**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, enriching 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. Nonlinear hillslope profiles, traditionally associated with soil-mantled landscapes, can exist 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.*

Understanding the geomorphic evolution of landscapes is essential for deciphering the history and development of landforms. Fort 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 low and high relief surfaces and identifying boundaries between areas of differing erosion rates (Mudd and Furbish, 2007; Hurst et al., 2012). Researchers have used this to explore how landscapes change and mature over time, by analyzing spatial changes in morphology. Here we investigate the interplay between relevant bedrock properties, topographic change, and the evolution of Last Chance Canyon in southern New Mexico. We use the space for time argument to describe how an erosional wave formed as a result of base level fall and was attenuated by thick beds as it propagates upslope, leaving a familiar signal well described by the nonlinear hillslope model etched into a bedrock landscape.

While previous studies have explored landscape transience driven by knickpoints upstream within the channel network, our work introduces a novel perspective by considering the influence of large, exposed beds rather than the nature of the underlying bedrock (Mudd and Furbish, 2007; Hurst et al., 2012). We contend that these substantial beds protect the landscape above them from a erosional wave moving up in elevation, causing the landscape to appear diffuse and shallow above large beds. We propose that, in bedrock landscapes, these ideal conditions exist due to interplay between bedrock properties and the historical context of the landscape. Furthermore, we demonstrate that “ideal” landscapes can exist in arid bedrock landscapes and demonstrate the mechanisms that generate conditions necessary for these relict landscapes to propagate temporally. Our measurements, facilitated by high-resolution drone imagery, provide a visual narrative of the landscape's temporal transformation, offering insights into the broader implications of these findings for our understanding of geomorphic processes and landscape evolution. We seek to elucidate the impact of bed thickness variations on hillslope geometry, the influence of hillslope location- relative to the erosional signal originating at the base of the range- and elevation its form, and the combined effects of these variables on the landscape's morphology.

Throughout this research, we draw upon previous studies that have explored landscape transience and the influence of erosion rates on hillslopes (Schoenbohm et al., 2004; Gallen et al., 2011; Anderson et al., 2012; Prince and Spotila, 2013). We aim to discern whether Last Chance Canyon exhibits patterns of hillslope disturbance, as observed in other landscapes where intensified erosion occurs downstream of channel knickpoints (Mudd and Furbish, 2007; Hurst et al., 2012). Additionally, we consider how perturbations propagate upstream and affect the entire landscape, driven by factors such as drainage area and sediment transport (Whipple and Tucker, 1999; Royden and Perron, 2013; Mudd and Furbish, 2007; Reinhardt et al., 2007; Prince and Spotila, 2013). 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). In summary, our research sets out to advance the field of geomorphology by exploring the role of large beds in landscape evolution, challenging existing paradigms, and enhancing our understanding of geomorphic processes. Through a comprehensive analysis of Last Chance Canyon, we strive to uncover the complexities that govern landform development and contribute to the broader knowledge of landscape dynamics.



**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 low order watersheds, called LC1 and LC3 in Last Chance Canyon, southern New Mexico, USA. We sampled 3 transects in LC1 and 4 transects in LC3 to capture variations in bed thickness and hillslope morphology. Last Chance Canyon has horizontally bedded to near-horizontal bedrock, and it is currently tectonically inactive (Hill, 1987; Hill, 2006). Last Chance Canyon's geological characteristics have been shaped by its Permian-era origins, with interbedded carbonate and siliciclastic bedrock of varying thicknesses deposited in a shallow lagoon behind a reef complex to the south (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). LC3 and LC1 differ notably in terms of elevation and slope. LC1, at a slightly higher elevation, features generally lower slopes, while LC3 displays somewhat steeper slopes. Bed thickness comparisons show similarities between LC1 and LC3, but notably thicker beds are evident in the downstream-most transect of LC3.

In March and May 2018, and in February 2021, we measured depth to saprolite and bedrock in the seven transects (3 in LC1 and 4 in LC3), aligning our measurements with ≈12.2 m contour intervals from USGS topographic contour maps to ensure convenient and unbiased sampling. Both LC1 and LC3 display minimal regolith, with an average depth to saprolite of 5.6 cm and depth to bedrock of 20.1 cm. 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 measure exposed beds on the hillslopes.

We identified inflection points in the landscape first using a map with a 10-meter DEM, where we visually determined places on hillslopes that appeared to be changing from generally high to low sloping areas and noticed that this appeared to be at approximately 16.7 to 21.8 degrees, ultimately adopting a value of 20 degrees as our marker due to the lower resolution of the DEM. We observed that at lower elevation areas, slope was higher, until it started decreasing at elevations which change for the different transects- we interpret these slope breaks to be inflection points where we can bin landscape sections into different categories. Subsequently, with a higher resolution 1-meter DEM, we examined curvature and slope along seven transects. We pinpointed locations with less noisy curvature as areas where the landscape became gentler and potentially relict. The transects exhibited a pattern of decreasing slope from higher to lower slopes, creating a transition zone where slope decreased slightly, typically below 20 degrees, before increasing again. Above this second inflection point, slope decreased steadily, indicating a diffuse section. For each transect, we identified two inflection points (arrows on figure 2): one where slope shifted from higher to intermediate values and another where slope decreased to a lower, more diffuse state.

Our study in Last Chance Canyon, has shown three conclusions that shape the landscapes geometry. Firstly, the variance in bed thickness has a profound impact on hillslope form, with thicker beds diminishing the signal of transience above them and possibly changing the direction of erosion into the hillslopes. Second, the hillslope's location within the landscape engenders distinct forms, with lower elevation hillslopes and hillslopes with greater drainage areas bearing the more pronounced imprint of the erosional wave resulting from base level fall. Lastly, the combined influence of these factors drives the intricate morphology of the hillslopes: Thick beds inhibit and redirect the erosional wave 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 erosional wave's direction of movement as governed by thick beds.

A graph with lines and dots

Description automatically generated with medium confidence

**Figure 2 - a. Slope map of Last Chance canyon with values plotted across it. The contour lines correspond to elevations which are interpreted as approximate inflection points for hill and channel slope (1550m for LC 3 and 1640m for LC 1). b. Percentage of slope values from the hillslopes in LC3 and LC1. c. Cumulative frequency plots of bed thicknesses from the 4 surveyed hillslope transects on LC3 and the 3 surveyed hillslope transects on LC1. CHANGE OUTLINE OF LC3 SAME AS SLOPE VALUE**

The presence of substantial beds significantly impacts the inflection points and hillslope morphology in Last Chance Canyon. 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 relict 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. 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.

A collage of snow covered mountains

Description automatically generated

**Figure 3 - a. Slope map of Last Chance canyon with values plotted across it. The contour lines correspond to elevations which are interpreted as approximate inflection points for hill and channel slope (1550m for LC 3 and 1640m for LC 1). b. Percentage of slope values from the hillslopes in LC3 and LC1. c. Cumulative frequency plots of bed thicknesses from the 4 surveyed hillslope transects on LC3 and the 3 surveyed hillslope transects on LC1. CHANGE OUTLINE OF LC3 SAME AS SLOPE VALUE**

Due to the substantial 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. 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 lower inflection point is situated at a higher elevation, around 1660 meters. This configuration results in an angled landscape in LC3, the angle being dictated by the elevations of the lower inflection points. In contrast to LC3, LC1 presents a distinct scenario. LC1 lacks the presence of large, competent beds at its base, and as a result, the erosional wave has managed to propagate nearer to the ridgeline in all three of its transects. There is a 15.73 m bed at the very base of the most downstream transect in LC1, but its location speaks to it being recently exposed on the landscape and it’s signal has likely not yet been expressed on the landscape. It's also worth noting that the transects in LC1 are relatively closer together and at similar elevations when compared to the transects in LC3. This proximity indicates a similar history for the three transects, and the lack of large beds at the scale of the one in LC3 has allowed the erosional wave to travel upward, 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.

What sets LC3 apart is the 1) presence of a very large bed near the base of the watershed, and 2) the longer length that the erosional wave has had to move across relative to LC1. The lower inflection points in LC3 create a relatively linear angle angled upwards in elevation, moving progressively from lower to higher elevations across the watershed. Conversely, the upper inflection points in LC3 exhibit a non-linear angle, curving and flattening as you move from upstream to downstream. This observation can be attributed to the presence of larger bed thicknesses in the lower elevation sections of LC3. 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 downstream sections or transects of LC3. In contrast, in the upstream part of LC3, the beds are not as substantial, and the erosional wave, while diffused by the time it reaches them, propagates only a short distance upstream of the beds.

There is a clear relationship between the thickness of the beds below the lower inflection point and the vertical distance between the lower and upper inflection points. When larger beds are present below the lower inflection point, the vertical separation between the upper and lower inflection points tends to be greater. This occurs because substantial beds are typically situated at lower elevations, causing the erosional wave to cross them and ascend until it eventually reaches and halts at the upper inflection point. 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.

The bed thickness below the lower inflection point attenuates the erosional signal at elevations above it, leading to the lower inflection point being at a lower elevation. In contrast, the thickness of the bed below the upper inflection point alters the angle between the two inflection points. Thicker beds result in a larger angle, while thinner or absent beds lead to a smaller angle. The maximum angle observed in our study is 0.4 degrees. This change in angle is a consequence of the interaction between bed thickness and the erosional wave above the lower inflection point, where the wave has already been attenuated. 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 at a bed just below the upper inflection point. The size of the bed below the upper inflection point affects the angle between the inflection points, resulting in a greater angle when a thicker bed is present. Where there are no measured beds below the upper inflection point, at 1654 m elevation at the farthest downstream transect in LC1 and one at 1613 m elevation in the second transect upstream in LC3, this represents the farthest the erosional wave has propagated before “petering out” of its own accord and with no input from a thick bed.

As the erosional wave advances from the base of the range towards its summit due to base level fall, it encounters these beds. When it encounters more resistant or competent beds, the wave diffuses, making the erosional signal less apparent at elevations beyond the reach of these competent, large, and thick beds.­­­­ Beyond the upper inflection point, the signal from the erosional wave dissipates. This outcome is influenced by the hillslope's location in the landscape and the extent to which the erosional wave has been able to ascend in elevation. The thickness of the beds it encounters plays a critical role in this process. In our specific landscape, 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. At this juncture, the wave is attenuated and eventually ceases at the upper inflection point. The vertical distance between the upper and lower inflection points is greater when the erosional wave has not encountered substantial beds, as these beds reduce the impact and imprint of the erosional wave on hillslope form.

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 in the canyon are characterized by steeper, higher-gradient slopes while the upper inflection points 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 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. Simultaneously, its intensity is influenced by the increase in alluvial material contributed by the hillslopes as it moves upstream. 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. The diffuse hillslopes at the top of Last Chance Canyon have a base level that is pinned by the thick beds downslope of them. Together, these findings highlight the complex interplay of bed thickness, hillslope positioning, and the erosional wave in shaping hillslope morphology, providing valuable insights into the processes that drive hillslope dynamics within this unique landscape.

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