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

Sam Anderson1, Nicole Gasparini1, Joel Johnson2

1Earth and Environmental Science, Tulane University, New Orleans, 70118, USA

2Jackson School of Geosciences, University of Texas at Austin, Austin, 78712, USA

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

**Abstract.** In this paper 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 landscape is composed of horizontally to near horizontally bedded rock, have relatively little regolith, and yet some hillslopes appear diffusive despite the lack of soil cover. We posit that differences in bed thickness influence hillslope shape here in Last Chance canyon, where thinner bedrock generates a more diffusive geometry resembling the idealised convex hillslope 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 these 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 and less diffuse where there is more thickly bedded rock and become shallow and diffuse 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.

We believe that in the relatively steep downstream channel sections slope is primarily controlled by the coarse alluvial cover. We further posit that the upstream diffuse landscape has a baselevel that is essentially fixed by the steep downstream reaches, resulting in a stable configuration where channel slopes have adjusted to bed thickness.

ADD CURVATURE AND SOIL PIT STUFF AND TIE IT TOGETHER. Maybe… combo of drainage area and bed thickness which control channel steepness. Like theres a threshold bed thickness down channel which causes for a HS to appear diffuse.

# 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.

I RECOMMEND WE DEFINE AND DESCRIBE WHAT AN IDEAL HS IS.

Foto of end member parts of LS.

# 2 Field Area

Because of their differing morphology and accessibility, we collected data from different sections of two different first to second order watersheds, called LC1 and LC3 (map figure 1). 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 the drone 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). PebbleCounts is a Python based product for the detection and sizing of sediment grains from drone images. We used the k means with manual (KMS) method, which allows an operator to validate measured grains to mitigate error. Due to the relatively large size of the orthomosaics we utilized the PebbleCounts-Application, which subset the images to manageable sizes (photo sieve fig). To further streamline the process, we developed a application which loops through the subset images and then compiles the all of the data for a channel section into a single file. All of which is in the GitHub repository for this paper.

## 3.3 DEM and Orthomosaic analysis

We measured the bed thickness, the vertical distance between the upper and lower horizontal bedding planes, of every exposed bed on the seven hillslope transects using the high-resolution orthomosaics in the ArcScene program (figure showing Sophia method).

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 point) using the 3DEP 1m DEM (hillslope schematic figure). We also measured all beds within the same window and found average bed thickness, the sum of all thicknesses, and the largest bed thickness. If necessary, the window distance was reduced in proximity to the channel or ridgeline so that measurements were only taken from the hillslope in question and did not cross either the channel nor the ridgeline.

We used a 10 m digital elevation model (DEM) of Last Chance canyon along with 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 (map 2, with ksn, slope histogram, transects, and grain size dist in channels).

**Here will be how curvature changes up channel, compare LC1 and 3. 3 should be more strait forward. 1 will be weird. Maybe more reflective of whats happening in the channel. See if I cant link drainage area or channel steepness (channel/hs interactions) to hillslope diffusivity.**

## 4.2 Bed Thickness and Hillslope Morphology

As the average, max, and sum of all bed thickness within the 80 m window increases slope measured over the same window distance also increases (local slope vs bed thickness figure). We chose to measure slope and bed thicknesses over a 80 m window because it diminished slope errors from boulders and plants over relatively larger distances. Furthermore, as the average bed thickness for a entire hillslope transects increases, the slope of the entire transect likewise increases (total slope figure) MAYBE THIS FIG GETS DELETED. Beds are generally thinner in the upstream sections of the landscape, where hillslopes shallow.

In Last Chance canyon, hillslopes are more diffuse in the more thinly bedded rock, but not in the more thickly bedded rock (curve vs distance fig). Furthermore, hillslopes with less variance in bed thickness appear more diffuse. Diffusive hillslopes are convex near the ridgeline and become more concave as the hillslope approaches the channel. We plotted curvature values by distance from the channel in the seven hillslopes. We then plotted the slope values and the r squared values for the seven transects against max bed thickness and found that where the max bed thickness is lower, the slope of the distance vs curvature function is more negative and has a higher r-squared value, both indicating a more diffusive shape.

## 4.3 Size of Alluvium affects channel morphology

As the diameter of sediment increases the channel steepness also increases (the d10, d50, etc. ksn figure). Smaller sediment sizes corresponds to the shallower upstream hillslopes.

## 4.4 Bed thickness affects channel morphology

Max bed plane thickness of each of the transects affects both the size of the sediment in the channel below as well as the channel steepness of the channel below. (figures of bed thickness effect on grain size, and on channel steepness)

## 5 Discussion

FOR NOW: its ideas…

I wonder if we can separate the effect bed thickness has on where a hs looks diffusive or not by tracking changes up channel and comparing between lc1 and 3. Worst comes to worst if it’s not just distance up channel we can say that it’s a combo of bed thickness and drainage area. Like maybe the spread in the data with max bed thickness vs r squared and slope of function is from drainage area.

How do I explain away slope change with bed thickness? Is it too duh?

Does bed thickness affect the inflection point between non linearity and linear slope shape? Does it affect the transition from convex to concave curvature? Is there a threshold thickness? Or proximity to a large bed?

Idealized hillslope is probably a better word than diffusive. Describe what idealized means tho…

Strait HS is where curve is 0. Maybe see location/elevation where hs become strait? Is there a pattern?

Look at max bed thickness vs large boulder thickness. Or max bed thickness vs D50, d84, all the d’s etc.

# 6 Conclusions

We present several observations about the effect of bed thickness on landscape morphology in Last Chance canyon. We suggest that bed thickness influences hillslope geometries. hills steepen across units with thicker beds. Conversely, hills are shallower in thinly bedded units. Furthermore, hillslopes with smaller max bed thickness appear more diffusive.

The size of boulders in the channel also impacts channel morphology. More thickly bedded rock on the hillslopes contributes larger sized, and more geomorphically relevant, alluvium to the channel. This coarse sediment armors the channel and causes channel steepness to increase. In Last Chance canyon, channel sections that contain larger alluvium are generally steeper.

# Old 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.

# New References

Mudd, Simon & Furbish, David. (1625). Influence of chemical denudation on hillslope morphology. Geomorphology J. Geophys. Res. 109. 10.1029/2003JF000087.

Shobe, C. M., Tucker, G. E., and Anderson, R. S. (2016), Hillslope-derived blocks retard river incision, Geophys. Res. Lett., 43, 5070– 5078, doi:10.1002/2016GL069262.

Neely, A. B., DiBiase, R. A., Corbett, L. B., Bierman, P. R., & Caffee, M. W. (2019). Bedrock fracture density controls on hillslope erodibility in steep, rocky landscapes with patchy soil cover, southern California, USA. Earth and Planetary Science Letters, 522, 186-197.

Ben-Asher, M., Haviv, I., Roering, J. J., & Crouvi, O. (2019). The potential influence of dust flux and chemical weathering on hillslope morphology: Convex soil-mantled carbonate hillslopes in the Eastern Mediterranean. Geomorphology, 341, 203-215.

Gilbert, G. K. (1909). The convexity of hilltops. The Journal of Geology, 17(4), 344-350.

Culling, W. E. H. (1960). Analytical theory of erosion. The Journal of Geology, 68(3), 336-344.

Roering, J. J., Kirchner, J. W., & Dietrich, W. E. (1999). Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. Water Resources Research, 35(3), 853-870.

Tucker, G. E., & Bras, R. L. (1998). Hillslope processes, drainage density, and landscape morphology. Water resources research, 34(10), 2751-2764.