**The effect of Bed Thickness on Hillslope Morphology and Sediment Size in Last Chance Canyon, New Mexico**

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**Abstract.** Here we explore the effect that variance in bed thickness has on grain size distributions, channel, and hillslope form in Last Chance canyon, New Mexico, USA. Here, the hillslopes are composed of horizontally to near horizontally bedded rock. This study focuses on hillslopes that lack regolith, but have similar morphology to hillslopes We posit that differences in bed thickness influence hillslope shape here in Last Chance canyon, where thinner rock generates more diffusive hillslopes resembling the idealised convex shape endemic of soil mantled landscapes. We used drone photos to construct high resolution orthomosaics and digital elevation models (DEMs) of seven hillslope transects and stream channels at the base of each transect from two proximal watersheds. Using the DEMs and orthomosaics, we measured bed thicknesses, slope, and curvature on the hillslopes and grain size distributions at the base of each hillslope. We find that hillslopes are steeper where there is more thickly bedded rock, and shallow in thinly bedded rock. Furthermore, sediment input to channels is controlled by bed thickness on hillslopes and affects channel morphology. Thickly bedded rock units on proximal hillslopes contribute larger sized colluvial sediment to the channels, which steepen as a result. ADD CURVATURE AND SOIL PIT STUFF

# 1 Introduction (NOT MY DOG)

Variance in relevant bedrock properties influences the production and size of sediment on hillslopes (Johnstone and Hilley, 2015), erosion rates (Dixon et al, 2012), and landscape form (Glade, 2017; Hurst, 2013). Rock properties, specifically fracture spacing, has been shown to influence rock surface slope (e.g., Brook and Tippett, 2002; Matasci et al., 2015; Moore et al., 2009; Selby, 1980), erosion, and imprints its signature into the topography (Molnar et al., 2007; Clarke and Burbank, 2011; St. Clair et al., 2015; Voigtlander et al., 2017; Eppes and Keanini, 2017; Eppes et al., 2018). Soil depth, a function of both soil production and erosion rate, has been shown to affect hillslope convexity (Roering, 2008). Soil mantled hillslopes are thought to generate convex hillslopes, however, in Last Chance canyon, sandstone hillslopes with predominantly exposed bedrock are convex in shape and resemble soil mantled hillslopes. But what about these bedrock hillslopes causes them to look like soil mantled hillslopes? Why do predominantly sandstone hillslopes appear diffusive while carbonate hillslopes are steep and shear?

In this study, we seek to understand the effect that changes in rock properties have on sediment production and erosion. More specifically, we ask what controls weathering, soil production, and sediment movement on hillslopes with high spatial variability in rock properties? how is sediment removed so that diffusive looking landscapes are generated in thinly bedded sandstone and not in the more thickly bedded carbonates? To answer these questions, we will couple a hillslope sheet wash component with the overland flow model to explore sediment delivery from hillslopes to channels. We will inform our model runs with realistic hydrographs reconstructions and field measurements of sediment size. and distance between bedrock beds. We will also measure sediment depth, bulk lithology of less than gravel sized colluvium, and the lithology of larger sized sediment.

# 2 Field Area

Because of their differing morphology and accessibility, we use data gathered from different sections of two, first to second order watersheds, called LC1 and LC3 (map figure). Last Chance Canyon has horizontally to near horizontally bedded bedrock and is currently tectonically inactive (Hill, 1987; Hill, 2006). 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 various thicknesses (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).

# 3 Methods

## 3.1 Field Survey

We used a DJI Mavik 2 pro to take photos of seven hillslope transects in each of the two watersheds from elevations of approximately 20 meters above LC1 and LC3. We then used Agisoft Metashape software to process these images and to produce orthomosaics and DEM’s with a sub cm scale spatial resolution.

We measured the depth of regolith above bedrock by digging soil pits at 20m intervals, when possible, down each of the seven transects.

## 3.2 Sediment Size Measurements

We measured the diameter of alluvium in channels at the base of the seven hillslope transects with the PebbleCounts image analysis package (Purinton and Bookhagen, 2019). We used the manual method, in which sediment grains were chosen by an operator, to mitigate error. Due to the relatively large size of the orthomosaics we utilized the PebbleCounts-Application, which subset the images to manageable sizes (Purinton & Bookhagen, 2021). To further streamline the process, we developed a more user friendly application which loops through the images created and applies our method to each of the subset images and then compiles the large amount of data into a single file containing all the data from the watershed image. All of which is in the GitHub repository for this paper.

## 3.3 DEM and Orthomosaic analysis

We measured bed thicknesses on the hillslope transects using ArcScene and the high-resolution DEMs and orthomosaics generated using drone imagery. Here, bed thickness is defined as the vertical distance between the upper and lower horizontal bedding plane.

At 20m intervals beginning at the channel and moving up each hillslope transect, we measured slope and curvature over a 80m window (40m upslope and 40m downslope of each 20m interval) using the 3DEP 1m DEM (hillslope schematic figure). The window distance was reduced in proximity to the channel or ridgeline so that measurements were only taken from the hillslope in question.

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 ksn maps 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).

# 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.

## 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.

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

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 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).

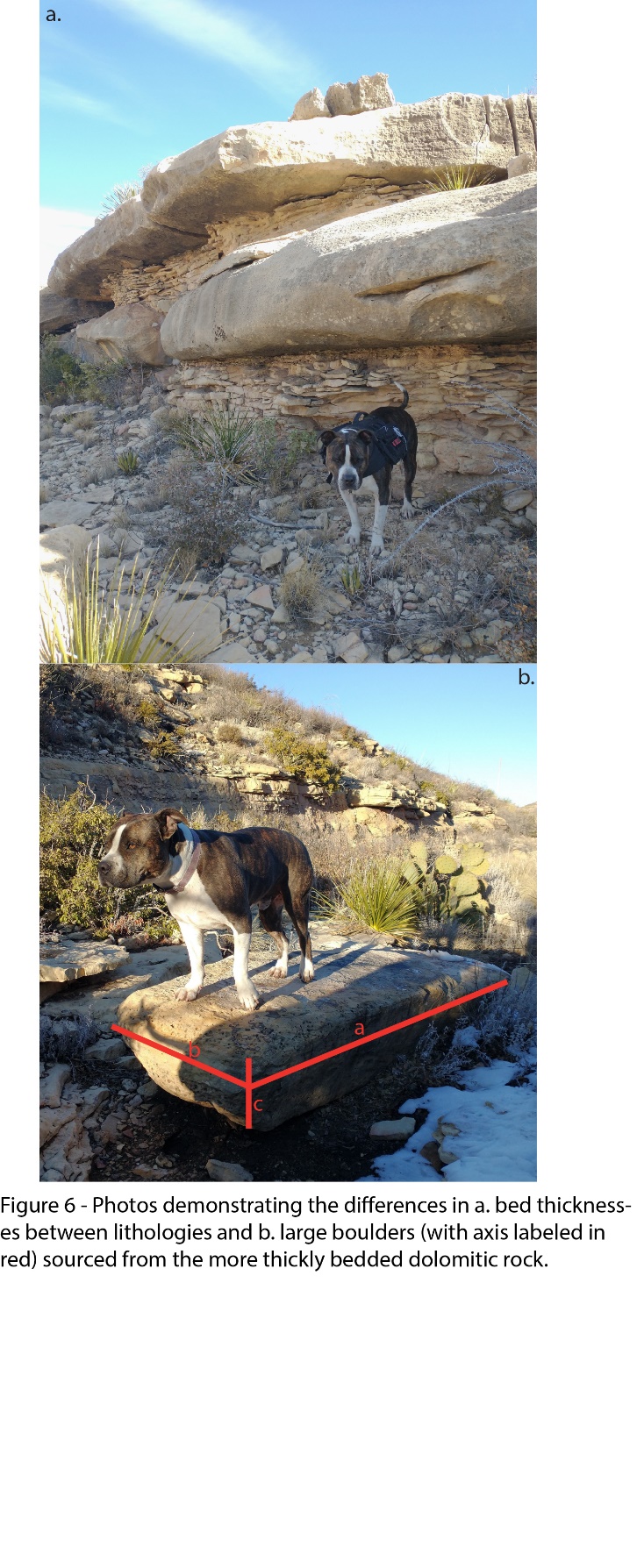


Figure 7: Relief (calculated using a 500 m window) vs. Boulder volume, calculated by multiplying the a, b, and c axis, for all boulders we measured in the field.

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.

Chart, scatter chart

Description automatically generated

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.

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.

Chart, line chart

Description automatically generated

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.

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 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.

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).

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

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.