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

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Evaluating the effect of multiple processes on the hillslope form requires

"In the intricate tapestry of Earth's surface, the enigmatic sculpting of hillslopes stands as a testament to the dynamic interplay of bedrock properties, sediment processes, and landscape evolution, casting a profound influence on our understanding of geomorphological phenomena."

Here, we explore the effect that variations in hillslope bed thickness have on hillslope form in Last Chance canyon, New Mexico, USA. The landscape is composed of horizontally bedded rock. The hillslopes have relatively little regolith, yet most hillslopes have a convex diffusive shape despite the lack of continuous soil cover. We posit that differences in bedrock bed thickness influence hillslope shape in Last Chance canyon, where thinner bedrock generates a more diffusive geometry resembling the idealised convex hillslope shape endemic of soil mantled landscapes. We used drone photos to construct high resolution orthomosaics and digital surface models (DSMs) of seven hillslope transects from two headwater catchments. Using these DSMs and orthomosaics, we measured bed thicknesses, slope, and curvature on the hillslopes. We find that hillslopes are steeper and less convex where there is more thickly bedded rock and become shallower and convex in thinly bedded rock. These observations suggest a tight coupling between hillslope bedrock properties, hillslope form, channel grain size distribution, and channel steepness.

recognition of the potential for strong dynamic coupling between atmospheric and tectonic processes has sparked intense cross disciplinary investigation and debate on the question of whether tectonics have driven long-term climate change or vice versa.

Evaluating conflicting theories about the influence of mountains on carbon dioxide cycling and climate requires understanding weathering fluxes from tectonically uplifting landscapes. The lack of soil production and weathering rate measurements in Earth’s most rapidly uplifting mountains has made it difficult to determine whether weathering rates increase or decline in response to rapid erosion. Beryllium-10 concentrations in soils from the western Southern Alps, New Zealand, demonstrate that soil is produced from bedrock more rapidly than previously recognized, at rates up to 2.5 millimeters per year. Weathering intensity data further indicate that soil chemical denudation rates increase proportionally with erosion rates. These high weathering rates support the view that mountains play a key role in global-scale chemical weathering and thus have potentially important implications for the global carbon cycle.

# 2 Field Area

We conducted fieldwork in Last Chance Canyon, located in the Guadalupe Mountains of southern New Mexico, USA. Because of their morphology and accessibility, we collected data along 2 different tributaries, called LC1 and LC3 (figure 1), and seven different hillslope transects that terminate at the base of each of the 2 stream channels (3 transects in the LC1 watershed and 4 transects in the LC3 watershed). These transects were chosen to capture variations in bed thickness and hillslope shape across the two watersheds. By examining the influence of bed thickness on hillslope form and sediment input to channels, we aim to better understand how changes in bed thickness correlate with boulder characteristics, stream channel shape, hillslope form and the morphology of Last Chance Canyon. Over the small spatial area and range of vertical elevations of the specific study channels, climate varies minimally. Last Chance Canyon has horizontally to near horizontally bedded bedrock and is currently tectonically inactive (Hill, 1987; Hill, 2006). During Permian time, a shallow lagoon existed behind a reef complex to the south and deposited what would become interbedded carbonate and siliciclastic bedrock of various thicknesses (Hill, 2000; Phelps et al., 2008; Kerans et al., 2017). The Guadalupe mountains were uplifted during basin and range extension beginning 27 million years ago, exposing the previously buried bedrock (Chapin and Cather, 1994; Ricketts et al.., 2014, Hoffman, 2014; Decker et al., 2018). Rock unit descriptions from published maps lack the relevant information needed to constrain bed thickness (NPS, 2007).

Last Chance canyon tributaries have upstream sections with relatively shallow channels and lower gradient hillslopes, and a knickzone downstream which has steep channels and hillslopes (map figure 2). LC1 has shallower hillslopes than LC3, and smaller bed thicknesses. Stream channels transition from steep to shallow at approximately 1640 m for channel LC1 and at approximately 1550 m for channel LC3. The transition from steep to shallow is more subtle in LC1.

I picked the inflection point as 20 because I made a lower resolution slope map where the difference in colors was more obvious. On a lot of the transects there is a distinct line between the darker colors (higher slopes) to lighter colors (shallower slopes) and this was where the slope transitioned from the <16.7 slope to the <21.8 slope. I picked 20 because it was a whole number close to 21.8.

# 3 Methods

## 3.2 DEM Analysis

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).

## 3.3 Field Survey

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.

## 3.4 Drone Based Photogrammetry

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

## 4.1 Last Chance Canyon Morphology

Last Chance canyon has diffuse­ upslope sections and lower gradient hillslopes, and a downslope area which is relatively steep. which has steep hillslopes (map figure 2). LC1 has generally shallower hillslopes than LC3,. Based on channel steepness maps and field observations, we find that hillslopes transition from steep to shallow at approximately 1640 m for channel LC1 and at approximately 1550 m for channel LC3. The transition from steep to shallow is more subtle in LC1- χ changes less than in LC3. Both LC1 and LC3 have relatively little regolith. Both LC1 and LC3 have relatively little regolith. On average the depth to saprolite was 5.6 cm (standard deviation = 5.3 cm) and depth to bedrock was 20.1 cm (standard deviation = 15.5cm). (standard deviation = 5.3 cm) and depth to bedrock was 20.1 cm (standard deviation = 15.5cm).­

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**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 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.

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.­­­­

## 5 Discussion

In Last Chance canyon, hillslopes appear more diffuse in more thinly bedded rock at elevations higher than the thick beds at elevation 1540 m in LC3 and elevation 1640 m in LC1. The term "idealized hillslope" may provide a more accurate descriptor than "diffusive." Furthermore, hillslopes with less variance in bed thickness appear more “idealized”.

Bed thickness varies across the landscape and etches their signal on it’s morphology. In Last Chance canyon, differences in measured bed thickness affect morphology in multiple ways. Here, we introduce three key interpretations from our study. (1) Relatively thick beds cause hillslopes to steepen and straiten downslope of them and thinly bedded areas upslope of thick beds appears diffuse. (3) We interpret that thick beds slow and inhibit the signal from the erosional wave moving up channel as a result of baselevel fall. Thick beds here are inflection points between low sloping and diffuse relict topography above them and steep adjusting topography below them.

## 5.1 Bed Thickness and Hillslope Morphology

Figure with bed thickness mapped across hillslope transects

## 5.3 Do Thick Beds Protect Relict Topography Upslope of Them?

3d schematic, make figure that shows the slope of the inflection point across the landscape and describe it as space for time

We interpret that erosion is inhibited due on the hillslope due to the presence of thick bedrock and in the steep reaches of our study channels due to large boulders and bigger alluvium that we interpret to be immobile.

Our observations further underscore the significance of bed thickness in shaping the overall landscape morphology. The transition from upstream to downstream sections of the landscape, where hillslopes tend to become shallower, aligns with the thinner bedrock beds typically found in upstream regions, as well as smaller sediment and boulders. This systematic variation in bed thickness across the landscape accentuates the concept of hillslope convexity and its dynamic relationship with bedrock properties.

## 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.

10-24-23

I want to relate this back to the landscape. I have a buncha plots which speak to a buncha different things going on, but not a lot of focus. I want to say that HS are “ideal” and appear diffusive above a certain point. Maybe that point is a big bed, or series of beds. What happens at that “inflection point”? I can show that graphically by plotting the transects with beds mapped across them. Maybe it’ll give me focus. After I’ll try and plot curvature and slope down each transect in a cell by cell measurement. Maybe after I can plot some of the metrics above and below that point to show how morphology changes?

I also want to express the effect that drainage area has. Maybe I could frame this as “distance from the inflection pt on the landscape”, or like distance above and below? Or something like that. I want to make the 3d schematic that Nicole drew out, which was oriented up channel at a watershed (schematic, lc 1 or lc3 or both) and draw a line at the infection point. I want to show the difference above and below this point. With this I can justify why the upchannel plots look more diffusive. Here I can say that whether this landscape is bedrocky doesn’t much affect whether it appears diffusive, it’s the max size (or amount of) beds

After this I can say that these large beds produce large sediment which armors the channel below (not above) and so everything below this point is steepend. Maybe steeper HS better transport large sediment downslope as well.

1. Plot out profiles with mapped beds, do curvature and slope measurements (mean, max, etc) above and below a inflection elevation, on windows, total. Find where curve is +, 0, and – and find inflection pts. Find elevation where above which is relict topo (diffusive) and below (adjusting) is it worth plotting the 1m and the drone dsm on the same fig?
   * 1. Make insets of curvature plots (curve on y axis, distance from channel on the x)
     2. Curvature is too messy, the 10m DEM didn’t work. Maybe I can use std dev, or when figure gets “messy”. Another workaround is plotting beds on a elevation profile and using that.
   1. Try and find a trend to see if these elevations change with drainage area
   2. Make more profiles and/or clip the DEM and get curvature values above and below between these elevations
   3. For example, elevation on y axis, curvature on x, lines separating elevation inflection pts- plot all curve values and see if they fit into bins. Then, do a multivariate t test to see if the populations are different
2. Make 3d map of the two watersheds with inflections drawn on
3. Re evaluate and potentially remake the weird curvature figure but make it above and below inflection points
   1. For example, remake the figure but adjust the r^2 and m values only using curvature values above the elevation where topo is relict (diffuse)

Also, I want some pics of the holes I dug to show how little regolith is here.

1. Make profiles all with same axis values
2. Map beds across each
3. Make figure with curvature on y and distance from channel on x (all axis will be the same)
   1. This will be an inset maybe
4. Use the combo of this data to identify inflection points to determine the following
   1. Elevation above which topo is relict and diffusive
   2. Elevations above which curvature is -, 0 and + respectively
5. Clip dem above/blow inflection of relic and adjusting elevation,
6. Bin curvature by elevations below + inflection, at 0, and above - curve values
7. Make plots

Some thoughts. A erosional wave will move up a horizontally bedded landscape and get “hung up” on large beds (max or total bed thickness as it moves). The intensity of the wave will diminish as it moves and gets ‘stuck’ on beds farther downstream. Also, its intensity will get modulated by the increase in alluvium contributed by the HS to the channels as it moves upstream. I think the presence of the wave will cause a horizontal landscape to respond in way where inflection point between the reliect and adjusting topography is not horizontal across the landscape, but is oriented in a positive direction with decreases in drainage area and/or increases in distance upstream. Because of this, natural curvature change across a hillslope is affected differently as one moves upstream

1. Is there a way to show how much the thickness of a bed can dampen the signal from the wave, even if its relative?
   1. It will do it in 2 ways, one via the bed itself, and the other by the size of the sediment the bed contributes to the channel.
      1. Maybe the bed thickness will change the angle, making it more steep. The difference between LC1 and LC3 expresses this (the inflection of LC1 is approx. 1640, same as paper 1)
   2. Also, this will vary with time, when the wave hits the bed it will be more hung up the close the bed is to the channel, as the distance the sediment has to travel from the hillslope to the channel will be longer and the sediment will be thicker

Some thoughts after looking at the profiles…. A erosional wave will move up a horizontally bedded landscape and get “hung up” on large beds (maybe max or total bed thickness is a good proxy measurement for this) as it moves upstream. The intensity of the wave will diminish as it moves and gets ‘stuck’ on beds farther downstream. This will vary spatially and temporally, when the wave hits a big ol bed it will be more hung up the closer the bed is to the channel, as the distance the sediment has to travel from the hillslope to the channel will be longer and the sediment will be thicker.(not exactly sure what this means, but most of this text is spot on to me. I know it’s a draft but I like the direction) Also, its intensity of the erosional wave will get modulated by more alluvium contributed by the HS to the channels as it moves upstream. I think the presence of the wave will cause a horizontal landscape to respond in way where inflection point between the reliect and adjusting topography is not horizontal across the landscape, but is oriented in a positive direction with decreases in drainage area and increases in distance upstream. Because of this, natural curvature change across a hillslope is affected differently as one moves upstream, where hillslopes will begin to look more diffuse at different elevations across the landscape. Take it in this direction! I love this.

Is there a way to show how much the thickness of a bed can dampen the signal from the wave, even if its relative? I think It will do it in 2 ways, one via the bed competency itself, and the other by the size of the sediment the bed contributes to the channel. Maybe something about the presence of beds ( maybe max or total bed thickness this seems the most likely to work to me) will change the elevation of the inflection point between relict and adjusting topo is upstream of the bed, where a thicker bed will cause the erosional wave to get “more hung up” yes and then make the next inflection point upstream to be at a higher elevation. (not sure I’m following. Do you mean that if there is a big bed in the hillslope, the erosion wave will get stuck on it, so the inflection point on the hillslope will be closer to that big bed? ) Maybe it could be the position of the largest bed is along the HS transect. Seemingly the difference between the inflection points in LC1 and LC3 expresses this (the inflection of LC1 is approx. 1640, same as paper 1) with very little difference between the elevation of downstream (1640m) and upstream inflection (1660-1670m). where in LC3, the difference is large (1560 downstream to 1660 upstream). A cursory look at the bed thickesses shows that LC3.3 (the farthest downstream transect) has some big ol beds in the adjusting section. 1.1, 1.2, and 1.3 do as well (and 1.4 has some bigish ones spaced across it. Maybe this is why lc1 doesn’t have much of a change in elevation in inflection pt? IDK, Im rambling now. (I’m a bit lost in this, but I like where you are going. I think I need a schematic/plots to help me through this. You are unraveling the landscape.)

From mudd- detection of transieince

many cases, one might wish to look for evidence of landscape transience across multiple hillslopes. One strategy is to look for a transition between low relief and high relief surfaces, which may be interpreted as separating slowly eroding from rapidly eroding portions of the landscape (e.g. Schoenbohm et al., 2004; Gallen et al., 2011; Anderson et al., 2012; Prince and Spotila, 2013). If changes in hillslope erosion rates are driven by the propagation of knickpoints up the channel network, one might expect to find a pattern of hillslope disturbance in which the proportion of the hillslope affected by the greater erosion rate increases downstream of the channel knickpoint (e.g. Mudd and Furbish, 2007; Hurst et al., 2012

. In addition, in most rapidly eroding landscapes, hillslopes tend to approach a critical slope angle (e.g. Roering et al., 2001; Binnie et al., 2007; DiBiase et al., 2010) and thus at high erosion rates, hillslope gradients become insensitive to erosion rate

Do we see this? Maybe in LC3

In landscapes with changing erosion rates at base level, signals propagate upstream and upslope (e.g. Whipple and Tucker, 1999). These signals then move up the channel network at a rate controlled by drainage area and the fluvial erodibility coefficient (e.g. Whipple and Tucker, 1999; Royden and Perron, 2013) and then spread to hillslopes (e.g. Mudd and Furbish, 2007; Reinhardt et al., 2007; Prince and Spotila, 2013). Because these signals propagate upslope, they can be thought of as ‘bottom-up’ drivers of landscape transience (e.g. Bishop, 2007). However, if erodibility coefficients or sediment transport coefficients change, or erodibility! we might reasonably expect the entire landscape to act in concert.

In soil mantled landscapes, the relationship between ridgetop curvature and hillslope relief can be a powerful indicator of landscape transience. Roering et al. (2007) demonstrated that normalized forms of relief (R\*) and hilltop curvature (E\*) should lie on a single curve if a hillslope is in steady state. Deviations from this curve, therefore, should indicate landscape transience, as demonstrated by Hurst et al. (2013a). In this contribution I show that one should be able to resolve a doubling of erosion rate using this technique, and that the signal should persist for hundreds to thousands of years in most landscapes

Maybe use relief vs curvature BUT AT LEAST SLOPE BREAK IS USED

(e.g. Schoenbohm et al., 2004; Gallen et al., 2011; Anderson et al., 2012; Prince and Spotila, 2013

I have 4 figures

1. should be a map that introduces location and describes stuff relevant to study
2. should be the profiles, with inflection, beds mapped, and ideal hillslopes projected out
3. make plot of curvature above point? If not find some other process related plot
   1. maybe include bed thickness vs slope
   2. bed thickness vs curvature above / below inflection
4. should be 3d maps, with xais= drainage area / y axis = inflection point and LC1 and 3 plotted on it

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

A graph of different sizes and shapes

Description automatically generated with medium confidence