich, W. E. (12 2001). Sediment and rock strength controls on river incision into bedrock. Geology, 29(12), 1087–1090. doi:10.1130/0091-7613(2001)029<1087:SARSCO>2.0.CO;2

Spotila, J. A., Moskey, K. A., & Prince, P. S. (2015). Geologic controls on bedrock channel width in large, slowly-eroding catchments: Case study of the New River in eastern North America. Geomorphology, 230, 51–63. doi:10.1016/j.geomorph.2014.11.004

Thaler, E. A., & Covington, M. D. (2016). The influence of sandstone caprock material on bedrock channel steepness within a tectonically passive setting: Buffalo National River Basin, Arkansas, USA. Journal of Geophysical Research: Earth Surface, 121(9), 1635–1650. doi:10.1002/2015JF003771

Tranel, L. M., & Happel, A. A. (2020). Evaluating escarpment evolution and bedrock erosion rates in the western Guadalupe Mountains, West Texas and New Mexico. Geomorphology, 368, 107335.

US Geologic Survey, 2017, 1/3rd arc-second digital elevation models (DEMs). USGS National Map 3DEP downloadable data collection.

Verdian, J. P., Sklar, L. S., Riebe, C. S., & Moore, J. R. (2021). Sediment size on talus slopes correlates with fracture spacing on bedrock cliffs: implications for predicting initial sediment size distributions on hillslopes. Earth Surface Dynamics, 9(4), 1073–1090.

Whipple, K. X., & Tucker, G. E. (1999). Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research: Solid Earth, 104(B8), 17661–17674. doi:10.1029/1999JB900120

https://doi.org/10.5194/egusphere-2022-1285
Preprint. Discussion started: 5 December 2022

Wobus, C., Whipple, K. X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., … Sheehan, D. (01 2006). Tectonics from topography: Procedures, promise, and pitfalls. Tectonics, Climate, and Landscape Evolution. doi:10.1130/2006.2398(04)

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

Yanites, B. J., Becker, J. K., Madritsch, H., Schnellmann, M., & Ehlers, T. A. (2017). Lithologic effects on landscape response to base level changes: a modeling study in the context of the Eastern Jura Mountains, Switzerland. Journal of Geophysical Research: Earth Surface, 122(11), 2196–2222.

Yanites, B. J. (2018). The dynamics of channel slope, width, and sediment in actively eroding bedrock river systems. Journal of Geophysical Research: Earth Surface, 123(7), 1504–1527.

Zaleski, E., Eaton, D. W., Milkereit, B., Roberts, B., Salisbury, M., & Petrie, L. (1997). Seismic reflections from subvertical diabase dikes in an Archean terrane. Geology, 25(8), 707–710.