**The effect of Bed Thickness on Hillslope Geometry in Last Chance Canyon, New Mexico**

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*This study challenges conventional paradigms of arid bedrock landscapes, deepening our understanding of geological processes and their role in landscape evolution. Hillslopes in Last Chance Canyon, New Mexico, USA, adopt a convex nonlinear shape above an adjusting and/or linear section of the landscape despite limited regolith, a departure from traditional expectations for arid bedrock landscapes. This study focuses on hillslopes in first- and second-order watersheds in which the landscape is composed of horizontally bedded rock with a variety of thicknesses. We hypothesize that interplay between spatial variations in bedrock thickness and uplift can enable relict and low sloping parts of the hillslopes to exist, and persist temporally. Nonlinear hillslope profiles, traditionally associated with soil-mantled landscapes, can occur where thin and erodible bedrock sits atop thick and resistant bedrock. High-resolution orthomosaics and digital surface models (DSMs) of seven hillslope transects from two headwater catchments were generated from drone photogrammetry and were used to measure bed thicknesses to test this hypothesis. The United States Geological Survey (USGS) 1m digital elevation models (DEMs) were used to measure slope, curvature, and other relevant topographic metrics. In Last Chance Canyon, hillslopes have a constant high slope well described by a linear model in lower elevation sections made up of thickly bedded rock, while in the thinly bedded erodible landscape sections, slopes are shallower and well described by the nonlinear model. We posit that thicker beds which are closer to the base of the landscape, where the signal from base level originated, can attenuate the erosional signal moving up elevation, shielding relict and erodible landscape sections from being completely eroded away. Furthermore, we infer that in the thickly bedded high slope areas, slopes are primarily controlled by competent beds which are resistant to the erosional signal. In the relict topography, hillslopes are steeper at higher elevations where the signal from baselevel fall is weakest. Our interpretations of bed thickness measurements and topographic metrics demonstrate the control that both bedrock properties and uplift have on hillslope geometry, and that, in this case a combination of thick beds underlaying thin beds and past uplift have formed a landscape which is described by the nonlinear diffusion model.*

Hillslopes which are well described by the nonlinear model exist in a variety of locales. However, scientific literature documenting diffusive hillslope form in arid landscapes with exposed bedrock is noticeably lacking. Bedrock competency, which control the morphology of bedrock hillslopes, have been shown to influence erosion rates and rock surface slope (e.g., Brook and Tippett, 2002; Matasci et al., 2015; Moore et al., 2009; Selby, 1980), and imprint 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). In stream channels, landscape evolution models have demonstrated that the influence of erodibility contrasts is most pronounced in horizontally bedded landscapes, and whether more competent bedrock erodes faster or slower than more erodible bedrock depends on whether harder rock is on top of softer or vice versa (Perne et al, 2017; Forte et al., 2016). Furthermore, horizontal or dipping planar rock layers with varying erodibilities result in evolving landscapes that do not attain a topographic steady state. However, these landscapes can exhibit quasi-equilibrium forms that depend on the orientation of these layers (Perne et al; 2017).

Here we introduce a novel perspective by considering the influence of exposed bedrock thickness rather than the nature of the underlying bedrock (Mudd and Furbish, 2007; Hurst et al., 2012) on variance in landscape form. Furthermore, we demonstrate that a familiar signal well described by the nonlinear hillslope model form can exist in arid bedrock landscapes and demonstrate the mechanisms that generate conditions necessary for these relict landscapes to propagate temporally. We contend that thick and relatively competent beds protect the landscape above them from a erosional wave moving up in elevation, causing the landscape to appear diffuse and shallow in thinly bedded rock at some elevation above these large beds. We propose that, in parts of Last Chance canyon, the combined effect of the position of varying bedrock thicknesses relative to each other as well the spatially variant influence of the erosional signal originating at the base of the range can allow for relict hillslopes, nonlinear in form, to persist temporally. By investigating the interplay between ridgetop curvature and hillslope relief, we aim to identify indicators of landscape transience, building upon previous studies by Roering et al. (2007) and Hurst et al. (2013a).



**Figure 1 - a. Slope map of Last Chance canyon with values plotted across it. b. c. Cumulative frequency plots of bed thicknesses from the 4 surveyed hillslope transects on LC3 and the 3 surveyed hillslope transects on LC1.**

The research presented here is from two proximal first to second order watersheds, which we named LC1 and LC3 in Last Chance Canyon. We sampled 3 transects in LC1 and 4 transects in LC3 to capture variations in bed thickness and hillslope morphology (Figure 1). Last Chance Canyon has horizontally bedded to near-horizontal bedrock, and it is currently tectonically inactive (Hill, 1987; Hill, 2006). The Guadalupe mountains, of which Last Chance canyon are located in, are a Permian reef and shelf complex (Hill, 2000; Phelps et al., 2008; Kerans et al., 2017). The Guadalupe Mountains experienced uplift during basin and range extension approximately 27 million years ago, exposing previously buried bedrock, (Chapin and Cather, 1994; Ricketts et al., 2014; Hoffman, 2014; Decker et al. 2018). While the tectonic history of the Guadalupe mountains remains incompletely constrained, significant uplift and internal tectonic deformation are thought to have last been active in Miocene to early Pliocene time [Polyak et al., 1998; Hill, 1998, 2000; Decker et al., 2018]. Modern day rates of regional extension near the Rio Grande rift are very low (≈0.12 mm/yr over 100 km; Berglund et al., 2012).

We used a drone to take photos of the 7 hillslope transects at approximately 20 meters above the highest elevation of the 7 hillslope transects and used Agisoft photoscan to generate high resolution digital surface models (DSMs) with 0.027 to 0.28 m resolution (we refer to these as DSMs rather than DEMs because vegetation is not removed from the DSMs) and orthomosaics of the 7 hillslope transects. We used the orthomosaics to identify and the DSMs to measure exposed beds on the hillslopes using ArcScene. We identified inflection points in the landscape first using slope plots generated from the USGS 1m DEM, where we determined places on the seven hillslope transects that change from a constant high slope to low sloping areas at slopes of 30 degrees. We interpret these slope breaks to be inflection points where we can bin landscape geometries into linear and nonlinear sections.

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**Figure 2 –a. 4 hillslope profiles from LC3, and b. 3 in LC1 with beds plotted on top of the profiles. Arrows are inflection points where the landscape goes from linear to nonlinear. Slope plots that correspond to the profiles in b. LC3 and d. LC1. Slopes of 30 degree are marked, above which, the landscape is steep and linear, and below the landscape is shallower and nonlinear. The trendlines are linear fits to the part of the hillslope that are concave.**

At the highest elevations for 5 of the transects, there is a diffuse section with constantly decreasing slope towards the ridgeline. In this section beds are relatively thin (average = 0.9 m, standard deviation = 0.4, max bed thickness = 2 m). At the lowest elevation of all the transects except the two far upstream transects in LC3, from the channel to some elevation above, slope values are high and can be described by a linear function. In this section beds are relatively thick (average = 2.9 m, standard deviation = 3.2, max bed thickness = 19 m). A t-test between bid thickness in the concave section and the linear section demonstrates there is a statistically significant difference between the groups or conditions you are comparing (T stat = 4.6, T critical = 2.0, P = 2.4E-5). In general the landscape is predominantly bedrock, but where there is regolith, it is a relatively thin mantle of material. The average depth to saprolite is 6 cm, and the average depth to bedrock is 20 cm (figure 3). We used slope transects to determine locations where slope steadily decreases towards the ridgeline as areas where the landscape is convex. In the two lowest elevation transects in LC1 the hillslopes have constant high slope values at the base of the hill, and a convex shape where slope values are lower and decrease towards the ridgeline. In between these sections there is a transition zone where slope decrease below 20 degrees, before increasing again, at which point they begin to be convex and slope decreases steadily towards the ridge. In LC1, where the three transects are proximal, the slope of the function fitted to the convex portion of the landscape, situated above the linear section is consistent across all three transects (average = , standard deviation = ). Whereas in LC3, where the transects are more spaced out relative to LC1, a linear fit of the slope values in the convex section increases with transect elevation.

  
**Figure 3 – Photo of a soil pit from Last Chance canyon.**

In Last Chance Canyon, differences in the bed thickness, and their position on the landscape relative to other beds and to the channel, influence hillslope form. Here, thicker beds steepen the hillslope and set the inflection point between steep linear slope and other hillslope geometries just above the thick bed or series of beds (Figure 2). Furthermore, thick and resistant beds attenuate the erosional wave moving upslope, diminish the signal of transience above them, and seemingly change the direction of erosion into the hillslopes, causing a slightly concave shape above them. Hillslope form changes depending on location within the landscape, with the concave section in lower elevation hillslopes bearing a more pronounced imprint of the erosional wave resulting from base level fall. Lastly, the combined influence of these factors defines the morphology of the hillslopes: Thick beds *seem to* inhibit and redirect the erosional signal as it progresses upslope, and the presence of thin beds above these thick beds allow for the hillslopes to be shallow and diffuse. These conclusions underscore the intricate interplay between bed thickness, hillslope position relative to the erosional wave, and the way the erosional signal is imprinted above thick beds at the transition between convex and steep, linear hillslopes.

Understanding the geomorphic evolution of landscapes is essential for deciphering the history and development of landforms. For this, the "space-for-time substitution" has proven to be a valuable tool, allowing researchers to investigate how landscapes change and mature over time (Schoenbohm et al., 2004; Gallen et al., 2011; Anderson et al., 2012; Prince and Spotila, 2013). This approach includes discerning transitions between different terrain forms and identifying boundaries between areas of differing erosion rates (Mudd and Furbish, 2007; Hurst et al., 2012). In the case of Last Chance Canyon, you can utilize the concept of space-for-time substitution by examining the inflection points where hillslope forms change. These inflection points indicate shifts in the landscape's characteristics, often associated with different phases in the landscape's development. By analyzing these inflection points along the canyon, one can gain insights into the canyon's evolutionary history. For example, if you observe that the lower inflection points, between linear and nonlinear sections, in the canyon are characterized by steeper, higher-gradient slopes while the upper inflection points, between concave and non-concave sections, exhibit lower slopes and relict features, this suggests a spatial progression from a more actively adjusting and erosive landscape near the base of the canyon (younger stage) to a less dynamic, older landscape further upstream. In essence, these inflection points serve as markers in space that represent different phases in the canyon's development. By analyzing the spatial distribution and characteristics of these inflection points along the canyon, you can infer the temporal evolution of Last Chance Canyon, demonstrating how it has changed and matured over time.

In Last Chance Canyon, thicker beds steepen hillslopes and define the inflection point between steep linear sections and other hillslope geometries, highlighting the significance of bed thickness to landscape form in arid bedrock landscapes. Conversely, concave hillslope geometries exist where there is thinly bedded rock above thickly bedded sections. These thinly bedded areas require the protection provided by thick beds to prevent erosion from erasing their presence. This is evidenced in the lower elevation hillslopes in LC3 where the concave part of the hillslope is shallower at lower elevations, where the erosional wave's effect is more pronounced. These findings underscore the necessity of thick beds in preserving the more delicate thinly bedded relict topography.

Due to the substantial, 20m thick bed, at the base of LC3, the erosional wave is effectively impeded and diffused as it ascends the slope. Consequently, the inflection points in LC3 are distributed at varying elevations (Figure 3). At the lowest downstream point of LC3, the inflection points are positioned at a lower elevation, approximately 1550 meters and the location of the 20m thick bed. In contrast, at the top of LC3, the entire transect is concave. This configuration results in an angled landscape in LC3, the angle being dictated by the elevations of the inflection points. In contrast to LC3, the transects in LC1 are relatively proximal, and, and as a result, controlled by a large series of beds that manifest at similar elevation points on the three transects. This proximity indicates a similar history for the three transects, and the signal is consistently inhibited at approximately the same elevation for the three transects. This causes the inflection points to be at a similar elevation in LC1 with only a slight positive upslope trend which is interpreted to be a small signal from the erosional waves upslope direction of propagation.

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**Figure 3 - 3D maps of a. LC3 and b. LC1 with inflection points marked. c. Distance of the transect downstream vs. Elevation of the inflection point for each transect. d. Thickness of bed below inflection point where slope goes from being linear to nonlinear vs. the vertical distance above the bed where the hillslope becomes diffuse.**

In Last Chance canyon, thicker beds are generally found at lower elevations, contributing to steeper slopes in those areas due to adjustments resulting from base level fall. As the erosional wave advances, it climbs until it intersects the lower inflection point where it encounters more resistant or competent beds. Below the lower inflection point in all seven transects, the landscape features steep, high-gradient segments indicative of active adjustment in response to the erosional wave's upstream progression. At the first inflection point, the erosional wave encounters an obstruction, resulting in temporary stalling and some diffusion, while the landscape retains its steep and adjusting character below this point. In elevations higher than the lower inflection point but lower than the higher inflection point, the lingering influence of the erosional wave is observed, although diffused. Above the second inflection, higher elevation inflection point, the landscape exhibits lower slopes and is interpreted to be concave and reminiscent of the pre-base-level fall topography. The thickness of beds below the lower and upper inflection points significantly affects the elevation and angle between these inflection points (Figure 3, c.). When larger beds are present below the lower inflection point, the vertical separation between the upper and lower inflection points tends to be greater. If the lower beds are thinner, or non existent, then the elevation that the wave has propagated to will be higher or will have reached the ridgeline. Its important to note that all three transects in LC1 feature a series of substantial beds at approximately 1640 meters in elevation. These beds exhibit similar thicknesses, and they effectively obstruct the erosional signal, causing it to propagate upward to the higher inflection point at roughly the same distance for all three transects within LC1. Where LC3 the transects are spaced farther apart and the thickness of the beds below the lower inflection point are more variant, causing the distances between the upper and lower inflection points to be more disparate.

Futhermore, our observations indicate that at the point in the landscape where a very thick bed or series of thick beds is directly under a thinly bedded rock, hillslope geometry appears convex. This attenuation results in a subtle convex shape in the hillslopes just above the thick beds, reminiscent of the outcomes seen in Perne's modelling results. As the erosional wave ascends, it encounters a substantial bed at a lower elevation. This interaction causes the wave's signal to change direction, become diminished, and ultimately cease just below where hillslope geometry becomes concave. Where there are no measured beds below the upper inflection point is the location at which the erosional wave has propagated before “petering out” of its own accord and with no input from a thick bed. In LC3, the presence of an approximately 20-meter-thick bed near the base of the watershed obstructs the progress of the erosional wave, here, the wave's direction is altered, prompting it to erode into the hillslope and form a distinctive nick point in the landscape. Below this point, slopes are steep, while above it, slopes become shallower. In contrast, LC1 features relatively thick beds at similar elevations, leading to the development of gentler slopes at the inflection points. In the downstream sections, these substantial beds act as obstacles, impeding the erosional wave and causing it to diffuse above them. As this diffused signal advances upslope, it does so at a different angle. It appears to move parallel to the large beds into the landscape situated just above them, particularly in the two lower elevatoin transects of LC3. In contrast, in the higher elevation part of LC3, the transects are concave, with only slight deviations- at mapped beds- from a slope constantly decreasing towards the ridgeline.

Top of Form

In summary, our exploration of Last Chance Canyon's hillslope geometry has revealed three critical conclusions. Firstly, the variability in bed thickness significantly influences hillslope form and geometry. Second, the location of a hillslope within the landscape results in distinct forms, with those at lower elevations bearing a more pronounced imprint of the erosional wave stemming from base level fall. These two factors dynamically interact to shape hillslope morphology, with larger beds at lower elevations inhibiting and altering the direction of the erosional wave as it propagates upslope. This intricate relationship between bed thickness, hillslope position, and the erosional wave's behavior represents a fundamental driver of the observed hillslope morphology within the Last Chance Canyon landscape. Furthermore, an erosional wave progressing through a horizontally bedded landscape encounters challenges when reaching large beds, leading to a loss of intensity as it becomes 'stuck' downstream. This presence of the erosional wave prompts the landscape to react by orienting the inflection point between relict and adjusting topography positively with diminishing drainage area and/or increasing distance upstream, impacting the natural curvature change across a hillslope. Lastly, our interpretation suggests that large beds diminish the erosional signal at higher elevations from base level fall, causing concave sections lower in elevation to have lower slopes. Together, these findings highlight the complex interplay of bed thickness and signals from past uplift in shaping hillslope morphology, providing valuable insights into the processes that drive hillslope dynamics within this unique landscape.

# 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.

https://pubs.geoscienceworld.org/gsa/geology/article-abstract/45/4/311/195361/Block-controlled-hillslope-form-and-persistence-of?redirectedFrom=fulltext

https://pubs.geoscienceworld.org/gsa/geology/article/36/5/367/29716/Geomorphic-response-to-uplift-along-the-Dragon-s

https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/1998wr900090

Johnstone SA, GE Hilley (2015), Lithologic control on the form of soil-mantled hillslopes. Geology, 43(1), 83-86, doi:10.1130/G36052.1

4 figures, 3000 words (science), 18,500 characters (geology), referenced summary (200 words), 6 pages 2500 words (nature), 5 pages 3000 words (science)