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Dissertation Prospectus

## Summary

Signals from climate and tectonics are imprinted in the morphology of eroding landscapes. Because these processes influence stream channel and landscape morphology, interpreting topographic form is vital to understanding interplay between different geomorphic processes and the bedrock they act upon (Wobus et al., 2006; Whittaker et al., 2007; Tranel et al., 2015; Yanites, 2018). Like climate or tectonics, variation in the resistance of bedrock to erosion can be expressed in landscape and stream form (Duvall et al. 2004, Jansen et al., 2010; Bursztyn et al., 2015; Forte et al., 2016; Yanites et al., 2017). Erodibility, a property of bedrock which represents susceptibility to erosion, is a linear coefficient in the stream power law. Higher erodibility values imply that more material is removed given the same stream power. However, converting measurements of rock properties into a quantity which represents nonresistance to erosion do not currently exist. Magnitudes for rock erodibility vary widely, further confounding attempts to link field measurements to values in the stream power law.

Assigning erodibility values to lithologic properties is complicated at best, and the research goals I propose here will not attempt such an undertaking. However, I will try to understand how bedrock properties are expressed in Last Chance canyon, New Mexico, and how they are exaggerated or confounded by interplay with sediment. Specifically, I ask three questions: (1) how are changes in bedrock properties expressed in landscape morphology and which properties are relevant? (2) how effectively and over what time scales do differently sized sediment armor bedrock and blur the signal that underling rock properties imprint in topography? (3) how do varying bedrock properties influence the production and size of sediment?

In the first project, **Building a Bimodal Landscape in Last Chance Canyon**, We explore how rock properties and channel morphology vary with rock type in Last Chance canyon, Guadalupe mountains, New Mexico, USA. The rocks here are composed of horizontally to sub-horizontally interbedded dolomite and sandstone. We focus on first and second order channel sections where the streams have a lower channel steepness index ($k_{sn}$) upstream and transition to a higher $k_{sn}$ downstream. We hypothesize that lithological differences in bed thickness, fracture spacing, and inherent rock strength influence the steepness values, both locally through influencing bulk bedrock strength but also nonlocally through coarse sediment and boulder production. We collected discontinuity intensity data (the length of bedding planes and cracks per unit area), Schmidt hammer rebound measurements, and measured boulder size at every 40-foot elevation contour to test this hypothesis. Bedrock and boulder minerology were determined using a lab-based carbonate dissolution method. High resolution orthomosaics and DEMs were generated from drone photos. The imagery was used to map channel sections with either exposed bedrock or with sediment cover. The high-resolution DEM was used to measure channel slope and relief. We find that discontinuity intensity affects Schmidt hammer rebound values. Channel steepness

is higher where reaches are primarily incising through more thickly bedded dolomitic bedrock. Where there are more thinly bedded sandstone layers exposed, channel steepness tends to be lower. Furthermore, the effect of rock properties on channel morphology is confounded by sediment input from hillslopes. Thickly bedded rock units on surrounding hillslopes contribute larger sized colluvial sediment to the channels with higher $k_{sn}$. Larger and more competent dolomitic sediment armors both the dolomite and the more erodible sandstone reaches and dampens the negative effect sandstone bedrock has on channel steepness. We hypothesize that in the relatively steep, downstream channel sections channel slope is independent of bedrock properties, owing to the near continuous boulder cover throughout the high $k_{sn}$ reaches. We further posit that the upstream low $k_{sn}$ reaches have a baselevel that is essentially fixed by the steep downstream reaches, resulting in a stable configuration where channel slopes have adjusted to lithologic differences and/or sediment armor.

In the second project, **Storm Events drive Sediment Transport in Last Chance canyon,** we investigate how discrete storm events influence sediment flux, size distributions, and residence time in first and second order streams in Last Chance canyon. In this study, we identify the storm properties necessary to produce stream flow that entrains and transports different sediment sizes. To accomplish this, we will develop a Landlab component that calculates the threshold shear stress to mobilize sediment. We will use the OverlandFlow model (Adams et al., 2017) to determine stream discharge hydrographs for storms of varying intensity and duration. We will use modeled precipitation data (NOAA, 2011) to model realistic storm distributions for Last Chance canyon. We will use drone photos to build high resolution orthomosaics to determine grain size distributions in different channel sections and use this to inform our model. With these methods, we plan to determine 1) storm intensities and durations necessary to move the differently sized sediment, and 2) the residence times of the differently sized sediment within channel sections of varying steepness. We hypothesize that only very large storms will 'do geomorphic work' by removing larger grains from the steep dolomitic channel section, while smaller storms will be able to transport smaller sediment from the shallow channel section. We further hypothesize that the large sediment armors bedrock at timescales necessary for stream channel morphology to reflect their presence. This study will help to constrain the imprint storms have on landscape morphology and elucidate geomorphic processes between shorter time scales and timescales necessary for the landscape to adjust.

The third project, Bed Thickness affects Hillslope and Channel Morphology in Last Chance Canyon, explores the effect that variance in rock properties has on sediment production, hillslope shape, and channel slope in Last Chance canyon. Many studies assume that convex, soil mantled hillslopes are formed by processes that can be modeled as diffusive. However, in Last Chance canyon, bedrock hillslopes in the more thinly bedded sandstones have a convex form similar to what is observed in many soil mantled landscapes, while hillslopes in the more thickly bedded carbonates resemble a steep bedrock landscape. We hypothesize that 1) the spacing of bedding planes influences hillslope morphology and that more thinly bedded sandstones produce convex hillslopes, 2) at some critical bed spacing length, hillslopes will transition from being convex to steep and shear, and 3) below these steep, thicky bedded hillslopes, where large sediment breaks off hillslopes and falls into proximal channels, channels will steepen regardless of erodibility. We use drone surveys to generate high resolution DEMs and orthomosaics to examine the topographic form of hillslopes, to measure bed spacing in Last Chance canyon, and we will use field measurements to determine soil depth on hillslopes. We will investigate sediment production and delivery to channels to examine how sediment size and production vary among rock layers and how interplay with channels affects landscape morphology.

**Timeline/Work Plan**

| | **Project 1: Rock Properties and Landscape Morphology** | **Project 2: Flash flooding and sediment transport** | **Project 3:** |
|---|---|---|---|
| **Already Completed Work** | -Project is completed | -Drone surveys of stream channels | -Drone surveys of hillslopes |
| **Fall 2021** | - Finish edits | -Field work<br>-Photo sieve sediment<br>-Finish Multi Grain Size sediment transport component | -Field work<br>a) Drone surveys<br>b) Measure soil depth<br>d) Measure grain size |
| **Spring 2022** | - Submit manuscript | -Finish Multi Grain Size sediment transport component | - Process drone surveys and measure sediment, bed thicknesses, and hillslope morphology |
| **Summer 2022** | | - UNESCO internship | - UNESCO internship |
| **Fall 2022** | | - UNESCO internship | - UNESCO internship |
| **Spring 2023** | | - Write manuscript<br>- Defend June of 2023 | - Write manuscript<br>- Defend June of 2023 |
| **Summer 2023** | Defend | Defend | Defend |

**Project 1**

Collaborators: Nicole Gasparini, Joel Johnson, Brent Goehring

**Introduction**

Recent field studies and numerical experiments emphasize the importance of the interplay between bedrock fracture patterns, erodibility, and the competency and relevance of sediment on channel and landscape morphology. Because stream channel form changes with variance in rock properties (Duvall et al. 2004), interpretation of channel geometry is vital in understanding a landscape's response to lithologic variance (Kirby and Whipple, 2012; Perron and Royden, 2012). Fracture patterns in bedrock are an important influence on erodibility, where more densely fractured bedrock can erode faster than more sparsely fractured rock (Molnar et al. 2007). Bedrock fractures in source rock have been used as a proxy measurement for grain size of alluvium and has been demonstrated to affect channel slope and landscape relief (Dibiase et al. 2018). Likewise, the size and relevance of alluvium depend on the bedrock properties from where grains were sourced (Verdian et al, 2021). Grain size impacts channel geometry and can cause channels to steepen relative to channels which lack coarse alluvium (Thaler and Covington, 2016; Johnson et al. 2009). These studies demonstrate the importance of variance in bedrock properties to channel and landscape morphology, nonetheless our community lacks a quantitative understanding of how measurable rock properties control landscape form and evolution.

To systematically determine the effects of different bedrock properties on erodibility we measure discontinuity intensities (the length of cracks and bedding planes per unit area) and Schmidt hammer rebound values from stream channel reaches of varying lithology. We measure the largest sediment grain in the channel within different channel sections to calculate grain size and shape. To quantitatively identify lithology, we use a carbonate dissolution method to identify bedrock and boulder minerology. High resolution orthomosaics and DEM's were generated from drone photos and were used to map channel sections with exposed bedrock and record slope and relief values at different scales.

**Hypothesis**

The major hypothesis to be tested is as follows: A combination of slope and bedding plane spacing controls discontinuity intensity, and therefore erodibility in the horizontally bedded rock units in Last Chance canyon. Erodibility in the more thickly bedded rock units is more independent of slope than more thinly bedded rock units, where erodibility is very dependent on slope. The topography of Last Chance canyon will reflect bedding thickness and thicker bedded units will achieve steeper slopes than thinly bedded units which tend to erode to a shallower slope.

Furthermore, the effect of rock properties is confounded by interplay with sediment input from hillslopes and thickly bedded rock units on surrounding hillslopes contribute larger sized colluvial sediment to the channels, leading to steeper channel slopes. Larger and more competent sediment armors both the thick and thinly bedded rock, blurring signatures from contrasting rock units in the morphology of the landscape. Within channel sections which are inundated with sediment, bedrock erodibility is independent of bedrock properties and the topography will instead reflect on the amount, size, and competency of the bedrock armor.

**Methods**

In March and May of 2018, and in February of 2021, we surveyed five channels which we had preselected based on DEM analysis, mapped geology, and accessibility (figure 1). We studied reaches of varying length in five different channels in Last Chance Canyon. At every 40m contour interval we surveyed bedrock when exposed, measured the largest boulder, and took rock samples from each to confirm minerology.

We used the NED 10 m digital elevation model (DEM) of Last Chance canyon to determine channels of interest to survey and to ascertain the location and elevation of where channel transitions from steep and shallow channel sections. We used TopoToolBox to generate longitudinal stream profiles, $k_{sn}$ maps, and $\chi$ (chi) plots of all surveyed channels (TopoToolBox, 2018). The channel steepness index, or $k_{sn}$, is a measure of channel gradient normalized for drainage area and allows for the comparison of slope along a single channel or among multiple channels to isolate erosional and/or bedrock erodibility patterns (Kirby & Whipple 2012). $\chi$, like $k_{sn}$, is a way of identifying changes in channel slope in a single channel or in multiple channels. Because channels can adjust to more resistant lithologic units by steepening across them (Duvall et al. 2004; Jansen et al. 2010), we used $\chi$ plots and $k_{sn}$ maps to detect changes in slope that could be due to differences in erosional efficiency.

We used a Schmidt hammer to take a minimum of 30 rebound values in each reach we surveyed that had exposed bedrock (Niedzielski et al. 2009). We discarded Schmidt hammer values which were less than 10, which is the minimum value the device can read, as they represent multiple values and make statistical analysis of the data difficult (Duvall et al., 2004). Schmidt hammer values were recorded at roughly evenly spaced intervals up the thalweg of each channel regardless of weathering or presence of fractures. All Schmidt hammer values were taken perpendicular to the bedrock surface. Schmidt hammer values are also affected by proximal discontinuities. Lithologic and climatic context is necessary in interpreting the dominant control on Schmidt hammer values.

We used a GoPro5 attached to the end of a selfie stick to take wide-angle HD videos of the bottom of 18 different reaches of varying size. We used Agisoft Photoscan to generate high resolution orthomosaics of each reach using the GoPro videos and then traced all discontinuities with Adobe Illustrator. We placed a rock hammer of known length on the bedrock surface when taking video to scale each orthomosaic to the correct length. We then used Fraqpac, a Matlab software suite, to determine the average discontinuity intensity, which is the average length of fractures and bedding planes, per square meter, of each reach (Heely, 2017). All discontinuities by which bedrock could be plucked from the thalweg were traced, including bedding planes and fractures created by weathering (Spotila, 2015).

We used a drone, DJI Mavic 2 pro, to take photos of the five surveyed channels from elevations of 20 meters above the five stream channels, and 120 meters above adjacent hillslopes for three of the five channels. We used Agisoft photoscan to generate high resolution DEMs (0.027 to 0.28 m) and orthomosaics of the five channels and three adjacent hillslopes. We used the DEMs to take relief and slope measurements, and the orthomosaic to identify locations where stream channels were inundated with sediment or where bedrock was exposed.

At each 40m elevation contour interval we took rock samples from bedrock, when exposed, and from the largest boulder in the stream channel to ensure correct categorization of lithology. The minerology of each rock sample was assumed to be representative of the minerology of the reach or boulder it was taken from. Our efforts to determine lithology in the field was complicated because samples oftentimes contained both carbonate minerals, dolomite and calcite, and quartz. To find a quantifiable ratio of the amount of carbonate in each sample, we ground each rock sample up using a jaw crusher and disk mill. The ground up sample was rinsed in water a minimum of five times, dried in an oven over night, and then weighed the following morning. We dissolved the carbonate minerals by soaking each sample in Nitric acid for at least 24 hours. The sample was again rinsed in water a minimum of five times and dried overnight. We then reweighed each sample to determine the amount of carbonate minerals which had dissolved and assigned the sample a ratio amount of carbonate mineralogy. To ensure the validity of this methodology, we replicated this processes on six of the samples and used a microscope to check that all carbonate minerals had been dissolved. For one of the samples, we replicated this process five times. All replicate measurements demonstrated the similar results (standard deviation of 0.62%, and variance of 0.39%), giving credence to our methodology.

**Results**

Last Chance canyon tributaries have upstream sections with relatively shallow channels and lower gradient hillslopes, and a knick zone downstream which has steep channels and hillslopes (figure 3). We used $\chi$ plots and field observations to identify the points at which stream channels transition from steep to shallow channel sections to be at approximately 1550 m for channels 3, 4 and 5 and approximately 1640 m for channels 1 and 2, and the contact between alluviated and bedrock channels to be at approximately 1400 m. We used a t test to verify that hillslopes above 1550 m and from above 1640 are statistically different from hillslopes from 1400 to 1550 m.

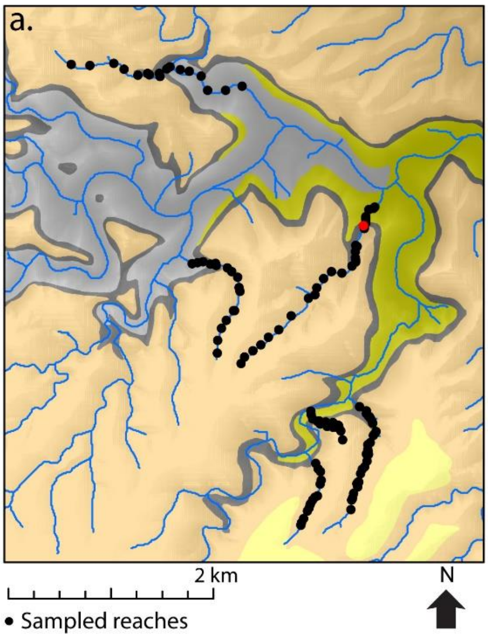
In Last Chance canyon, slope and bed thickness affect both discontinuity intensity and Schmidt Hammer values (figure 2). Bedding planes are zones of weakness by which bedrock can be plucked, and both they- and fractures- were treated as discontinuities (Spotila, 2015). Because the units here are horizontally to near horizontally bedded, thinly bedded sandstones with higher slopes have more exposed bedding planes and lower Schmidt hammer values. Discontinuity intensity and rebound values are invariant with slope in the thickly bedded carbonates.

The average discontinuity intensity and Schmidt Hammer value from the thinly bedded sandstones in the steep channel section, where more bedding planes are exposed, is 7.98 $m^{-1}$ (n = 2, stdev = 5.04) and 31.6 (n = 61, stdev = 1.2) respectively. The average discontinuity intensity of the more thickly bedded dolomites in the steep channel section is 2.34 $m^{-1}$ (n = 6, stdev = 0.56) and they have an average Schmidt Hammer value of 36.1 (n = 240, stdev = 0.70). Within the upstream channel sections, the reaches have a shallower slope, fewer exposed bedding planes, and less of an effect on measured discontinuity intensity as evidenced by the smaller average discontinuity value, 0.77 $m^{-1}$ (n = 3, stdev = 0.16), and larger average Schmidt Hammer value, 41.7 (n = 88, stdev = 0.97), in sandstones. Dolomite reaches have a slightly higher discontinuity intensity of 1.51 $m^{-1}$ (n = 6, stdev = 0.32) and an average Schmidt Hammer value of 37.1 (n = 90, stdev = 0.98) in the shallow channel section.

We ran four separate t-tests for two independent samples on mean Schmidt hammer values in Last Chance Canyon. We compared Schmidt hammer values between dolomites and sandstones in the shallow and in the steep part of the channel and found them both to be of different populations. Schmidt hammer values for sandstones in the steep section were statistically different from sandstones in the shallow section. Schmidt hammer values for carbonates in steep and in shallow sections were of the same statistical population. This the only test of the four in which the null hypothesis was accepted and further demonstrates the lack of effect slope has on rock strength in carbonates.

In the shallow upstream channel section, there is more exposed bedrock in the stream channels and where there is sediment armoring the channels it is relatively small. In the steep channel section, the stream channels are inundated with large alluvium. As relief increases the volume of carbonate boulders increases exponentially (figure 5). The volume of sandstone boulders also increases, but less dramatically than the carbonate boulders. Of the boulders we measured, 70% of the boulders in the steep section and 64% of the boulders in the shallow channel section are carbonate. Carbonate boulders were more cubic than sandstone boulders, they had a shape factor ($d_{min}/d_{max}$) of 0.36 while sandstones were 0.29.

*Figure*




b.

| Approximate thickness (m) | Rock Unit | Description | Approximate Elevation (m) |
|---|---|---|---|
| | Queen Formation | Predominently sandstone with some dolomite near the base of the unit. | |
| | | | 1700 up |
| 150 m | Greyburg Formation | Mostly 2.5 to 15 cm thick sandstone bedswith few 2.5 cm to 3 m thick dolomite beds | |
| | | | 1540 - 1560 |
| 30 m | Upper San Andres Formation | 0.5 cm to 1 m thick dolomite beds with one to three sections of thinly bedded sandstone. | |
| | | | 1440 - 1510 |
| 0 - 130 m | Lower San Andres Formation | 0.3 to 1.5 m thick dolomite beds with some medium to very grained sandstone beds. | |
| | | | Varies |
| 0 -150 m | Sandstone tongue of the Cherry Canyon Formation | Very fine grained, well sorted quartz sandstone with scattered, irregular chert nodules. | |
| | | | 1400 |

*a. Geologic map of Last Chance canyon with b. a description of mapped lithologies (King, 1948; Boyd, 1958; Hayes, 1964; USGS, 2017). The reach marked as a red circle is shown in figure 5 and 11. Approximate elevation and thicknesses apply only to the section of Last Chance canyon displayed here.*

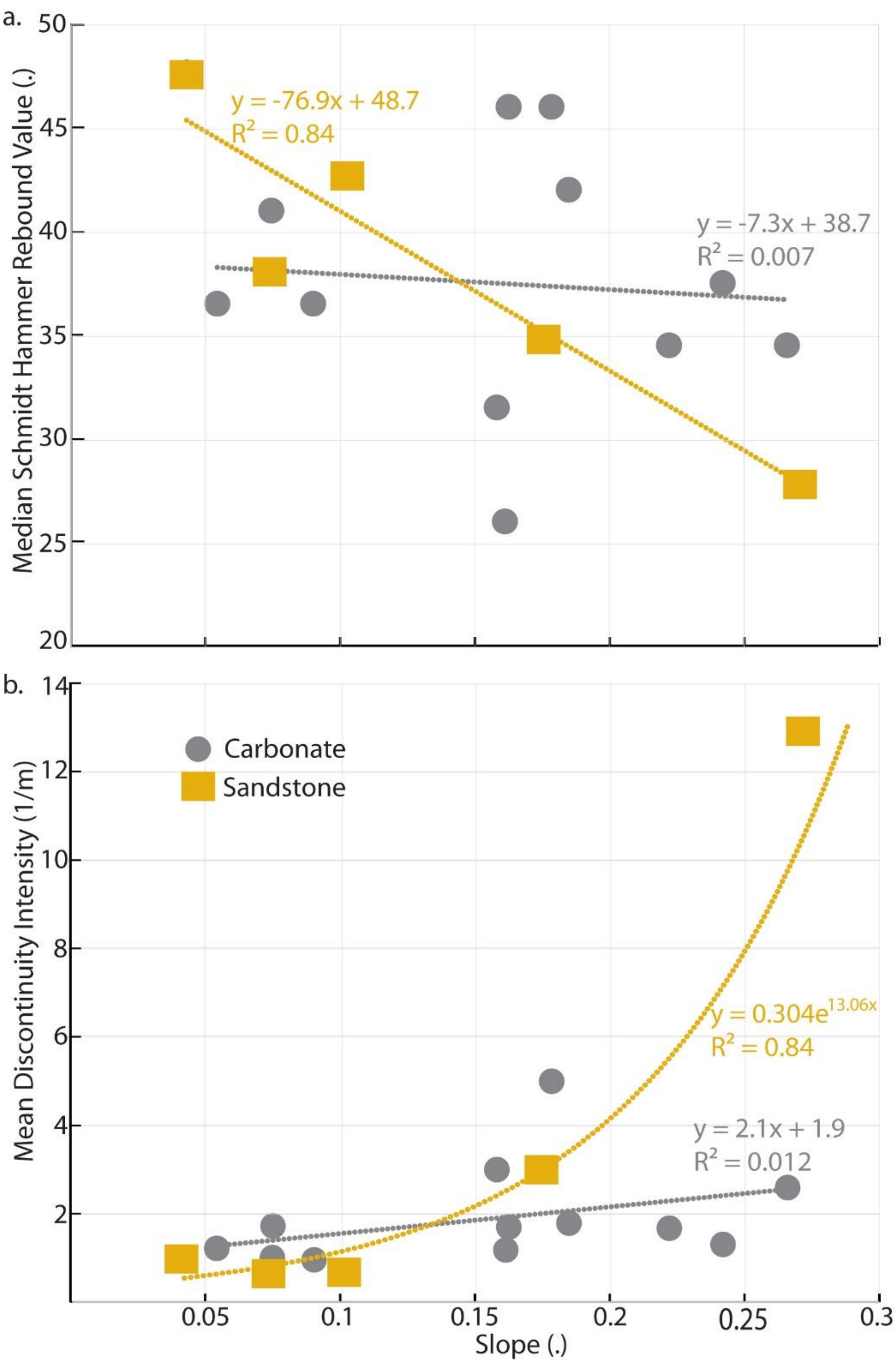



*Figure Slope vs. a. mean Schmidt Hammer rebound value and b. mean discontinuity intensity for 5 sandstone and 11 carbonate reaches. We calculated slope over a distance of 150 m downstream and 150 m upstream of each reach.*

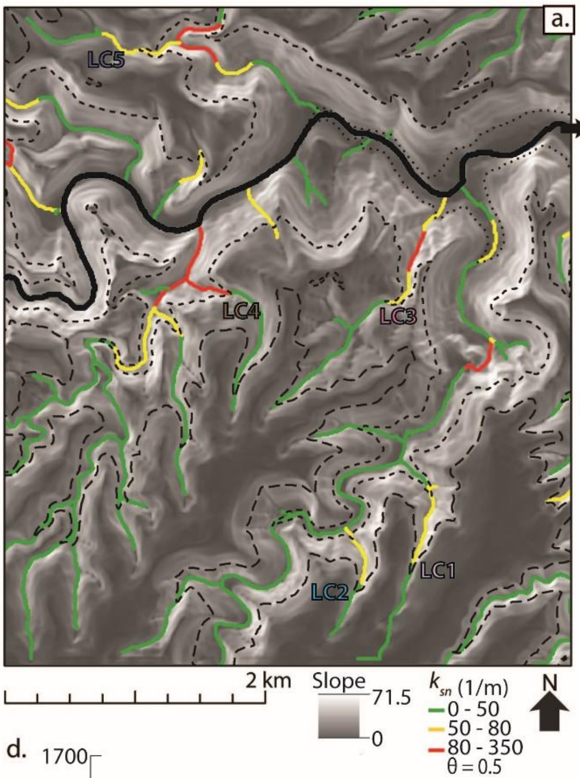
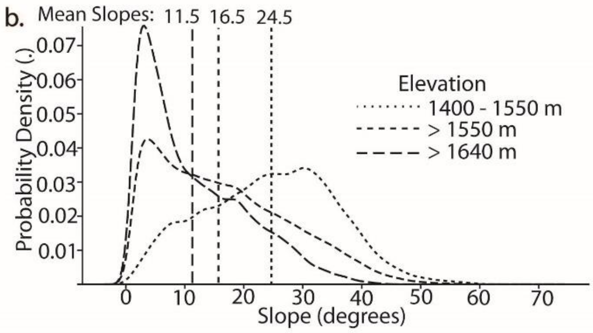
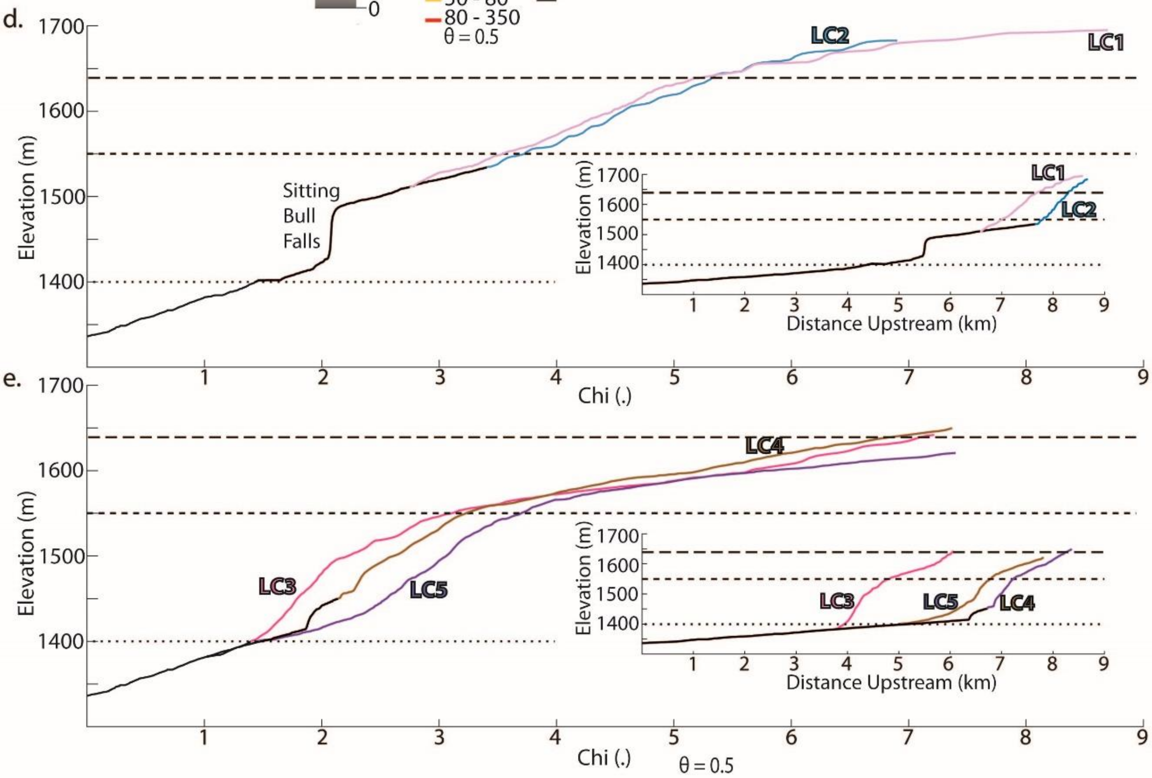



*Figure* Slope map of Last Chance canyon with $k_{sn}$ values plotted across it. The contour lines correspond to elevations which are interpreted as approximate inflection points for hill and channel slope. b. Density plot of slope values from the shallow landscape sections, >1640 and > 1550 m, and the steep section, 1400 to 1550 m. c. Chi plots of LC1 and LC2 and d. LC3, LC4, and LC5 with inset of channel profiles. Channels are labeled and color coded to match channel labels on 7a. in c. and d. Channel sections which were not surveyed, and with the exception of Sitting Bull falls and a knickpoint at the base of LC4, are alluviated are indicated in black.



**Project 2**
Collaborators: Nicole Gasparini, Joel Johnson, Kyle Straub, Angel Monsalve
**Introduction**

The topographic signal from variance in bedrock properties can be blurred, removed, or exaggerated by the presence of sediment armor (Duval et al., 2004; Johnson et al., 2009; Finnegan et al., 2017). The presence of larger boulders, sourced from thicker units and bedrock with larger discontinuity spacing, causes stream channels to steepen (Thaler and Covington, 2016; DiBiase et al. 2018) (figure 4). As the time that alluvium effectively armors stream channels increases, channel morphology will be influenced by the sediment armor. The residence time of boulders in stream channels depends primarily on storm intensity and duration, which drive stream discharge, and on relevant sediment properties like size. How large must sediment be to armor channels, withstand mobilization by storms, and remain in streams at timescales necessary for the landscape to reflect their presence? How intense must storms be to generate runoff that mobilizes large boulders and incises into bedrock? Without answers to these questions, attempts to link geomorphic processes across temporal scales will be confounded.

In this study, we explore the relationship between the storm hydrograph and the size of sediment armoring the channel on landscape morphology. In prior studies we found that low order stream channels in Last Chance Canyon are inundated with large alluvium in the steep reaches (figure 5). More specifically, we ask: (1) How often is relatively large sediment entrained, in comparison with smaller sediment, in Last Chance canyon? And (2), what is the relationship between channel steepness and the residence times of large alluvial armor? To address these questions, we will couple a landscape evolution model which calculates entrainment of sediment based on shear stress with the Landlab OverlandFlow component (Adams et al., 2017) and inform our model experiments with storm and sediment size data from Last Chance canyon, New Mexico. This study will rectify assumptions about the effect of differently sized sediment on topography from the storm hydrograph to time scales relevant for the landscape to reflect geomorphic processes. Furthermore, I seek to demonstrate that the baselevel of upstream channel reaches is effectively pinned at the transition from finer (upstream) to coarser (downstream) sediment and knickpoint celerity is slowed in stream channels with large sediment armor.
**Hypotheses**

Rare storms are required to overcome the threshold shear stress necessary to move large sediment. Storm duration is an important hydrograph characteristic in removing smaller sediment out of the system but will not influence the flux of larger sediment. Because of this, storms will more frequently incise into bedrock which is armored by smaller grains than channels with larger alluvial armor.

The larger sediment grains, which are primarily sourced from dolomitic bedrock, are mostly immobile on timescales necessary for landscape morphology to reflect their presence. Because large boulders are effectively immobile, erosion ceases where they armor the channel bedrock, and baselevel is pinned in any channels draining to these armored reaches.

**Methods**

We will calculate shear stress using the OverlandFlow component (Adams et al., 2017), which routes runoff from a model storm across a DEM and can be used to determine relevant information like water discharge and velocity. OverlandFlow is a component in Landlab, a Python-language, open-source, flexible library of different earth surface processes components that can be easily coupled together (Hobley et al. 2017). We will calculate shear stress using the using vertically averaged streamwise and cross stream velocities, and a drag coefficient that varies inversely with depth (Monsalve, 2016).

$$\tau_{bn} = \rho C_d \left(u_n^2 + v_n^2\right)$$

The drag coefficient (Cd), will be calibrated for each discharge using height to discharge rating curves (Yager et al, 2012). Approximate vertically averaged velocity will be calculated using a two-dimensional solution. We will also use the depth slope product to find shear stress and compare results with the averaged velocity method.

We will couple a Landlab component, which we will design, that uses the shear stress information found using OverlandFlow and determines whether sediment is moved depending on its size (Monsalve, 2016). We will use a shear stress averaged over a 10 m patch to determine the threshold shear stress necessary to move the median sediment size. We will use the equations below to relate the total shear stress found using the depth slope product ($\tau_T$)and the average velocity method of calculating shear stress ($\tau_{\mathrm{var\ D50}}$).

$$c_p = 5.31\left(\frac{D_{50j}}{D_{50}}\right)^{2.52}, \quad \bar{\tau} = \bar{\tau}_{var\,D_{50}}$$

$$c_p = 6.52\left(\frac{D_{50j}}{D_{50}}\right)^{2.46}, \quad \bar{\tau} = \bar{\tau}_T$$

$$e_p = -0.37\ln\left(\frac{D_{50j}}{D_{50}}\right) + 0.70, \quad \bar{\tau} = \bar{\tau}_{var\,D_{50}}$$

$$e_p = -0.33\ln\left(\frac{D_{50j}}{D_{50}}\right) + 0.61, \quad \bar{\tau} = \bar{\tau}_T$$

$$\bar{\tau}_j = c_p \bar{\tau}^{e_p}$$

Where *Cp* and *ep* vary with grain size, *D50j* is the median grain size of a reach, and $\tau_j$ is the shear stress necessary to mobilize sediment grain size *D50*. Threshold shear stress values will be used to estimate sediment transport rates and make interpretations about spatial patterns of sediment transport and grain size distributions in different channel sections.

We will use a DJI Mavic 2 pro to take photos 20 meters above select channels to build high resolution orthomosaics and measure grain sizes. We will use PebbleCounts (Purington and Bookhagen, 2019) to determine grain size distributions for different channel sections. We will use these distributions to generate packages of differently sized sediment and add them to the channel in our model environment.

We will use the NOAA Atlas from the Office of Water Prediction to determine storm intensities and durations for different recurrence (NOAA, 2011. This data source provides intensity and duration estimates for 5-minute to 60-day storms for 1-to-1000-year recurrence intervals. Averages and upper and lower bounds of the 90% confidence interval are provided at 30-arc second resolution. Data regarding intensity and duration will be used to drive the OverLandFlow component and generate storms which mimic real storms from our study area. Recurrence intervals for these data will allow for our model to reflect temporal scales. We will determine the recurrence intervals for storms that do not mobilize sediment and will eliminate them from our model runs.

**Analysis**

To link the hydrograph and sediment size, we will examine sediment mobility and flux in different channel sections for different storms. Storms which strip sediment armor of different sizes will have different recurrence intervals. We expect that sediment residences times will vary with storm intensity and storms with higher recurrence intervals will be required to move larger alluvium. Storms that can remove sediment armor and do geomorphic work will occur less frequently in channel sections with larger grain sizes. However, the more frequent, less intense storms should be able to remove smaller sediment and erode into the upstream shallower channel sections which are covered by smaller sediment. This methodology will help elucidate how variance in storm characteristics affects sediment size distributions, and alluvial residence times.

To quantify the influence of storms on the time for landscape morphology to respond to the changes in sediment size, we measure the size of sediment in the channels and the recurrence interval required to move sediment of differing sizes. We seek to quantify a link between channel steepness and the residence time of large sediment armor using comparisons between sediment size and channel steepness in LC 1 and LC 3. Variance in sediment size affects channel and landscape morphology (figure 4), and we will relate residence time in channel with degree of steepening. We expect that sediment sourced from dolomite is large enough (figure 5) to stop erosion and pin baselevel for channel sections above it. Furthermore, we will quantify the degree to which celerity in the steep knickzone has been slowed by the presence of large dolomitic armor.

(m)

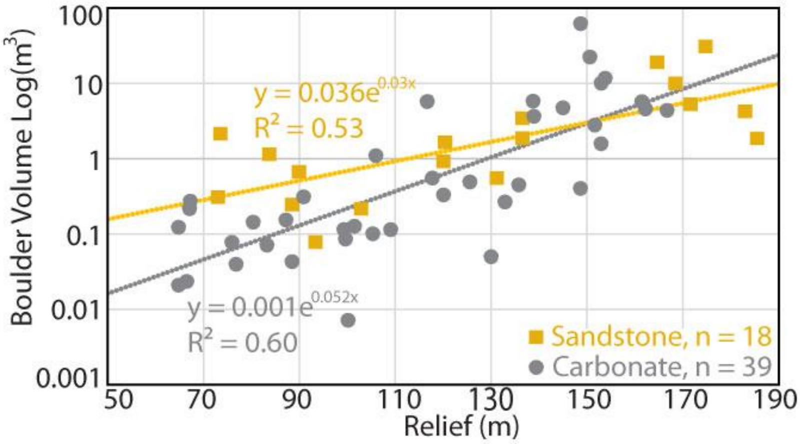



*Figure - Slope vs. a. mean Schmidt Hammer rebound value and b. mean discontinuity intensity for 5 sandstone and 11 carbonate reaches. We calculated slope over a distance of 150 m downstream and 150 m upstream of each reach.*

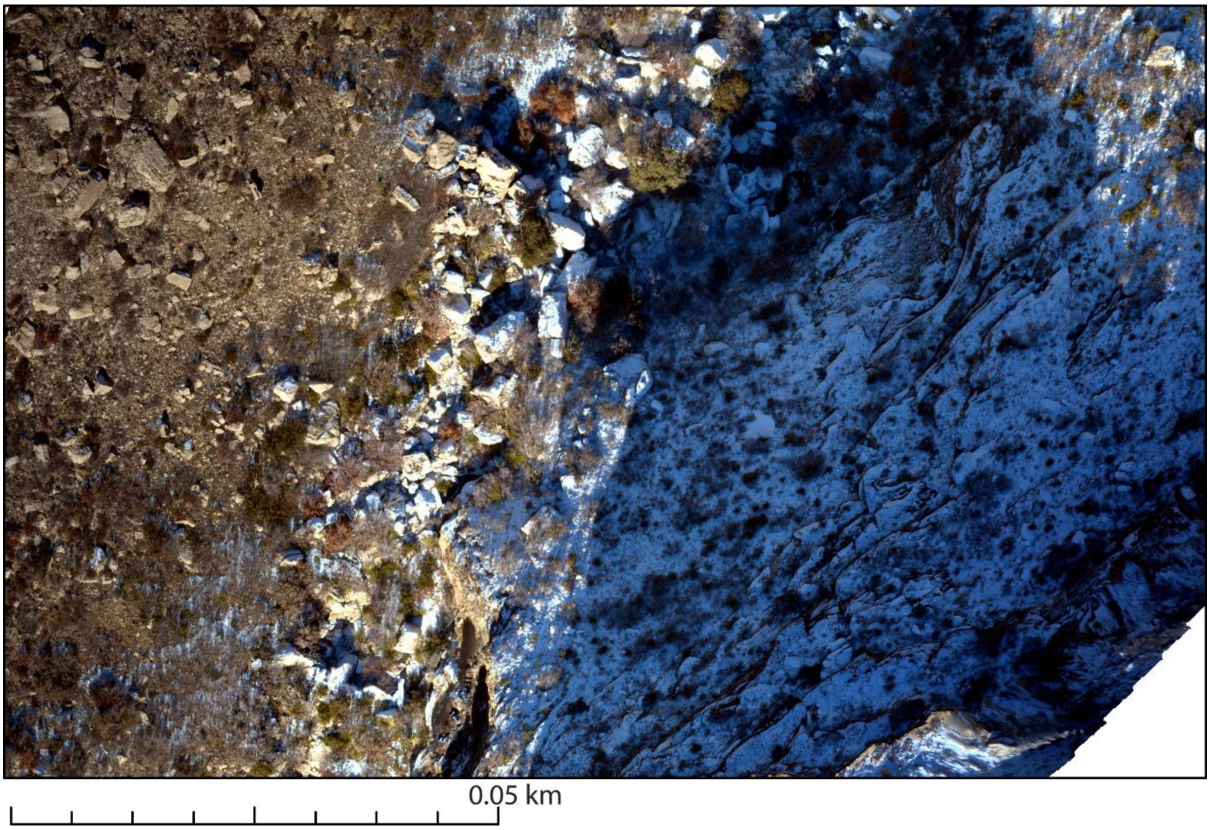



*Figure 5 – Orthomosaic from drone footage of large sediment in the steep channel section of LC*

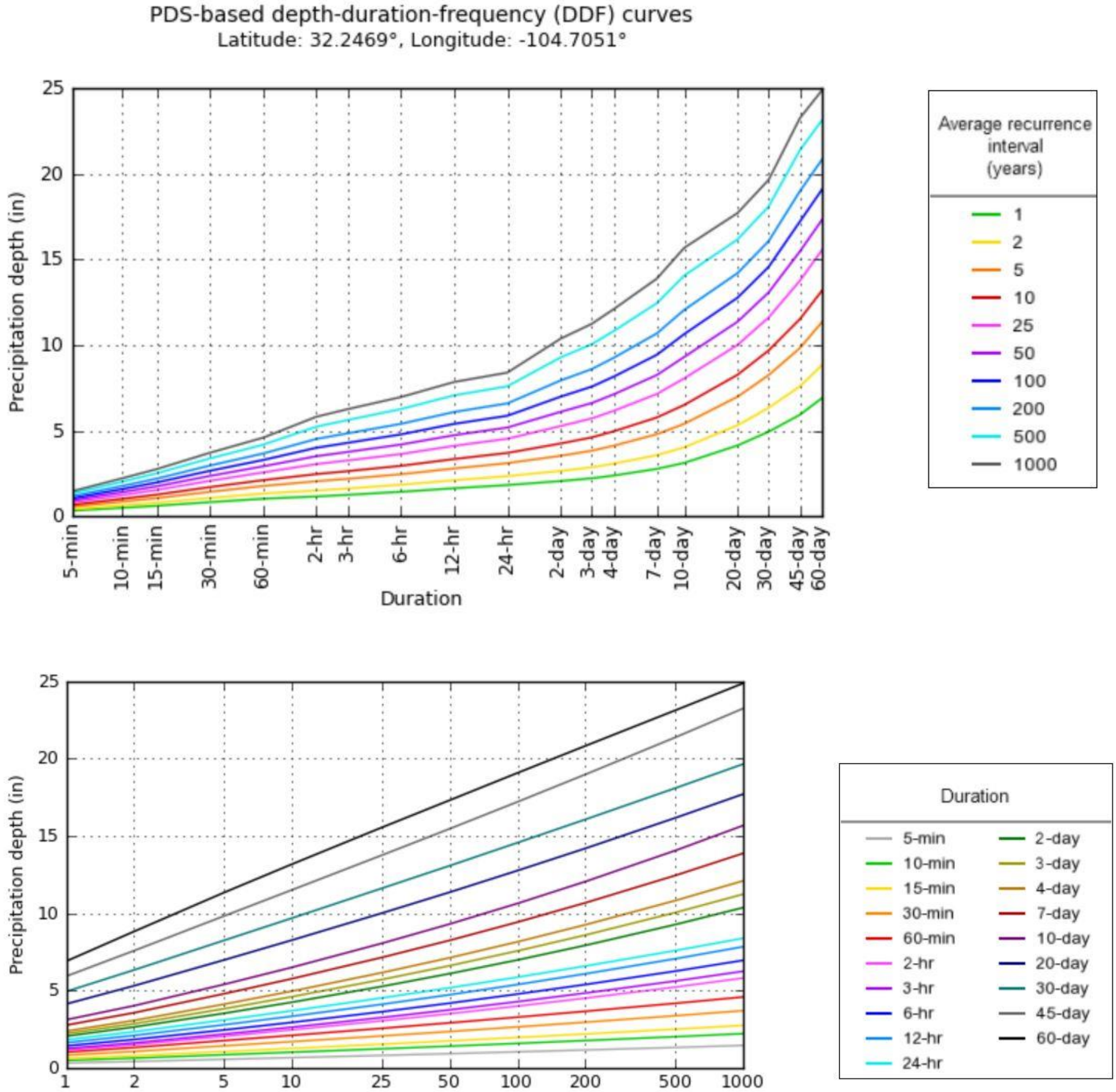



*Figure 6 – Relevant modeled climate data for Last Chance canyon taken from NOAA's Hydrometeorological Design Studies Center.*

**Project 3**

Collaborators: Nicole Gasparini, Joel Johnson

Convex hillslopes exist in a variety of locales, and processes controlling soil mantled sediment transport are thought to lead to this convex form. However, scientific literature on hillslope morphology in arid landscapes with exposed bedrock is conspicuously lacking. Rock properties, which are assumedly quite relevant in bedrock hillslopes, have been shown to influence erosion rates and rock surface slope (e.g., Brook and Tippett, 2002; Matasci et al., 2015; Moore et al., 2009; Selby, 1980), and imprint its signature into the topography (Molnar et al., 2007; Clarke and Burbank, 2011; St. Clair et al., 2015; Voigtlander et al., 2017; Eppes and Keanini, 2017; Eppes et al., 2018). Soil mantled hillslopes are thought to generate convex hillslopes, however, in Last Chance canyon, thinly bedded bedrock on hillslopes with exposed bedrock are convex in shape and resemble soil mantled hillslopes, while hillslopes with more exposed and thickly bedded rock are vertical and shear. But what causes these thinly bedded hillslopes to have a convex form while the thickly bedded bedrock on hillslopes are steep and linear? And does interplay between these two distinct hillslope morphologies and channels exaggerate this bimodal landscape?

In this study, we seek to understand the effect that changes in bedrock thickness have on sediment production, grain size, and hillslope morphology and process. We seek to identify morphological variables, like hillslope length, gradient, and distance from the channel and ridgeline, which exaggerate or blur the signal from bedrock properties on landscape form. More specifically, we ask what controls sediment production and movement on hillslopes with high spatial variability in rock properties. How thin do beds need to be to generate a convex hillslope? How does variability in bed thickness affect hillslope convexity? To answer these questions, we will compare distributions of bed thickness to convexity and the slope of hills proximal to channels of interest. We then will quantify initial sediment production and size as a function of bed thickness in bedrock. With this data we will attempt to link bed thickness to hillslope morphology. We will take field measurements of sediment depth to bedrock and saprolite and take samples to quantify the degree of weathering in both. We will use high resolution DEMs and orthomosaics to measure bed thickness, zones of bedrock exposure and sediment cover, hillslope gradient, length, and distance from the channel and ridgeline. We will then compare landscape form in different parts of Last Chance canyon to determine what about sediment size and production has caused the distinct bimodal landscape form in LC3 that LC1 lacks, and why the steep section in LC3 is steeper than in LC1.

**Hypothesis**

We hypothesize that spacing of beds influences hillslope morphology and that more thinly bedded units create more diffusive, convex hillslopes. Conversely, hillslopes with bed thicknesses above some critical length will steepen and become planer.

We further hypothesize that bed thicknesses in LC1 are less variable than in LC3, causing LC1 to lack the bimodal morpholgy that LC3 exhibits. In LC3 bed thicknesses will be much thicker at elevations below 1550 m, and much thinner above 1550 m. The thicker beds below 1550 m elevation in LC3 supply larger sediment causing channels to steepen relative to channels in LC1.

**Methods**

In October of 2021, we surveyed 5 hillslope transects in LC3 and 4 transects in LC1 which we had preselected based on DEM analysis, prior surveys, and accessibility. At every 40 m elevation interval we will dug soil pits, measured the depth to saprolite and bedrock and took a sample of each.

We used the NED 10 m digital elevation model (DEM) of Last Chance canyon as well as prior drone surveys to determine hillslopes of interest to survey. We used ArcMap to generate hillslope profiles of interest and then programmed transects into DGI Pilot PE in anticipation of taking drone surveys using a DJI Mavik 2 pro at 20 m elevation. With drone photos we will generate DEMs and orthomosaics (0.027 to 0.2 m resolution) of 9 hillslope transects using Agisoft. We will use the DEMs to make slope, distance, and relief measurements (supplemented with the 3DEP 1m resolution lidar). We will use the orthomosaics to measure grain size distributions with PebbleCounts (Purington and Bookhagen, 2019) and also fracture spacing of bedrock units.

We will quantify initial sediment sizes as a function of bed thickness. We then will determine grain size distributions at different locations on hillslopes to identify the factors which affect grain sizes across hillslopes and determine their effect on sediment armor in the channels. With this data we will attempt to link rock properties and hillslope morphology to identify how sediment size distributions affect stream channel slope. We will take field measurements of sediment depth to bedrock and saprolite and take samples to quantify the degree of weathering in both. We will use high resolution DEM's and orthomosaics to measure bed thickness, zones of bedrock exposure and sediment cover, hillslope gradient, length, and distance from the channel and ridgeline.

**Analysis**

Preliminary analysis demonstrates that the distance between bedrock bedding planes affects the shape and size of the large sediment measured in the channels. These data could help inform data regarding initial sediment size distributions on hillslopes. The maximum length of one of the axes of coarse sediment production on a hillslope is controlled by the distance between bedding planes. Carbonate rocks are generally more thickly bedded than sandstone rocks. Where hillslope relief increases, bedrock units are thicker, and the length of the a, b, and c axes increases for the carbonate boulders (figure 7). Because sandstone bedrock is more thinly bedded, the c axis will tend to reflect the distance between bedding planes from the source rock. The higher average shape factor, 0.36, of the more cuboid shaped carbonate boulders relative to the more rectangular cuboid sandstone boulder (average shape factor, 0.29), further speaks to the effect that the distance between bedding planes affects sediment shape. Because a sediment grain will tend to break across its shortest axis, the more elongate sandstone boulders are generally less competent than carbonate boulders. Because carbonate bedrock is thickly bedded, boulders sourced from this bedrock will tend to be larger and because they are more cuboid, they stay larger for longer than sandstone boulders.

In prior studies in Last Chance canyon, we observed a well-defined kink in the chi plot in LC 3, where in the higher elevation, lower relief and slope section above 1550 m, there is more exposed bedrock (figure 8), more exposed sandstone, and less and smaller alluvium armoring the channel (figure 4). Conversely, LC 1 lacks the conspicuous change in channel steepness, which is apparent in LC 3, due to the armoring of sandstone rock units and relative abundance of alluvium in the channel. Hillslopes steepen in more thickly bedded rock and shallow in hillslopes made up of more thinly bedded rock (figure 9). Lithology measurements from proximal hillslopes in LC 1 indicate that starting just above elevation 1550 m there are sandstone units in the channel as in LC 3, but they are buried by alluvium. By comparing LC 1 with LC 3 we can see how the signal from changes in rock properties is dampened by hillslope sourced alluvium and how the location of pinned baselevel can be blurred and change depending on the presence of sediment armor sourced from proximal hillslopes.

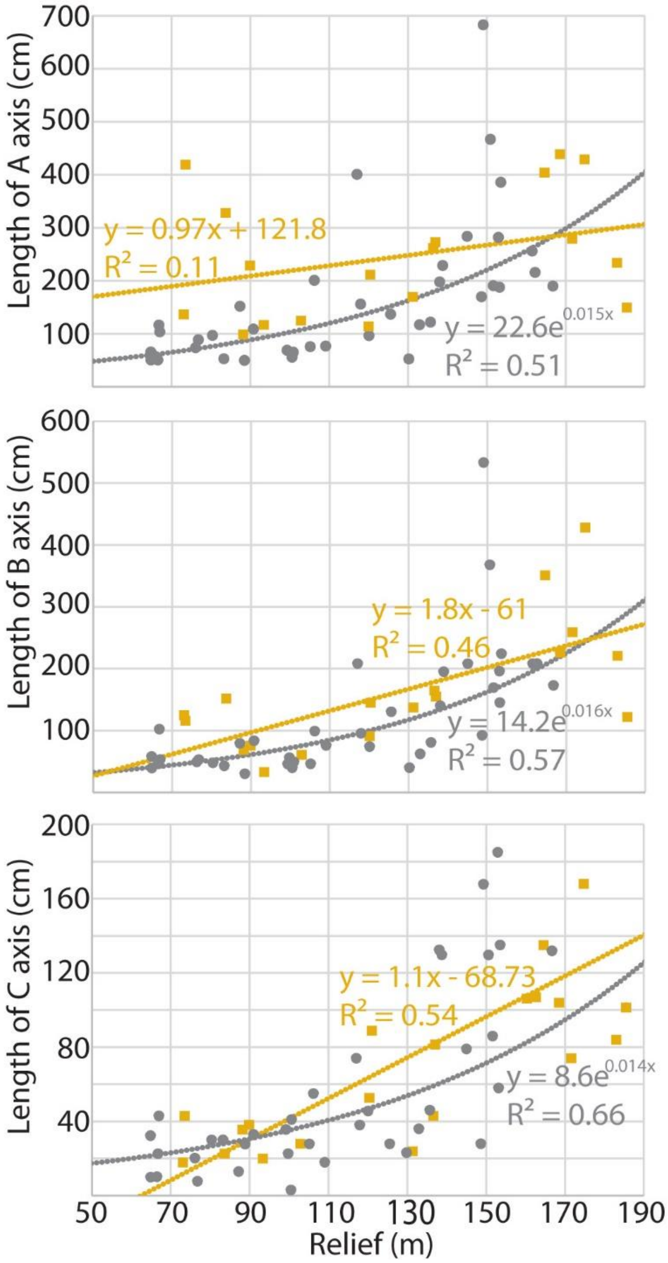



*Figure 7 - Relief (calculated using a 500 m window at the location of each boulder) vs. the length of the a, b, and c axis for all boulders measured in the field.*

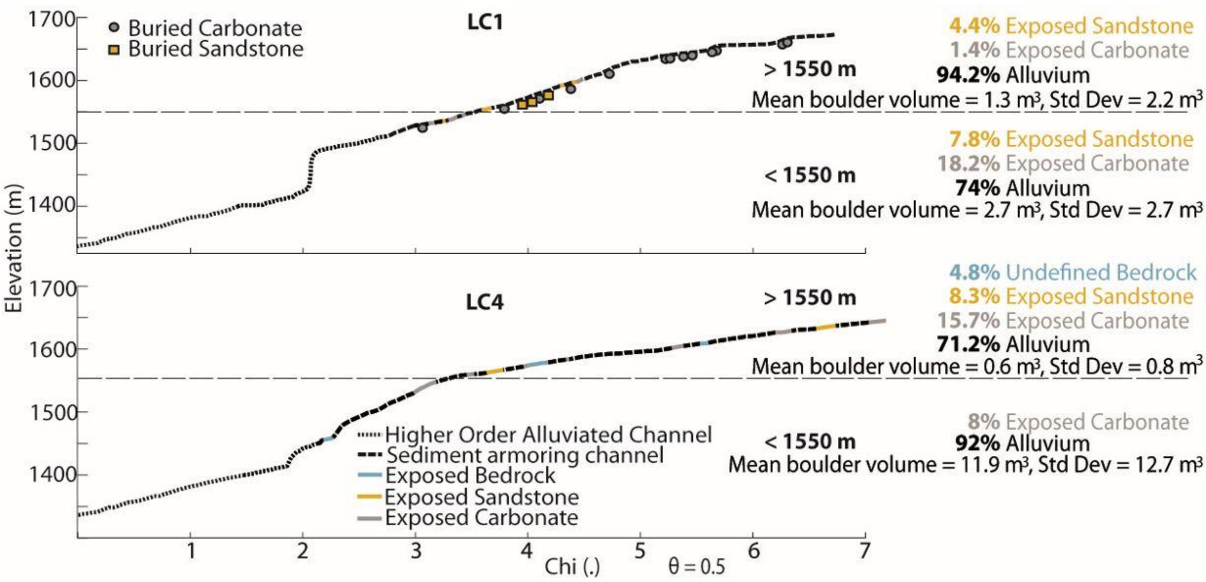



*Figure 8 – Chi plots of five channels in Last Chance canyon with exposed bedrock or sediment armor mapped. Where known rock type is shown. To the left of each channel, relevant statistics for each channel are displayed.*

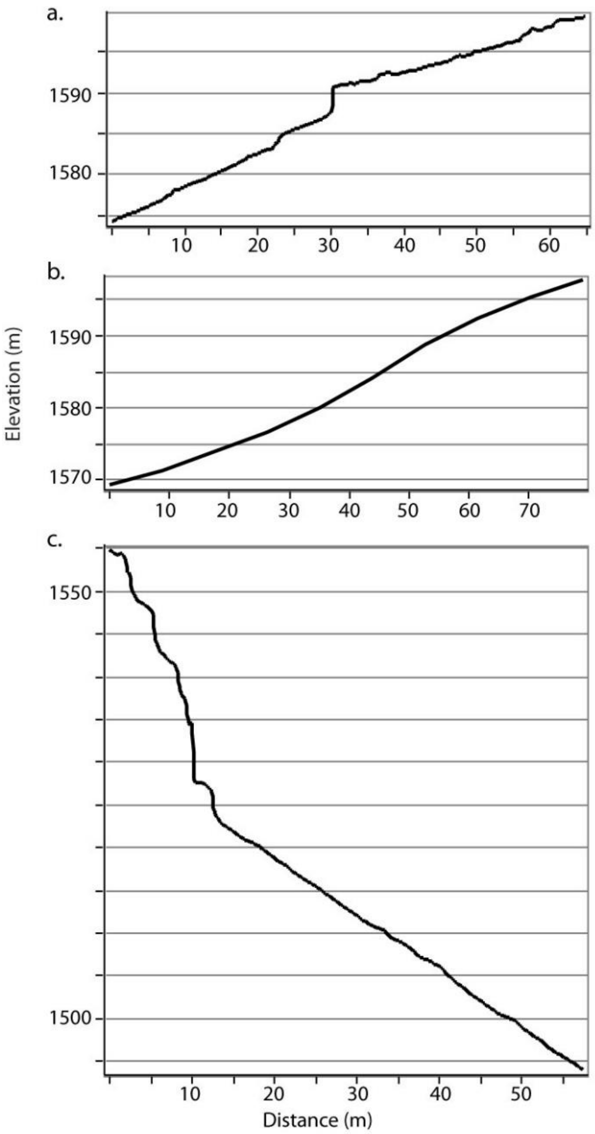



Figure 9 - Hillslope profiles of a. a high resolution, 0.3 m, shallow section, b. the same shallow section at low resolution, 10 m, and a high resolution ,0.3 m, profile in the steep channel section.

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