**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, have a convex shape above a steep linear section of the hillslope despite limited regolith, a departure from traditional expectations for bedrock landscapes without a developed soil cover. This study focuses on hillslopes in first- and second-order watersheds in which the landscape is composed of horizontally bedded rock with varying thickness. 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. Convex 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) 1 m digital elevation models (DEMs) were used to measure slope, curvature, and other relevant topographic metrics., Near the channel hillslopes are straight with a uniform high slope made up of thickly bedded rock, but where the hillslope is thinly bedded, slopes are shallower and convex. We posit that thicker beds which are closer to the base of the hillslope, where erosion of the channel drives hillslope erosion, can attenuate the erosional signal moving up hillslope, 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 erosion ratehave on hillslope geometry, and that, in this case a combination of thick beds underlaying thin beds and a hypothesized wave of erosion have created bedrock hillslopes that follow the form predicted by a nonlinear diffusion model.*

Hillslopes that have a convex to straight profile are predicted by the nonlinear diffusion equation and 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 controls the morphology of bedrock hillslopes, has 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 onto landscape morphology (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; Neely et al., 2019). In stream channels, landscape evolution models have demonstrated the influence of erodibility contrasts on the morphology and erosion patterns in horizontally bedded landscapes. ( Forte et al (2016) found that less erodible bedrock may erode faster or slower than more erodible bedrock depending on whether harder rock is above or below the softer rock). However, sediment cover may reduce the morpohlogic and erosion contrasts between river reaches with varying erodibility (Guryan et al, 2024). 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 hillslope formwell described by the nonlinear diffusion sediment transport model can exist in arid bedrock landscapes without a soil mantle. and demonstrate the mechanisms that generate conditions necessary for these relict landscapes to propagate temporally. In Last Chance Canyon, think that to achieve a convex hillslope form, the landscape needs past uplift, relatively thinly and erodible rock on top of thicker and more competent bedrock, and, in the thinly bedded and more erodible section, there needs to be some competent bedrock. We contend that thick and relatively competent beds protect the landscape above them from an erosional wave moving up in elevation, causing the landscape to remain convex in thinly bedded rock above these thick beds that steepen without propagating the erosion wave upslope. Furthermore, in the convexsection, some of bedrock should be competent enough so the landscape is not eroded flat into a plateau. 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 convex hillslopes, to persist. 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 channel steepness 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 determined locations on the seven hillslope transects that change from constant slopes higher then 30 degrees to low sloping areas using slope plots generated from the USGS 1m DEM (USGS). We interpret these slope breaks to be locations where we can bin landscape geometries into linear and nonlinear sections.

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**Figure 2 –Four hillslope profiles from LC3, three in LC1 with beds plotted as circles sized according to their thickness. Arrows are where slope goes from above 30 degrees to below 30 degrees. where the landscape goes from linear to nonlinear. Below this are slope plots that correspond to the profiles in LC3 and 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 where slope increases linearly with distance downslope.**

At the highest elevations for five of the transects, there is a convex section with linearly decreasing slope towards the ridgeline. In this section exposed beds are relatively thin (average = 0.9 m, standard deviation = 0.4, max bed thickness = 2 m). Near the channel in five of the transects the hillslope becomes linear, and slope values are high, hovering around 30 degrees. In this section beds are relatively thick (average = 2.9 m, standard deviation = 3.2, max bed thickness = 19 m). A t-test between all the bed thickness in the convex section upslope section and all bed thicknesses in the steep linear section demonstrates there is a statistically significant difference between them (T stat = 4.6, T critical = 2.0, P = 2.4E-5). In general, the hillslopes are predominantly exposed bedrock, but where there is regolith, it is a relatively thin mantle of material (figure 3). Field measurements demonstrate that where there is regolith cover the average depth to saprolite is 6 cm, and the average depth to bedrock is 20 cm. We used slope transects to determine locations where slope linearly decreases towards the ridgeline as areas where the landscape is convex. In the two lowest elevation transects in LC3 the hillslopes have approximately uniform high slope values at the base of the hillslope, and a convex shape where slope values are lower and decrease towards the ridgeline. In between these sections there is a transition zone where slopes decrease below 20 degrees, just above thickly bedded sections, before increasing again, at which point slope decreases linearly towards the ridge. Near the ridgeline in LC1, where the transects are more spatially proximal, two of the hillslope transects are generally flat, while the other has a section which can be described as convex. 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 LC3.1, 32.25132, -104.70392.**

In Last Chance Canyon, differences in the bed thickness, and bed position on the landscape relative to other beds and to the channel, influence hillslope form. Here, thicker beds steepen the hillslope and set the location between steep linear slopes and other nonlinear hillslope geometries just above the thick bed or series of beds and just below where bed thicknesses become thinner (Figure 2). Conversely, hillslopes with exclusively thin beds are shallow, and, depending on the thickness and number of exposed beds and the position on the landscape, can be convex. Thick and resistant beds attenuate the erosional wave moving upslope, diminish the signal of transience above them, and seemingly change the direction of erosion perpendicular into thinner, presumably weaker beds, causing a concave region just above thickly bedded hillslope sections, as in 3.1, 3.2, and, to a lesser extent, 1.2 (Figure 2). Hillslope form changes depending on location within the landscape. Slopes in LC3 are shallower in the convex sections in hillslope transects farther downstream due to a more pronounced imprint of the erosional wave resulting from base level fall, differing from LC1, where, above the linear steep section, the landscape flattens due to the lack of competent beds, and because the three hillslope transects are proximal and at the downstream end of the watershed. 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.

In Last Chance Canyon, thicker beds steepen hillslopes and define the location between steep linear sections and other hillslope geometries, highlighting the significance of bed thickness in shaping landscape form in arid bedrock landscapes. Conversely, convex hillslope geometries exist where there is thinly bedded rock above a thickly bedded section. These thinly bedded areas require the protection provided by thick beds below them to prevent erosion from erasing their presence. This is evidenced in the downstream hillslope transects in LC3 where the convex part of the hillslopes has shallower slopes than the farther upstream transects, and where the effects of the erosional signal are thought to be more pronounced. In LC1, where hillslope transects are spatially proximal and are all located in a downstream part of the watershed, the landscape transitions into a markedly different morphology, characterized by a flat, almost plateau-like appearance. This abrupt change in landscape morphology is attributed to erodible nature of the beds above the steep, linear section of the hillslope. LC3 also exhibits a steep, linear morphology in areas with thick beds, but unlike LC1, has competent beds close to the ridgeline. These relatively thin beds could be thick and competent enough to have allowed for slopes to linearly decrease towards the ridgeline, as opposed to LC1, which has no mapped beds near the ridgeline, and has been eroded flat.

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; 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). Due to the substantial, 20 m thick bed, at the base of LC3.1, and the series of thick beds at the base of LC3.2, the erosional signal from baselevel fall is effectively impeded and diffused as it ascends the slope. Consequently, the inflection points in LC3 are distributed at varying elevations (Figure 3). In the downstream parts of LC3, the inflection points are positioned at lower elevations, approximately 1550 meters and 1575 meters in LC3.1 and LC3.2 and just above the location of the 20 m thick bed in LC3.1 and a series of thick beds in LC3.2. This causes the location where the landscape changes from the linear steep section to the nonlinear low sloping section to change at higher elevations at farther upstream hillslope transects (Figure 4, c). 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 locations where the landscape transitions from steep to shallow slopes to be at a similar elevation in LC1.

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**Figure 4- 3D maps of a. LC3 and b. LC1 with the locations where the hillslope goes from slopes above 30 degrees to below 30 degrees marked with stars. c. Distance of the transect downstream vs. elevation of the location where slopes go from above to below 30 degrees.**

Our observations indicate that at some locations in the landscape where a very thick bed or series of thick beds is directly under a thinly bedded rock, hillslope geometry appears concave, reminiscent of the outcomes seen in Perne's modelling results (Perne et al; 2017). At contacts where competent bedrock is just below thin and weaker bedrock, the erosional signal from base level fall appears to have eroded into the hillslope. 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 convex. This morphology is most apparent in LC3.1 and LC3.2, where the presence of very thick beds just below beds which are few, and where they are mapped, are thin. Here, it appears as if the direction of erosion is oriented into the hillslope and a distinctive nick point is formed in the landscape. In LC3.3 and LC3.4, where the contact between thick and thin beds is less pronounced, the hillslopes are convex from the channel to the hillslope. In contrast to LC3, LC1 features relatively thick beds at similar elevations for all three of the transects and a section just above which appears subtly concave. This concavity appears slightly less subtle in LC1.1 and LC1.2 then in LC1.3, where it is essentially non-existent. We believe the shallow section in LC1 to have been eroded flat due to the thin and weak bedrock at the top of the watershed, possibly erasing any past, potentially less subtle, concave hillslope form.

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 convex 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.

# References

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

Brook, M. S., & Tippett, J. M. (2002). The influence of rock mass strength on the form and evolution of deglaciated valley slopes in the English Lake District. Scottish Journal of Geology, 38(1), 15-20.

Matasci, B., Jaboyedoff, M., Loye, A., Pedrazzini, A., Derron, M. H., & Pedrozzi, G. (2015). Impacts of fracturing patterns on the rockfall susceptibility and erosion rate of stratified limestone. Geomorphology, 241, 83-97.

Moore, J. R., Sanders, J. W., Dietrich, W. E., & Glaser, S. D. (2009). Influence of rock mass strength on the erosion rate of alpine cliffs. Earth Surface Processes and Landforms, 34(10), 1339-1352.

Selby, M. J. (1980). A rock mass strength classification for geomorphic purposes: with tests from Antarctica and New Zealand. Zeitschrift für Geomorphologie, 31-51.

Molnar P, RS Anderson, SP Anderson (2007), Tectonics, fracturing of Rock, and erosion. J. Geophys , need to work in ref on bedrock fractures and tectonics. Journal of Geophysical Research: Earth Surface, 112 F3, doi:10.1029/2005JF000433.

Clarke BA, DW Burbank (2011), Quantifying bedrock-fracture patterns within the shallow subsurface: Implications for rock mass strength, bedrock landslides, and erodibility, J. Geophys Res.--Earth Surf, 116, F04009, doi:10.1029/2011JF001987

St. Clair J, S Moon, WS Holbrook, JT Perron, CS Riebe, SJ Martel, B Carr, C Harman, K Singha, D deBrichter (2015), Geophysical imaging reveals topographic stress control of bedrock weathering. Science, 350, 6260, 534-538, doi:10.1126/science.aab2210

Voigtlander JV, MK Clark, D Zekkos, WW Greenwood, SP Anderson, RS Anderson, JW Godt (2017), Strong variation in weathering of layered rock maintains hillslope-scale strength under high precipitation. Earth Surf. Proc. Landforms, 43 6, 1183-1194, doi:10.1002/esp.4290 .

Eppes M-C, R Keanini (2017), Mechanical weathering and rock erosion by climate-dependent subcritical cracking, Reviews of Geophysics 55(2), 470-508, doi:10.1002/2017RG000557

Eppes M-C, GS Hancock, X Chen, J Arey, T Dewers, J Huettenmoser, S Kiessling, F Moser, N Tannu (2018), Rates of subcritical cracking and long-term rock erosion, Geology 46(11), 951-954, doi:10.1130/G45256.1

Forte AM, BJ Yanites, KX Whipple (2016), Complexities of landscape evolution during incision through layered stratigraphy with contrasts in rock strength. Earth Surface Processes and Landforms, 41(12), pp.1736-1757, doi:10.1002/esp.3947

Perne M, MD Covington, EA Thaler, JM Myre (2017), Steady state, erosional continuity, and the topography of landscapes developed in layered rocks, Earth Surface Dynamics, 5(1), pp.85-100, doi:10.5194/esurf-5-85-2017

Mudd, S. M., & Furbish, D. J. (2007). Responses of soil‐mantled hillslopes to transient channel incision rates. Journal of Geophysical Research: Earth Surface, 112(F3).

Hurst, M. D., S. M. Mudd, R. Walcott, M. Attal, and K. Yoo (2012), Using hilltop curvature to derive the spatial distribution of erosion rates, J. Geophys. Res., 117, F02017, doi:10.1029/2011JF002057.

Hurst, M.D., Mudd, S.M., Yoo, K., Attal, M. and Walcott, R., 2013. Influence of lithology on hillslope morphology and response to tectonic forcing in the northern Sierra Nevada of California, Journal of Geophysical Research: Earth Surface, 118(2), 832-851, doi:10.1002/jgrf.20049

Roering, J. J., Perron, J. T., & Kirchner, J. W. (2007). Functional relationships between denudation and hillslope form and relief. Earth and Planetary Science Letters, 264(1-2), 245-258.

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.

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.

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.

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.

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

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.

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.

Polyak VJ, WC McIntosh, N Guven, P Provencio (1998), Age and Origin of Carlsbad Cavern and Related Caves from 40Ar/39Ar of Alunite. Science 279, 1919-1922, doi:10.1126/science.279.5358.1919

Berglund HT, AF Sheehan, MH Murray M Roy, AR Lowry, RS Nerem, F Blume (2012), Distributed deformation across the Rio Grande Rift, Great Plains, and Colorado Plateau, Geology, 40(1), 23-26, doi:10.1130/G32418.1

Schoenbohm, L. M., Whipple, K. X., Burchfiel, B. C., & Chen, L. (2004). Geomorphic constraints on surface uplift, exhumation, and plateau growth in the Red River region, Yunnan Province, China. Geological Society of America Bulletin, 116(7-8), 895-909.

Gallen, S. F., Wegmann, K. W., Frankel, K. L., Hughes, S., Lewis, R. Q., Lyons, N., ... & Witt, A. C. (2011). Hillslope response to knickpoint migration in the Southern Appalachians: implications for the evolution of post‐orogenic landscapes. Earth Surface Processes and Landforms, 36(9), 1254-1267.

Prince, P. S., & Spotila, J. A. (2013). Evidence of transient topographic disequilibrium in a landward passive margin river system: knickpoints and paleo‐landscapes of the New River basin, southern Appalachians. Earth Surface Processes and Landforms, 38(14), 1685-1699.

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.

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.

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