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

Sam Anderson1, Nicole Gasparini1, Joel Johnson2, Grace Guryan2, Sophia Brieler1, Mikey Sison2

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](mailto:sanderson@tulane.edu))

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

*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, adopt a convex diffusive shape above an adjusting section of the landscape despite limited regolith, a unique departure from traditional expectations. We propose that variations in bedrock bed thickness significantly influence hillslope configuration, and enable relict and low sloping parts of the landscape to exist despite base level fall. Thinner bedrock fosters a diffusive geometry akin to the idealized convex hillslopes found in soil-mantled landscapes, and thicker bedrock inhibits erosional signal propagating upslope due to baselevel fall. Leveraging high-resolution drone imagery, we constructed orthomosaics and digital surface models (DSMs) for seven hillslope transects in two headwater catchments. Our measurements of bed thicknesses, slope, and curvature demonstrate the control that bedrock properties and uplift have on hillslope geometry. Of notable significance is the role of large beds in engendering inflection points across the landscape. These inflection points enable or blur the signal base level fall has on landscape morphology, depending on bed competency and proximity to the erosional signal originating at the base of the mountains.*

The field of geomorphology has long been driven by a quest to understand the temporal evolution of landscapes. Within this context, the concept of "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 involves discerning transitions between low and high relief surfaces, identifying boundaries between areas of differing erosion rates (Mudd and Furbish, 2007; Hurst et al., 2012). Understanding the geomorphic evolution of landscapes is essential for deciphering the history and development of landforms. Researchers have often employed this "space-for-time substitution" to explore how landscapes change and mature over time. This method relies on the spatial progression of landforms, a pattern that transitions from "young to old" under specific environmental conditions. 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 is attenuated by thick beds as it propagates upslope, leaving a unique signal etched into the 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 upslope moving erosional wave, causing the landscape to appear diffuse and shallow above large enough beds. Our measurements, facilitated by high-resolution drone imagery, provide a visual narrative of the landscape's transformation, offering insights into the broader implications of these findings for our understanding of geomorphic processes and landscape evolution. Our research raises several key questions and challenges prior work in this territory. 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.

As we delve into the geomorphology of Last Chance Canyon, we are motivated by a quest to unveil evidence of landscape transience across multiple hillslopes. Our primary focus is on the concept of "ideality" in hillslope morphology, where specific points on the landscape appear to exhibit idealized states used to describe the form of soil mantled landscapes. We propose that, in bedrock landscapes, these ideal conditions exist due to interplay between bedrock properties and the historical context of the landscape. Here, we challenge conventional paradigms in the field of geomorphology by demonstrating that the presence of large beds, rather than the nature of the underlying bedrock, significantly influences the "ideality" 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 diffuse relict landscapes to propagate temporally.

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.

A close-up of a map

Description automatically generated

**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.**

In Last Chance Canyon, situated in the Guadalupe Mountains of southern New Mexico, USA, our fieldwork concentrated on seven hillslope transects within two distinct watersheds, LC1 and LC3 (comprising 3 transects in LC1 and 4 transects in LC3). These carefully selected transects were instrumental in capturing variations in bed thickness and hillslope morphology across the two watersheds. Despite minimal climate variations in this limited spatial area and within the range of vertical elevations, Last Chance Canyon features horizontally bedded to near-horizontal bedrock, and it remains tectonically inactive according to Hill (1987) and Hill (2006). This geological landscape has its roots in the Permian era, with the presence of a shallow lagoon behind a southern reef complex, resulting in the deposition of interbedded carbonate and siliciclastic bedrock of varying thicknesses, as documented by Hill (2000), Phelps et al. (2008), and Kerans et al. (2017). The Guadalupe Mountains experienced uplift during basin and range extension approximately 27 million years ago, revealing previously buried bedrock, as noted by Chapin and Cather (1994), Ricketts et al. (2014), Hoffman (2014), and Decker et al. (2018). Unfortunately, rock unit descriptions in published maps lack the essential data necessary to constrain bed thickness (NPS, 2007). In Last Chance Canyon tributaries, higher elevation sections exhibit relatively lower gradient hillslopes, while downslope areas are characterized by steep hillslopes.

I selected the inflection point of 20 based on a lower-resolution slope map, where the transition from darker colors (indicating higher slopes) to lighter colors (representing shallower slopes) was notably distinct on many of the transects. This transition demarcated the shift from slopes less than 16.7 to those less than 21.8. I opted for the value 20 due to its proximity to 21.8 while being a whole number, simplifying the analysis. In the map, we can observe the two distinct watersheds: LC1 and LC3. Within LC3, we conducted measurements on four distinct hillslope transects. On the other hand, LC1 saw measurements taken from three hillslope transects. These two watersheds exhibit notable differences. Firstly, LC1 lies at a slightly higher elevation compared to LC3. This elevation disparity is reflected in the slope distribution, with LC1 generally having lower slopes, as evident in the slope distribution plot. Conversely, LC3 presents slightly steeper slopes. Additionally, the comparison of bed thicknesses reveals interesting distinctions between the two watersheds. Initially, bed thicknesses in LC1 might appear to be similar to those in LC3. However, a crucial difference becomes apparent when we examine the downstream-most transect in LC3, where bed thicknesses are significantly larger and thicker.

We used a 1 m digital elevation model (DEM) of Last Chance canyon to identify hillslopes of interest to survey, as well as channels at the base of the hillslopes. We calculated hillslope transects, slope, and curvature for 7 hillslopes and slope breaks along stream profiles at the base of the 7 hillslope transects (USGS, 2019).

In March and May of 2018, and in February of 2021, we surveyed 7 hillslope transects which we had preselected based on previous fieldwork, DEM analysis, mapped geology, and accessibility. Our investigation started in lower order channels and proximal hillslopes at elevations above 1400 m in channel LC3 and in elevations above 1500 in channel LC1 (map figure). USGS topographic contour maps of the field area use a 40 ft (≈12.2 m) contour interval. Following these maps for convenience and to ensure unbiased sampling, at every ≈12.2 m contour interval we measured the depth to both saprolite and bedrock along the 7 hillslope transects.

We used a drone, DJI Mavic 2 pro, to take photos of the 7 hillslope transects at approximately 20 meters above the highest elevation of the 7 hillslope transects. We 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 used Agisoft Photoscan (Agisoft PhotoScan Professional, 2018) to generate high resolution orthomosaics and DSMs first by aligning the frames from the GoPro videos, then building a dense cloud, then creating a DEM and finally making an orthomosaic.

# 4 Results

Our study in Last Chance Canyon, has revealed three pivotal conclusions that shape the region's hillslope geometry. Firstly, the variance in bed thickness has a profound impact on hillslope form, with thicker beds inducing notable alterations. Second, the hillslope's location within the landscape engenders distinct forms, with lower elevation hillslopes 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, particularly in areas where substantial beds inhibit and redirect the erosional wave as it progresses upslope. These conclusions underscore the intricate interplay between bed thickness, hillslope positioning, and the erosional wave's behavior, providing key insights into the genesis of hillslope morphology in Last Chance Canyon. This study offers a comprehensive understanding of the landscape's dynamics and enhances our knowledge of how bed thickness and hillslope location act as critical drivers in shaping the topography of the region.

The configuration of hillslopes within Last Chance Canyon varies significantly between LC1 and LC3 watersheds. LC3 exhibits diffuse upslope segments with lower gradient hillslopes that transition to a downslope region characterized by steeper hillslopes. In contrast, LC1 generally features shallower hillslopes compared to LC3, and this transition is more subtly pronounced in LC1. 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.

The presence of large beds significantly influences the inflection points and hillslope form in Last Chance Canyon. In LC3, an approximately 18-meter-thick bed near the base of the watershed obstructs the erosional wave's progress, resulting in steeper inflection points. In LC1, where relatively thick beds are located at similar elevations, the inflection points exhibit gentler slopes. These beds have a significant impact on the hillslope configuration, with the erosional wave behavior being a key factor.

Hillslope form exhibits distinctive characteristics above and below the inflection points. Below the lower inflection point, the hillslope appears steep and adjusting, reflecting the erosional wave's active influence. Above the upper inflection point, the landscape retains a relict quality and showcases lower slopes, resembling the pre-base level fall topography. The thickness of the beds below the lower and upper inflection points affects the elevation and angle between these inflection points.

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.

In summary, our research in Last Chance Canyon highlights the complex interplay of bed thickness, hillslope positioning, and the erosional wave in shaping hillslope morphology. This study contributes to a deeper understanding of landscape evolution and the critical role played by bedrock characteristics and location in influencing topographic features. These findings challenge conventional geomorphic paradigms and offer valuable insights into the processes driving hillslope dynamics in this unique landscape.

# 5 Discussion

In our study of Last Chance Canyon, employing the concept of space-for-time substitution, we have arrived at three pivotal conclusions that significantly influence the region's hillslope geometry. First and foremost, the variance in bed thickness emerges as a critical driver of hillslope form. Notably, thicker beds lead to distinct alterations in hillslope configuration. Second, the location of hillslopes within the broader landscape plays a crucial role in determining their unique forms. Hillslopes positioned at lower elevations bear a more pronounced imprint of the erosional wave resulting from base level fall, translating the spatial distribution into temporal development. Lastly, the combined influence of these factors generates the intricate morphology of the hillslopes, particularly in areas where substantial beds obstruct and redirect the erosional wave as it advances upslope.

The significant findings of our research shed light on the intricate relationship between bed thickness, hillslope location, and the behavior of the erosional wave. These findings underscore the pivotal role of bedrock characteristics and hillslope positioning in shaping the topography of Last Chance Canyon.

The implications of our study are substantial, as they offer valuable insights into the genesis of hillslope morphology. By identifying the key factors that influence hillslope form, we contribute to a deeper understanding of landscape evolution. The presence of substantial beds at lower elevations leads to steeper, adjusting slopes, reflecting the influence of base level fall. The interaction between the erosional wave and these beds causes the wave to diffuse and ultimately cease its influence at the upper inflection point.

Understanding the interplay between bed thickness, hillslope positioning, and the erosional wave has far-reaching consequences for the field of geomorphology. This knowledge challenges conventional paradigms and provides a more nuanced understanding of how landscapes develop and change over time.

However, it's essential to acknowledge the limitations of our study. While we've gained valuable insights into hillslope form, our research focuses on a specific landscape, Last Chance Canyon. Therefore, the generalizability of our findings to other regions may require further investigation. Additionally, our study does not delve into the precise mechanisms behind the erosion and adjustment processes. Further research is needed to understand the specific erosional dynamics in these landscapes.

As we look to the future, our findings open up exciting avenues for further studies and analyses. Researchers could explore the relationship between bed thickness and hillslope form in different geological settings and landscapes. Comparative studies in various regions would help validate and refine the concepts elucidated in our research. Additionally, investigating the underlying processes that drive the interaction between beds and the erosional wave will provide a more comprehensive understanding of landscape evolution.

In conclusion, our study in Last Chance Canyon has uncovered the intricate connections between bed thickness, hillslope location, and the behavior of the erosional wave, shedding light on the genesis of hillslope morphology. By identifying these key factors and their influence, we have enhanced our understanding of how landscapes evolve over time, contributing to the broader field of geomorphology and providing a foundation for future research in this area.

**random**

Last Chance Canyon exhibits diffuse upslope segments with lower gradient hillslopes, transitioning to a downslope region characterized by steeper hillslopes (see map figure 2). LC1 generally features shallower hillslopes compared to LC3. Analysis of channel steepness maps and field observations reveals that the hillslopes shift from steep to shallow at approximately 1640 m along channel LC1 and around 1550 m along channel LC3. This transition is more subtly pronounced in LC1. Notably, both LC1 and LC3 display minimal regolith, with an average depth to saprolite of 5.6 cm (standard deviation = 5.3 cm) and depth to bedrock of 20.1 cm (standard deviation = 15.5 cm).In this figure, we present a visual representation of bed distributions across seven hillslope transects. To accomplish this, we utilized digital surface models (DSMs) derived from drone imagery to identify and measure bed locations on the hillslopes. These transects encompass four hillslopes within the LC3 watershed and three within the LC1 watershed.

Additionally, we harnessed slope measurements from a 1-meter digital elevation model (DEM) provided by the USGS, and we conducted curvature measurements on the same 1-meter DEM. The purpose of these measurements was to pinpoint inflection points, marked by arrows in the figure. Each transect exhibited two inflection points: one at a lower elevation and another at a higher elevation.

It's noteworthy that LC3 differs from LC1 due to the presence of a substantial, approximately 18-meter-thick bed near the base of the watershed at an elevation of 15140 meters. This prominent bed acts as a barrier to the erosional wave, which is ascending the channel due to base level fall. As a result, the inflection points in LC3 exhibit steeper angles, reflecting the fact that the erosional wave has not yet reached the uppermost region of the watershed.

In contrast, LC1 features a relatively thick bed of about 5 meters near an elevation of 16140 meters on all three of the hill sub-transects. The existence of these beds in LC1 leads to the generation of inflection points at approximately the same elevation.

We utilized drone imagery to generate high-resolution orthomosaics for the seven transects distributed across the two watersheds, comprising three transects in LC1 and four in LC3. These orthomosaics were subsequently employed to measure bed thicknesses across all seven transects. Of particular note, within LC3, a notably substantial bed measuring approximately 20 meters in thickness was identified, positioned at an elevation ranging from 1530 to 1540 meters. This bed consists of two distinct layers, rendering it a significant geological feature. Directly above this thick bed, a discernible nick point has formed along the transect, marking a transition to a gentler, lower slope, with evidence of erosional activity into the hill slope just above the thick bed. Conversely, below this bed, the terrain becomes markedly steeper. The bed's significance lies in the geological history of the landscape, which involves base level fall as a consequence of mountain uplift. As these mountains rose, a wave of erosion propagated from the base of the range to higher elevations. Our analysis suggests that this erosional wave, upon encountering the exceptionally thick bed in the downstream-most transect of LC3, became obstructed, thereby inhibiting or diffusing the erosional signal at elevations above this bed, and, for clarification, this significant bed is situated between 1530 and 1540 meters in elevation within LC3.

Below the lower inflection point in all seven transects, a steeper, higher-gradient segment of the hillslope is evident, indicative of active adjustment in response to the erosional wave's upstream progression. At the first inflection point, the wave of erosion appears to have encountered an obstruction, causing it to stall temporarily while still managing to progress beyond this point, albeit with some diffusion. Below the first inflection point, the landscape retains its steep and adjusting character. Moving to elevations higher than the first inflection point but lower than the second inflection point, the lingering influence of the erosional wave, though diffused, is observable. Above the second inflection point, representing the higher elevation inflection point, the landscape features lower slopes and carries a relict quality, seemingly preserved and harking back to the landscape prior to the onset of base-level fall.

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. In contrast, at the top of LC3, the lower inflection point is situated at a higher elevation, around 1600 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, incompetent beds at its base, and as a result, the erosional wave has managed to propagate almost to the summit of all three of its transects. It's worth noting that these transects are relatively closer together and at similar elevations when compared to the transects in LC3. This proximity has allowed the erosional wave to travel upward, and the signal is consistently inhibited at approximately the same elevation for the three transects.

The configuration of hillslopes within Last Chance Canyon in our study area is intricately influenced by a range of dynamic variables and processes. Notably, two primary determinants of hillslope form are bed thickness and the placement of substantial beds along a hillslope transect. Additionally, the specific position of a hillslope transect, whether it is situated upstream or downstream, plays a pivotal role in shaping hillslope geometry. Lower elevation hillslopes bear a more pronounced imprint from the erosional wave's signal, which has moved upslope over time due to base level fall, effectively translating spatial distribution into temporal development. These lower elevation hillslopes exhibit a more prominent response to the erosional wave. LC3 introduces a unique aspect with its lower elevation hillslopes featuring substantial beds at their bases, which have modified the behavior of the erosional wave and its impact on hillslope form. In LC3, the erosional wave progresses upslope from lower elevations until it encounters a significant bed. At this juncture, the wave's direction is altered, prompting it to erode into the hillslope and form a distinctive nick point in the landscape.

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 phenomenon 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.

The key factor here is 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.

In LC1, the angle of the landscape is notably gentler. This is primarily because all the inflection points, both the lower and upper inflection points, align closely with a similar elevation.

What sets LC3 apart is the distinct nature of its landscape. The lower inflection points in LC3 create a relatively linear angle, 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.

The influence of bed thickness on hill slope geometry extends beyond just the bed below the lower inflection point. The thickness of the bed below the upper inflection point also has a distinct impact on hillslope form, albeit in a different manner.

In the case of the bed below the lower inflection point, its thickness inhibits the erosional wave and attenuates its signal at elevations above the lower inflection point. This results in the lower inflection point being positioned at a lower elevation than it would be in the absence of a large bed below it.

Conversely, the thickness of the bed below the upper inflection point causes a change in the angle between the two inflection points. When a thick bed is present below the upper inflection point, in contrast to a thinner or absent bed, the angle between the lower and upper inflection points increases. The maximum angle observed in our study is 0.4 degrees. When the bed below the upper inflection point is thin or non-existent, the angle between the two inflection points is smaller than it would be with a thicker bed.

Now, let's delve into the implications of these observations for hillslope geometry and how varying bed thickness affects this geometry. 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.

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 significantly affects the angle between the inflection points, resulting in a greater angle when a thicker bed is present.

Space-for-time substitution is a concept frequently employed in geomorphological research to understand how landscapes evolve over time. It's based on the idea that under specific natural environmental conditions, landforms tend to exhibit a spatial pattern where younger landforms are located closer to the source or point of origin, and older landforms are found further away. By sampling geomorphic types and characteristics in a spatial sequence, researchers can infer the temporal evolution of a landscape.

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, you 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.

## 

## 6 Conclusions

We present several observations about the effects of bed thickness on landscape form in hillslopes and proximal tributaries of Last Chance canyon. We suggest that bed thickness influences hillslope processes. Areas on a hillslope with relatively thick beds cause hillslopes to straighten and steepen below them. Conversely, hillslopes appear diffuse above these areas of exposed and thick beds.

Finally, we interpret that the large beds diminish the erosional signal at higher elevations from base level fall. The more diffuse hillslopes at the top of Last Chance canyon have a base level that is pinned by the thick beds downslope of them.

An erosional wave progressing through a horizontally bedded landscape encounters challenges when reaching large beds (maximum or cumulative bed thickness) and tends to lose its intensity as it becomes 'stuck' on beds further downstream. Simultaneously, its intensity is influenced by the increase in alluvial material contributed by the hillslopes to the channels as it moves upstream. The presence of this erosional wave prompts the horizontal landscape to react in a manner where the inflection point between the relict and adjusting topography is not horizontally uniform but instead orients positively with diminishing drainage area and/or increasing distance upstream. Consequently, the natural curvature change across a hillslope is impacted in varying ways as one progresses upstream.

Exploring the nuanced impact of bed thickness on the damping of erosional wave signals, we seek to quantitatively assess how this influence operates, even when considered in relative terms. This influence can be attributed to two primary factors: the bed itself and the size of sediment contributed to the channel. A significant observation suggests that variations in bed thickness may, in part, alter the angle, potentially intensifying the slope. This phenomenon is exemplified by the distinction between LC1 and LC3, where LC1 exhibits an inflection point at approximately 1640, consistent with findings in a prior study. Moreover, the effect of bed thickness is likely to exhibit temporal variability. When the erosional wave encounters a bed, the magnitude of its hindrance increases as the bed approaches the channel. This is due to the extended distance sediment must traverse from the hillslope to the channel, resulting in thicker sediment deposits.

Upon analyzing the landscape profiles, it becomes evident that erosional waves propagating up a horizontally bedded terrain tend to encounter obstacles in the form of substantial beds along their path. Notably, maximum or total bed thickness emerges as a promising proxy measurement for these impediments. As the erosional wave progresses upstream and becomes "hung up" on these beds, its intensity diminishes, especially as it confronts beds located closer to the channels. The increased distance that sediment must travel from the hillslope to the channel results in thicker sediment deposits, further exacerbating the wave's deceleration. Simultaneously, the wave's intensity is modulated by the greater volume of alluvium supplied by the hillslopes to the channels during its upstream journey. This dynamic presence of the erosional wave seems to induce an uneven response in the horizontal landscape. The inflection point, marking the transition from relict to adjusting topography, is not uniformly distributed but instead orients positively with diminishing drainage area and increasing distance upstream. As a consequence, natural curvature changes along the hillslope, leading to varying degrees of diffusion at different elevations across the landscape. While exploring these dynamics, one intriguing avenue for further investigation lies in assessing how bed thickness dampens the wave's signal, even in relative terms. This damping effect likely results from two key factors: the competency of the bed itself and the size of the sediment contributed to the channel. The location and size of the largest bed along the hillslope transect, such as LC3.3, may significantly influence the elevation of the inflection point between relict and adjusting topography upstream of the bed. This notion is further supported by differences between LC1 and LC3, where LC1 exhibits minimal changes in inflection point elevation (approximately 1640m), similar to findings in a prior study, while LC3 displays a substantial difference (1560m downstream to 1660m upstream). Intriguingly, LC3.3, the farthest downstream transect, features notable large beds in the adjusting section, paralleled by similar characteristics in LC1.1, 1.2, and 1.3, with LC1.4 also displaying comparatively substantial beds distributed across its span. This complex interplay in bed characteristics suggests a correlation with the limited elevation change in LC1's inflection point. Further clarification and visualization in the form of schematics and plots are warranted to comprehensively elucidate this intricate landscape evolution.

In summary, our exploration of Last Chance Canyon's hillslope geometry within the context of space for time has yielded three critical conclusions. Firstly, the variability in bed thickness exerts a significant influence on 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. Lastly, when we combine these two factors, we observe a dynamic interplay that shapes hillslope morphology. In particular, larger beds at lower elevations inhibit and alter 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.

# 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.

Mikey code https://github.com/mikafur32/PebbleCounts-Application-UI-and-Excel-Compiler/tree/main

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