Characterizing the evolution of detached limestone blocks on hillslopes: Konza Prairie, Kansas, United States of America

by

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Abstract

The landscapes we live in are dynamic. If we want to increase our understanding of the mechanisms at play and enhance our confidence when making landscape management decisions, then we must deduce what processes are most significant in landform formation, and what their rates are. The need for understanding is particularly strong in landscapes that remain in their natural state, for instance landscapes with soft bedrock or those incompletely covered by vegetation such as the Flint Hills in Kansas. In such locations, layers of harder lithologies, even when thin, are key controls on landscape formation. This is because blocks that detach from harder layers, armor soil downslope against erosion and create obstacles behind which eroding soil can accumulate. However, it is not known how properties of such detached blocks change during their stay on the hillslope, or which factors affect such changes. My objective in this study was thus to understand the mechanisms of production, transport and rates of change of blocks on hillslopes, specifically of Detached Limestone Blocks (DLBs) in the Flint Hills KS, USA. I used field measurements and Structure from Motion photogrammetry to quantify DLB position and properties on slopes under hard limestone layers. Observations from the sites suggested DLBs decrease in size with distance downslope, DLBs hardness values do not change significantly while being transported downslope, DLBs in either vegetation type harden at similar rates and have block orientations similar with the residing hillslope, and lastly, that slope steepness has an influence on DLB relative slopes, potentially highlighting different transport methods taking place in steeper hillslopes.

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Abbreviations

DLB – Detached Limestone Block

SfM – Structure from Motion

Tiles – DLBs which have substantially larger length and width than height

Piles – DLBs which have substantially smaller length and width than height

Equations

Cubiness = (Height x Length x Width) / ((Height + Length + Width)/3)^3

Acknowledgements

Firstly, I would like to thank Arnaud Temme for his supervision, advice, and guidance throughout this whole process. In addition, I would like to thank Abbey Marcotte and Michael Molloy for all the days they joined me during my fieldwork in Konza Prairie. The Geomorphology group at Kansas State University, including but not limited to Abigail Langston, Arnaud Temme, Abbey Marcotte, Colleen Gura, Jordan Watson, Nathan Brownstein, and Nick McCarroll, who were a tremendous source of inspiration. As well as the entire faculty of the Geography department at Kansas State University. Also, I would like to thank all the members of my committee for all their help and comments. Lastly, I would like to thank my parents, grandparents, other family members, and my close friends, without their constant love and support this thesis would not have been possible.

Introduction

Most of the world's landscapes evolve through an interplay between tectonic uplift and a range of erosional processes. When land gets uplifted (i.e. during continental collision), slope gradients with the surrounding land increase, and erosional processes such as landslides and creep are accelerated – first along the boundary and later, when river networks develop, also in the interior of the uplifted land. If uplift continues with constant rate, slope gradients will continue to increase until erosional processes remove mass from the land at the same rate at which it is added through uplift (Tucker and Hancock, 2010)

High plateaus and the hillslopes surrounding them are the last landforms to react to base level changes in a landscape due to fluvial processes carving valleys, which then cause slope gradients to steepen, leading to hillslope formation. During this adaptation to new base level conditions, hillslopes evolve to reach new base level conditions, but which factors affect this evolution, and their relative strength, are not entirely understood. One factor, lithology, explains how some rocks (such as granite and limestone) are better at resisting erosion than others (such as marl and shale), (Sklar and Dietrich, 2001). Clearly, this determining factor varies spatially across the Earth's surface (Stock and Montgomery, 1999), causing landscapes that have similar uplift histories to have dramatically different topographies – steeper and higher where rocks are comparatively resistant to weathering and erosion. However, some landscapes are formed of lithologies that alternate over very short distances. There is much less known about how hillslopes in such landscapes respond to base level change and erosion, leaving a distinct gap in the knowledge regarding how landscapes with heterogenous lithology change through time after uplift has ceased (Hurst et al., 2013).

Landscape Dynamics in Homogenous Lithology

Lithology has two main impacts on hillslopes: it co-determines weathering mechanisms and rates, and it co-determines geomorphic processes acting on weathered material on hillslopes (Clarke and Burbank, 2010; Glade and Anderson, 2018; Langston and Temme, 2019). Landscapes composed of homogenous lithology experience more equal erosion of hillslopes than landscapes overlying heterogenous lithology. This causes most soil-mantled hillslopes to be convex in form. Hillslope convexity is common in most hillslopes, with the degree of convexity depending on hillslope transport processes and rate of incision at base. Creep, rain splash, and biogenic transport play a significant role in the development of convex, soil-mantled hillslopes (Fernandes and Dietrich, 1997). Mechanisms that drive hillslope processes such as creep, bioturbation, and frost heave are well understood, but there are knowledge gaps when considering the weights of their individual impacts (Harris et al., 2008).

There are several things known about slope formation. First, the convexity of equilibrium soil-mantled slopes is due to the physical need for every location on the slope to be able to transport onward all incoming creeping material plus the material eroding from the location itself. Creep of surface material goes twice as fast when slopes are twice as steep, up to a threshold, then landslides are the main mechanisms of material transport (Roering et al., 1999). Additional knowledge about these interactions is needed because sediment transport connects hilltops and rivers, in upland channels bed material and sediment flux are composed almost completely of rock particles that have been removed from bedrock through physical and chemical weathering (Sklar et al., 2017). Very few field studies have characterized hillslope sediment supply as a function of lithology and delivery process, causing gaps in knowledge about these hillslope types (Migoń, 2013; Roda-Boluda et al., 2018; Ward et al., 2011).

Landscape Dynamics in Heterogenous Lithology

Hillslopes forming in rocks with different lithology not only display different weathering rates, and possibly different rates of creep between the different lithologies, but also exhibit complex interactions between these parts that are not easily predicted from properties of the individual lithologies. Rocks with different hydraulic properties are influenced by water in contrasting ways (Sullivan et al., 2019). For example, in a setting with mixed lithologies, limestone is permeable, and shale is not, therefore, water runs *over* shale and thus erodes its weathered product, whereas water runs *through* limestone, dissolving and widening cracks rather than eroding.

Rock properties also substantially determine which erosive processes have the greatest influence. Rocks that easily weather into fine-textured regolith and soil will experience erosion, whereas rocks that dissolve and break into hard blocks will provide large blocks to the hillslope. Lacking knowledge of how detached blocks are transported down hillslopes interferes with a complete understanding of hillslope topography.

Lithology thus has a significant control over regional topography. Topography itself also plays a major role in determining what geomorphic processes occur through regulating transport of material, organisms, and energy through the landscape (Swanson et al., 1988). Hillslope steepness has one of the strongest connections to erosion and weathering mechanisms. As slope steepness increases, the rates at which material is eroded also increases (Wischmeier and Smith, 1978). Topography influences surface water flow regimes spatially and temporally, controlling fluxes of material moving across the landscape. Surface water running down hillslopes causes significant erosion through increased velocity and variability, which causes hillslope erosion to be influenced by many factors. (Figure 1)

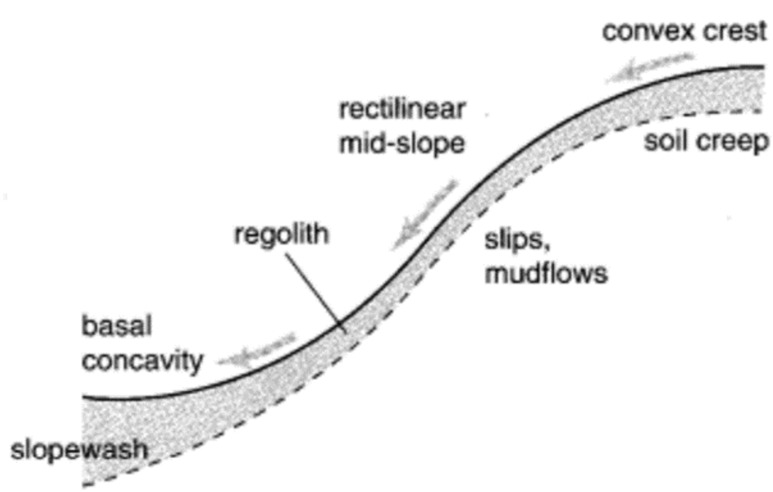

Figure 1. - Abstract illustration of soil transport and processes that facilitate that movement. At the top of the hillslope, steepness increases to facilitate transport of all arriving creeped material plus additional creeping material from every location (Fernandes and Dietrich, 1997).

Vegetation

Type and amount of vegetation significantly impacts which soil transport processes have the most influence on hillslope formation. Mainly, vegetation limits rain impact and surface water runoff, which can greatly inhibit soil transport (Zhao, 2019). This is accomplished through vegetation coverage intercepting rainfall and reducing kinetic energy of raindrops, thus preventing soil erosion. Rainfall energy has been identified as a primary cause of erosion on hillslopes, which is more likely to occur to areas lacking soil cover (Zuazo and Pleguezuelo, 2008). As a result, approximately one sixth of the land area in the world has been affected by soil degradation associated with global vegetation density reduction, and about half of the affected area has been reported as being damaged by water erosion (Hurni et al., 2008). Runoff and sediment losses have been shown to decrease exponentially with increasing vegetation coverage (Dong et al., 2015; Snelder and Bryan, 1995).

Vegetation has substantial effects on hillslope sediment because plant roots are predominantly located in the upper soil profiles. Schenk and Jackson (2004) estimated that on a global scale 95% of roots are in the top 2 m (Schenk and Jackson, 2004). Root structure and total ground cover differ between grasses and trees. Surprisingly, grasslands have higher percent of total ground coverage than forested locations (Roering et al., 2010). Additionally, roots in these landscapes do not have the potential forcing to pry rock blocks from ledges, which is possible with tree roots in forested locations. Not only do trees support and act as drivers of physical weathering, but chemical weathering rates are also increased through tree root infiltration, due to tree roots acting as valves that redirect surface water down root surfaces (Brantley et al., 2017). It remains unclear whether trees are more important as hillslope stabilizers or as catalysts of bedrock erosion and soil formation globally (Brantley et al., 2017). In semi-arid areas where water is a limiting resource for vegetation, trees must grow deep roots in fractured or porous bedrock, accelerating chemical weathering in the process (Lewis and Burgy, 1964).

The previous section highlights the substantial interactions that root systems have with near surface bedrock and with block release. After release, trees may act as stabilizers or mobilizers of surface transported blocks. Tree fall would cause the mobilization, whereas tree presence may support and stabilize blocks (Finke et al., 2013; Marijn Van Der Meij et al., 2020).

Figure 2. -Site photos showing different ground coverages between grassland (left) and forest (right) locations. Schmidt hammer for scale (length).

Block detachment from ledges

As a result from the processes described above landscapes developed in layered sedimentary rocks feature scattered blocks originating from the more resistant layer partly covering the less resistant layer (Glade, Anderson, & Tucker, 2017). Scarp or cliff landforms are eroded by rockfall, block by block mining, and slumping according to parent layer thickness, jointing and rock resistance to weathering (Howard and Selby, 1994). . In the context of this study in Kansas topographies, undercutting may be the most common process – but this has not been confirmed in literature.. Block size is determined by joint spacing and hardness of the original rock layer (Glade & Anderson, 2016).

Post-detachment block transport

In heterogenous lithologies, different rates of weathering cause more resistant blocks to remain on the slope surface. Continued erosion and transport of surface material leads to block movement downslope. However, the mechanisms involved in block detachment and block movement downslope remain largely unknown and are distinct from those governing smaller grain sizes (Abrahams et al., 1984; Schumm, 1967; Sklar et al., 2017). Simulations by Glade et al. (2017) presumed that detached blocks armor hillslopes and thus affect morphology. Specifically, a landscape evolution model was used to test feedbacks between weathering, block transport, and soil transport as explanations for landform shape. It was found that detached blocks can dictate hillslope shape, and substantially influence relief and persistence of topography. However, the role of block properties such as size and thickness relative to size has not been quantified.

Blocks can move downslope through two different mechanisms. First, through tumbling, where blocks are transported when a force is exerted on them. This process would result in faster movement when blocks are small, yet be inhibited by tile-shaped non-cubic blocks. Second, through creep, this is a process through which blocks are slowly transported downslope along with the rest of the mobile regolith. This process would presumably be more efficient for smaller blocks.

The steeper a slope is, the easier tumbling and rolling should become, and the less power should be required to start motion. Abrahams et al (1984), working in the American Southwest, found that overland flow of water has more effect on block transport than creep has on slopes of at least 24°. The slopes of the hillslopes in this study range between 24-31°. Our site varies in environmental variables from a more arid climate, primarily due to the higher density of surface vegetation of the prairie setting. The sites in this study have less influence of overland water flow. Extensive vegetation ground cover may cause creep to act as the driving force of block transport; however, few studies have measured the mechanisms of slow, block transport on hillslopes. One study was conducted in Western Colorado, USA by Schumm (1967), that found blocks transported by soil creep traveling downslope ranged from 3mm to 70mm per year, varying based on soil characteristics, microclimate, and accidental disturbances.

Post-detachment block weathering

As blocks move downslope, they are exposed to weathering processes. Different weathering processes dominate under different conditions and for different lithologies. Weathering of surface blocks can be divided into two main pathways: surface weathering, where block size steadily decreases through time by losses occurring along the surface, or fragmentation, when blocks fragment into multiple pieces(Román-Sánchez et al., 2021; Sharmeen and Willgoose, 2006). In a case where blocks mainly consist of limestone, surface weathering through dissolution may be the main weathering process. This would be because the gentle slopes of the prairie prevent block tumbling and subsequent fragmentation (Eppes et al., 2010; Hurst et al., 2012).

On the other hand, frequent prairie fires may have caused spalling due to thermal expansion. Case hardening is a dissolution related phenomenon witnessed in landscapes that have limited fragmentation of detached blocks, and where instead blocks experience weathering through dissolution (Dorn, 2004; Grab et al., 2011). This process is accomplished through evaporation of water from within detached blocks.This water contains previously dissolved minerals that are brought to the block surface and there recrystallizes, resulting in a harder block outside. Microclimates have a substantial effect on case hardening due to varying amounts of precipitation and rates of evaporation. For example, regions that experience hot dry summers with brief rains or semi-arid conditions may experience higher rates of case hardening.

Soil armoring by released blocks

Detached blocks begin stalling sediment transport after the moment of detachment. Blocks can act as colluvium dams that trap colluvium behind the blocks and downslope of the block sediment is pulled away (Principaud et al., 2018). Additionally, blocks protect sediment under them from erosion. This process is known as, soil armoring, and is described as the process of surface coarsening that occurs due to the selective removal of the finer transportable materials from the soil surface by overland flow, leaving coarser, less mobile materials behind (Fig. 3). As the fine transportable materials are progressively removed, the fine fraction of the soil becomes coarser and is more difficult to remove so that sediment transport decreases (Sharmeen and Willgoose, 2006). Detached blocks are an extreme example and decrease erosion by increasing soil armoring on underlying hillslopes through preventing sediment mobility.

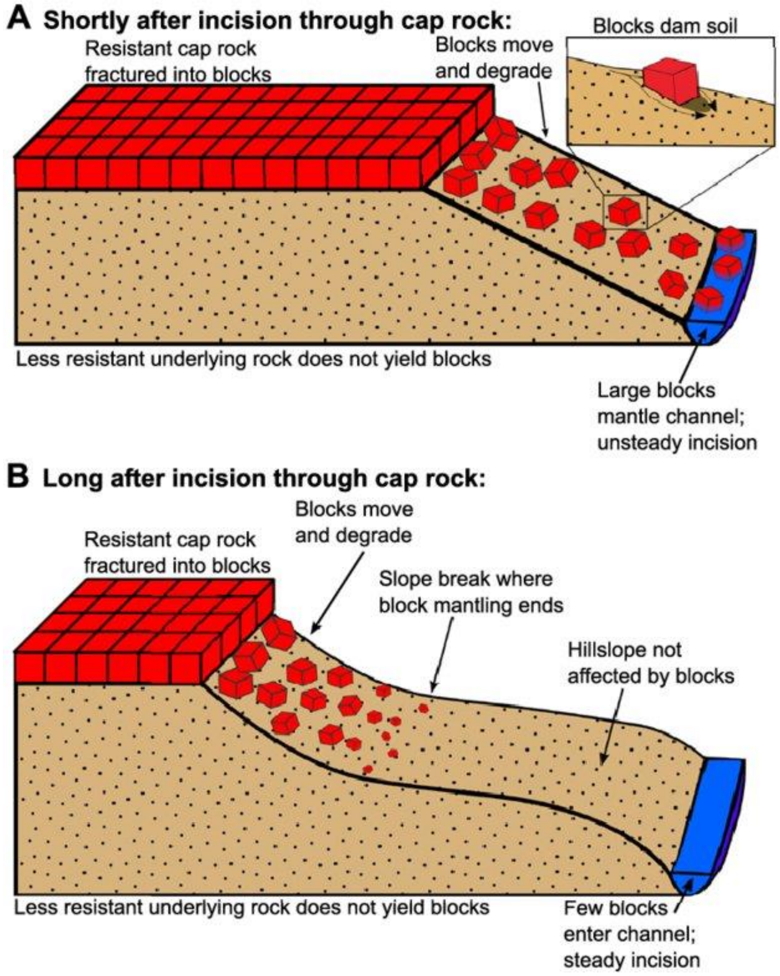

Figure 3. - Conceptual diagram from Glade et al., (2019, p. 651), that highlights how more resistant blocks detach to form surficial blocks that then are transported downslope through a variety of processes.

Objective

As I reviewed above, substantial gaps remain in our understanding of the role of blocks on hillslopes.My objective in this study is, to provide a better understanding of the factors and mechanisms that influence detachment and movement of detached blocks downslope. Konza Prairie Biological Station near Manhattan, Kansas in the United States was chosen as the study area because of the abundant presence of detached limestone blocks from the benches of the landscape. The area's protected status minimizes human impacts on the blocks.

Hypotheses

Based on the background presented above, I hypothesize that:

1. Detached Limestone Blocks (DLBs) decrease in size downslope from ledges. I expect this to be because any weathering processes should result in smaller blocks.
2. DLB hardness increases with distance downslope, due to the expected impact of case hardening on limestone lithology in a semi-arid climate.
3. DLB hardness increases more with distance downslope in grassland sites than under forest. I expect this because evaporation happens more rapidly in grassland settings than in forest settings.
4. Tile-shaped blocks have a steepness and orientation more closely mirroring the slope they are located on than cube-shaped blocks. I expect this because cube-shaped blocks should be more prone to tumbling than tile-shaped blocks. Tumbling is expected to change a blocks orientation and steepness relative to the slope.
5. DLBs on steeper hillslopes are less likely to have similar orientation and steepness to slope. This is expected because blocks on steeper slopes are more likely to tumble.
6. Block undercutting by erosion of the underlying shale is needed for block detachment. I expect this because a mechanical forcing is required to detach the limestone blocks from the ledge of detachment.

Study Areas

The main study area is the Konza Prairie Biological Station, located in the Flint Hills in northeastern Kansas, USA, hereafter referred to as "Konza Prairie". Konza Prairie is a National Science Foundation Long-Term Ecological Research and Biological Station since 1971 (Macpherson et al., 2008), and consists of 3,487 hectares of never-ploughed native tallgrass prairie. Konza Prairie is divided into 60 separate watersheds, each with a specific management strategy that includes periodic burns and grazers and is used for comparative ecological research (Vero et al., 2017). Above ground fauna and flora often define the prairie yet the below ground biomass can be of the same magnitude as the visible areas (Weaver, 1968).

Watersheds K1A and N1A were selected. Both watersheds are burned annually, but N1A is grazed by bison, whereas K1A is ungrazed. Four hillslopes were selected, one pair in Threemile limestone in a grassland location in K1A and another pair in Cottonwood lithology in a forested location in N1A (Figure 4). This study design was used to isolate effects of vegetation and lithology on DLB transport. A steeper and nearby flatter hillslope formed each pair of hillslopes, to also attempt to isolate slope steepness effect on DLB transport. Hypotheses 1 through 5 were tested using these four hillslopes.

The secondary study site is a roadcut along South Scenic Drive, also in Manhattan KS (39.17 N^{o}, -96.64 W^{o}). This site was the location where I expected to observe block release and test hypothesis 6. The area was chosen due to the clear exposure of alternating layers of shale and limestone that seemed to allow observation of block release better than flatter, soil-covered hillslopes. Observable erosion of both lithologies can provide insight into what processes are influencing hillslope formation in a natural setting.

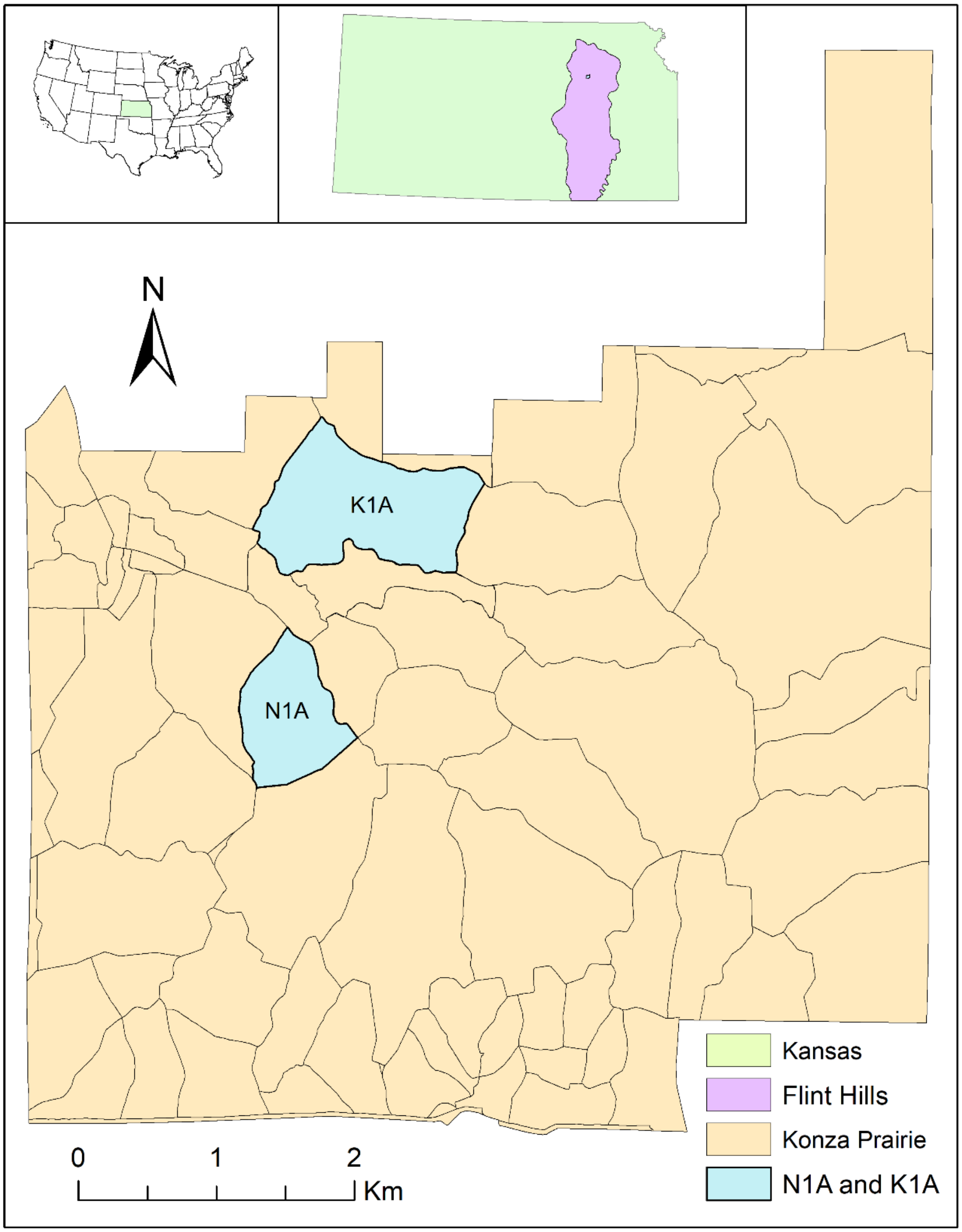

Figure 4. - Location of Kansas in the USA (A) and Konza Prairie and the Flint Hills in Kansas (B) (data from Konza Prairie Long Term Ecological Research Program, 2010; United States Census Bureau Geography Division, 2018; United States Environmental Protection A.

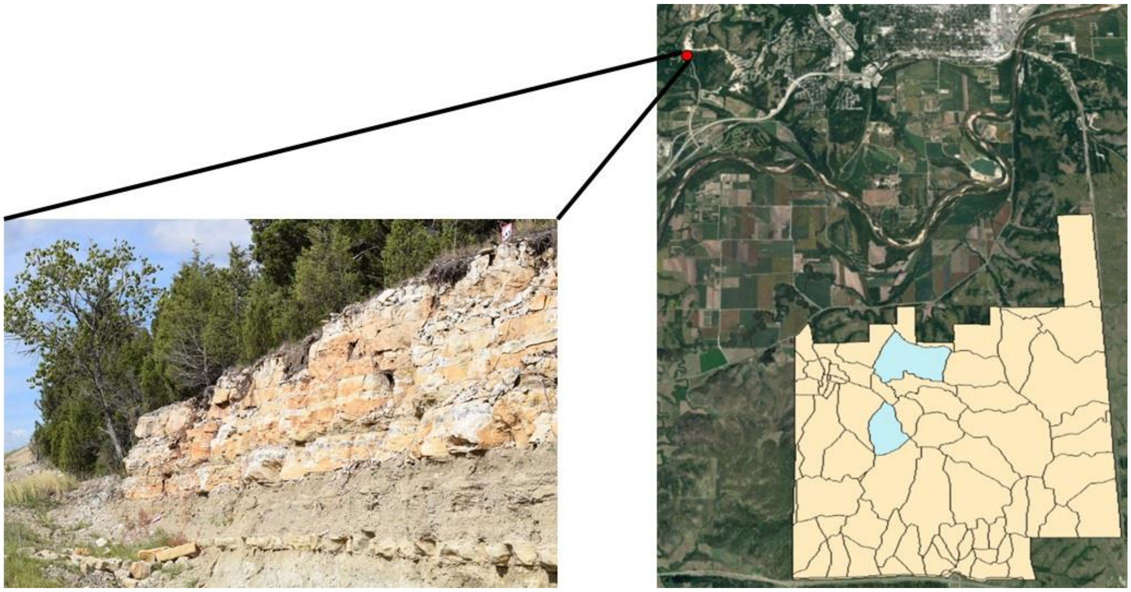

Figure 5. Field site #2 (Shown as a red dot) shown in relation to the other fieldwork sites of the study.

Climate

The Flint Hills region has a continental climate with hot summers, cold winters, moderately strong surface winds, and relatively low humidity. Average maximum and minimum temperatures in January are 8.6^{o}C and 3.2^{o}C, and are 33.2^{o}C and 20.0^{o}C in July(Abrams and Hulbert, 1987; Briggs et al., 2002). The average precipitation is 835 mm with 72% occurring during the 6 warmest months (Abrams and Hulbert, 1987). The area receives an average of 521 mm of snowfall per year, which equals ~52mm of liquid water. In 2019, there were 126 days with minimum temperature below 0^{o} C.

Geomorphology

Konza Prairie elevation ranges from 320 to 444m above sea level. A dendritic stream pattern has established, highlighting the fluvial influence on the landscape in planform (Knapp et al., 1998). Hillslope topography is nonetheless complex, with limestone benches and relatively steep slopes of shale-based material dominating the landscape (Vero et al., 2017). Underlying bedrock is characterized as alternating layers of horizontal units of high hydraulic conductivity limestone and low hydrologic conductivity mudstone (i.e. shale) layers which are 1 to 2 and 2 to 4 meters thick, respectively (Figure 6) (Macpherson, 1996). The two studied hillslopes under grassland in catchment K1A are situated in and below the lithological layer of the Threemile Limestone section, at approximately 400m elevation. The two studied hillslopes under forest in catchment N1A are located 40m lower in elevation and are associated with the Cottonwood Limestone layer (Figure 6) (Smith, 1991). The differences in limestone thickness and hardness between both layers complicated direct comparison between forested N1A slopes and grass-covered K1A slopes.

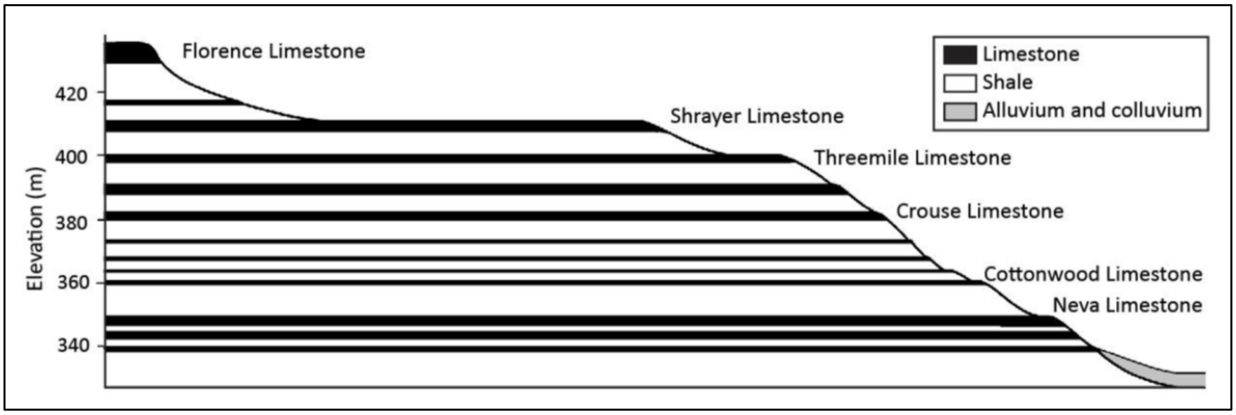

Figure 6. - Cross-section of lithological layers of bedrock units in Konza Prairie (Smith, 1991).

The stepped slope morphology was created through differing weathering resistances between chert-bearing limestones and less resistant shales (Figure 6,Figure 7). Tectonics played a limited role in this landscape, there is no presence of faults or folds in the area (Oviatt, 1998). Erosion of the geologic layers is caused by tributaries of the Kansas River, creating a landscape of dissected hills. Groundwater flow is influenced by a slight dipping angle of local bedrock by 0.19^{o} and vertical joints and fractures (Oviatt, 1998; Smith, 1991). Most soils in Konza Prairie are less than 1m thick, with the thickest soils located at the lower parts of slopes and in valleys (Macpherson, 1996). Macpherson 2018 found ~540kg/ha/yr of calcite is removed from Konza Prairie hillslopes through dissolution which translates into long-term, overall denudation rates of ~0.02 mm/yr.

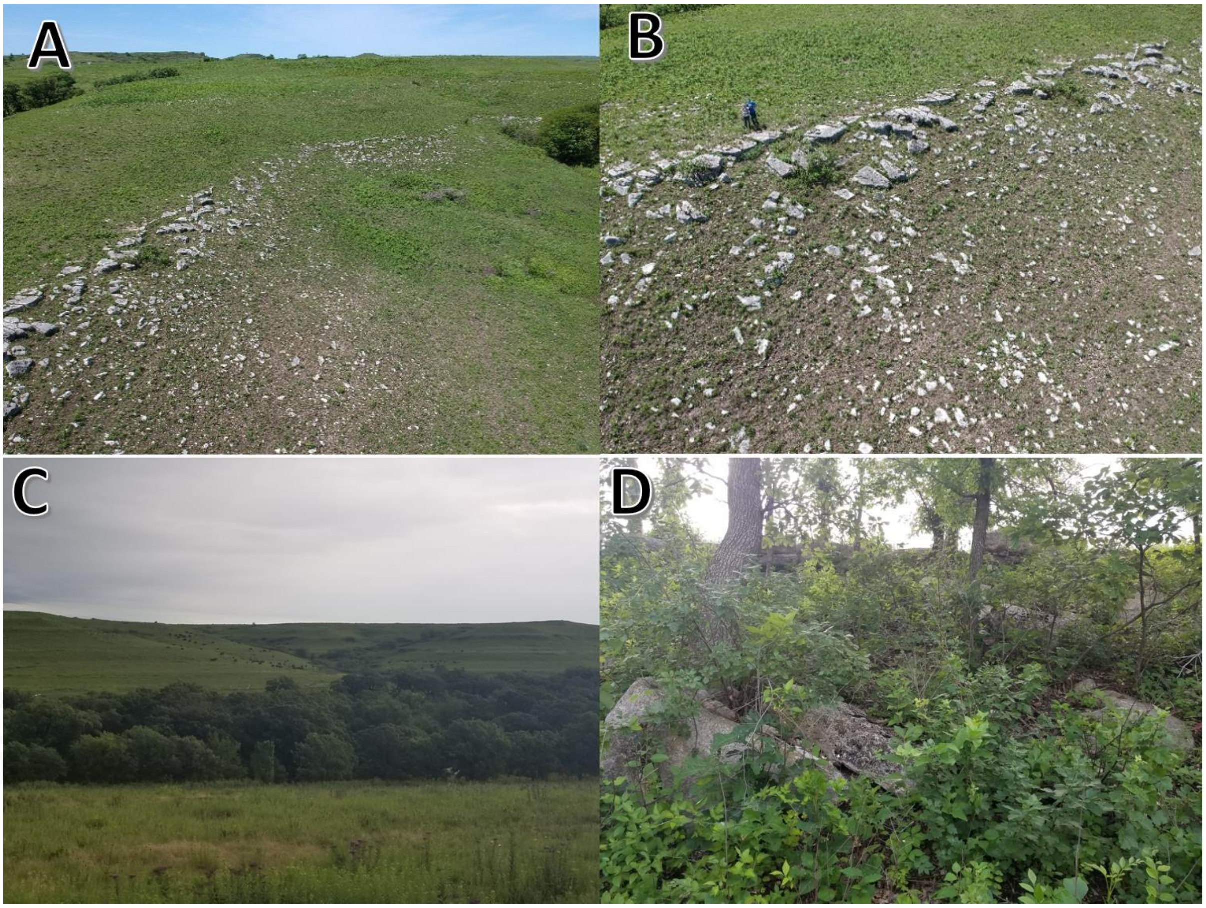

Figure 7. - Overview of the grassland locations with surrounding area (A). Two researchers located (upper left corner) in the "steep grassland" site to show scale of the sites (B). Bench and slope morphology (C). K1A site location showing forest vegetation (D). Photos taken by Abbey Marcotte (A and B) and Michael Stumpff (C and D).

Studied Hillslopes

Watersheds K1A and N1A are in the northwestern section of Konza Prairie. The two N1A sites, called here Grass 1 (G1) and Grass 2 (G2), are in high elevation (391m) grassland locations, with north facing slopes that clearly show the bench hillslope morphology (Figure 7, C). Grass 1 and Grass 2 differ in slope steepness (24^{o} vs 31^{o}). The two K1A sites, called here Forest 1 (F1) and Forest 2 (F2), are in lower elevation (360m) forested area, with slopes facing east in one site and west in the second (Figure 7, D). Forest 1 and Forest 2 also differ in slope steepness (25^{o} vs 29^{o})

N1A can be categorized as the “grassland and grazing” location, while K1A can be categorized as “forested and non-grazed”. The intention of the four sites is to attempt to isolate the influence of vegetation and slope steepness on DLB transport. There was also variation in the length of hillslopes of the site locations: the forest locations had a shorter overall slope (15m) than that of grassland locations(25m).

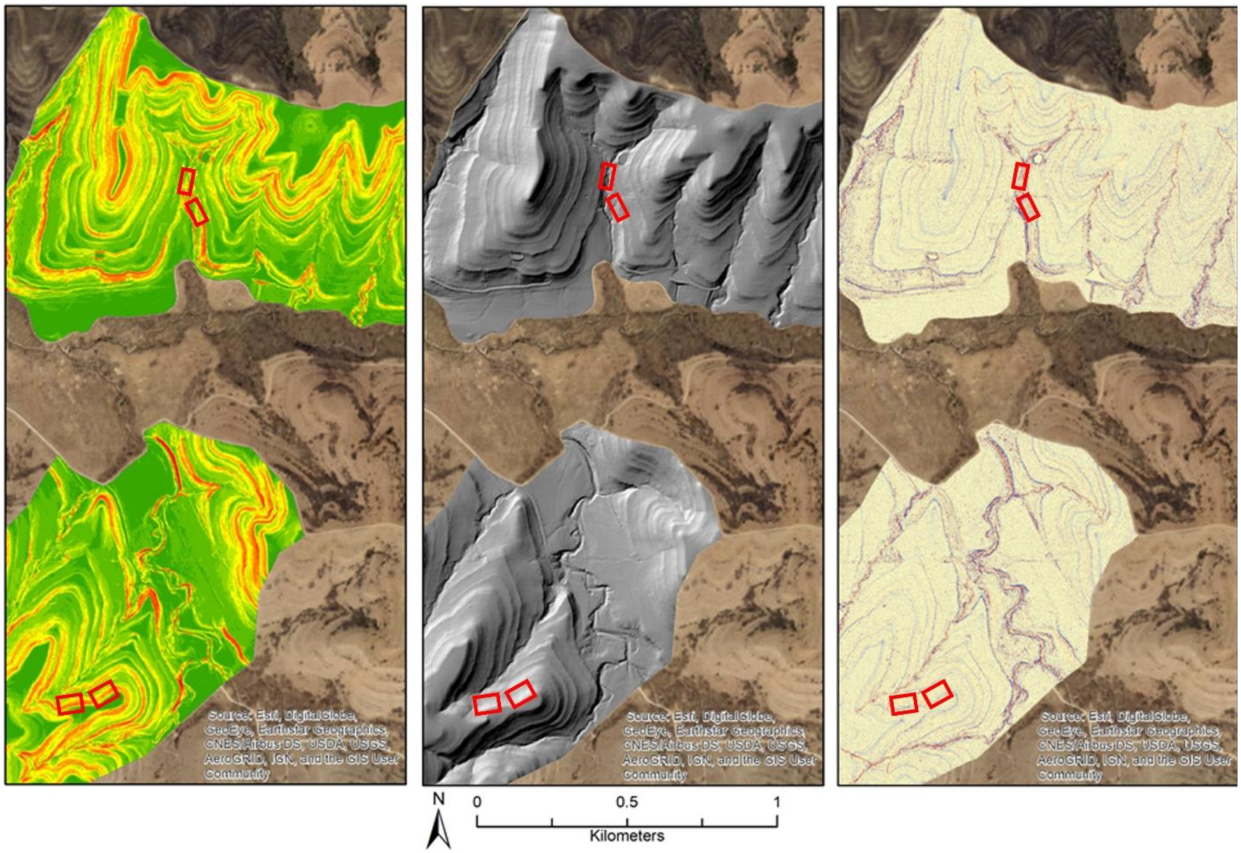

Figure 8. - Maps showing slope steepness, hillshade, and curvature of field sites observed in the study. Red boxes show the location and orientation of the observed hillslopes. Forest locations are located in the north of the image, while grassland locations are in the south (left to right).

Native Grazers (Bison)

The North American Bison is a large herbivore that ranges across the grasslands of central North America. Bison herds impact landscapes primarily through trampling, wallowing, and loading of slopes (Butler, 2006; Knapp et al., 1998). The two grassland hillslopes contain grazing bison that migrate throughout the two sites, which are believed to increase block fracturing and tumbling (Govers and Poesen, 1998).Bison are absent from the forested sites. Trails are visible in the landscape where the bison herd migrates along the slopes of the grassland sites. During fieldwork, there were multiple days I discovered that the grassland sites hillslopes were populated by a bison herd of ~20-30 specimens.

Figure 9 - Bison trails left behind in the tall grass of grassland locations (Left). A bison hoof print along the hillslope of the flat grassland location (Right).

Methods

Field work

Each limestone ledge exposure, the underlying hillslope, and the blocks on the hillslope were described in the same way. First, properties of the ledges were recorded. Since the ledge is the point of origin for DLB production, ledge properties can explain why certain trends appear in the properties of DLBs. Recorded properties were: thickness of the layer, dominant fracture direction, fracture spacing (the shortest distance from fracture to fracture), and hardness. Hillslope properties also influence block properties and determine transport rates. Therefore, second, properties of the hillslopes underlying ledge exposures were recorded: steepness and orientation (azimuth).

Thirdly, all blocks on each hillslope were described. A rectangular grid was applied to aid in organization and locating of blocks. Each individual grid cell was 5x5 meters (Figure 8). Inside each grid, all DLBs with a length or width larger than 25cm were described. In this way, 524 blocks were observed across the four slopes. Properties that were recorded for all blocks are orientation (azimuth), height, length, width, block slope (dip), pitting density, shape, distance to ledge, whether trees blocked transport, whether a DLB was supported by another DLB, and whether the block was submerged in soil material. Block slope was gathered using a level, while pitting density and shape were assessed in the field qualitatively.

Rock Surface Strength

Measurements of hardness were made using a Proceq Rock Schmidt Hammer on all blocks larger than 60 x 60 cm. Schmidt hammers provide measurements of surface hardness and are widely used for estimating mechanical properties of rock material (Aydin and Basu, 2005). The 60 x 60 cm threshold was used because only blocks weighing a few tens of kilograms or more provide reliable rebound or r values (Katz et al., 2000). Twenty hardness observations were made for each block to ensure that an accurate average could be calculated following the suggestions by Niedzielski (2009) and Selby (1980). (Niedzielski et al., 2009; Selby, 1980).

Data Analysis

Data were analyzed using Microsoft Excel and RStudio Desktop (Version 1.4.1106). R is a programming language and free software used for statistical computing that is widely used among statisticians and data miners for data analysis. Block orientation and steepness were expressed relative to the orientation and steepness of the slope that they were on to gain a measure of the conformity between blocks and slope. Linear models and ANOVA tests were used to test hypotheses. Cubiness was calculated using the formula found on page 3.

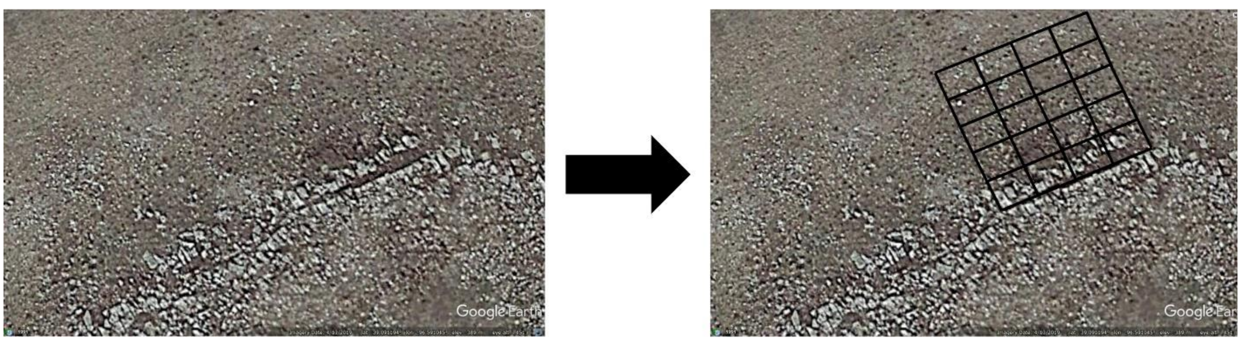

Figure 10. - Grid overlay method used to organize DLB's by location along an x and y-axis along the site hillslopes.

Structure from Motion

I used Structure from Motion (SfM) photogrammetry at the secondary study site along Scenic Drive in Manhattan, KS. Approximately monthly photosets were recorded to track evolution of a man-made, originally smooth vertical wall consisting of alternating layers of shale and limestone, mirroring the heterogenous lithology of the layers in the natural setting at Konza Prairie. Each photoset consists of ~1000 photos of the roadcut from varying angles and distances. Here, the November 2018 and November 2019 sets are used.

SfM methodology was chosen for this study because it is a low-cost photogrammetry technique that can be used to obtain high-resolution datasets at varying scales. Traditional photogrammetry methods require either GPS location and position of cameras or 3D locations of ground control points (Westoby et al., 2012), but this is costly. SfM methodology solves these issues, allowing for creation of fine-scale Digital Elevation Models (DEM) at a greatly reduced cost when compared with other methods of acquiring micro-scale DEMs (Locher et al., 2018).

The ability of SfM to produce fine spatial resolution, allows for increased knowledge of local phenomena as compared with regional analysis when using courser resolution DEMs. Analyzing small temporal scales can also be accomplished with a high frequency of photosets gathered from the study location. Ultimately, I conducted an annual analysis by comparing two datasets of photos taken one year apart. Comparing imagery over a temporal scale allowed for qualification of erosion rates and zones by assessing elevation differences through time. This allowed a much more detailed understanding of local processes that may differ from previous studies in other landscapes that have different environmental factors (James and Robson, 2012).

A Nikon D5300 Digital Single Lens Reflex (DSLR) camera was used. This camera takes photos that are 24.2 megapixels, with an ISO range from 100 – 12800. A lens with a fixed focal length of 50mm was used to avoid small focal length differences (Hesse, 2014). Photos were taken using Nikon's .NEF format and converted to. DNG using Adobe Digital Negative Converter. As mentioned above, a fixed focal length lens was used because varying zooms can negatively impact quality of the photos (Sanz-Ablanedo et al., 2012). The photo surveys were conducted systematically to ensure that all features along the site were captured in the survey. Initial photos were taken from a distance to capture the entire site, with additional photos taken from closer distances at differing angles. Markers with a known size were set in every photo survey to provide scale to the created coordinate system in Agisoft Metashape (Version 1.6.2). The markers have specific dimensions that can provide a scale to the resulting point clouds. Markers were located long the tops and bottoms of the site to make sure scaling was applied throughout the area.

The computer used for the processing consisted of: Intel Xeon Processor E5 (1620 @ 3.6 GHz, single CPU), 16 GB ram, 1 TB solid-state HDD and a NVIDIA Quadro K2200 4 GB graphics card. The "align photos" tool in the Workflow toolset was used on "High" accuracy to create the initial sparse point cloud. Photos that remained unaligned after 3 iterations of this step were removed before moving forward. Once photos were aligned, dense point cloud creation was performed at medium quality (due to computational limits of the PC). A scale was then applied to point cloud using the GCPs within the images, to assign real world distances to the cloud. At this point, the cloud was exported as an .LAS file for cloud-to-cloud comparison within Cloudcompare.

Cloudcompare software (Version 2.11.2) was used to overlay our resulting point clouds and accurately produce an image showing change through time periods. DoDs (Digital Elevation Models of Difference) are the final outcomes that can be derived from the initial photos taken in the field. In my case, DoDs were not achievable due to computational setbacks. Therefore, I settle for visual inspection of these final images, and manually highlighted areas of localized erosion or deposition.

Results

Ledge properties

The Cottonwood ledge in the forest locations (81.6 cm ± 25.3) is substantially thicker than the Threemile ledge in grassland locations (30.3 ± 16.9cm) ($p < 0.01$) (Table 1). The Threemile Limestone overlying the flat slope was the thinnest ledge in the study (15 ± 2cm). The ledge width is similar between Threemile (135 cm ± 45.5) and Cottonwood ledges (154 cm ± 42), with the flat Threemile site having the smallest width (102 cm ± 37). The fracture spacing is not similar between grassland and forest sites (Grass = 83 cm, Forest = 145 cm, $p < 0.01$). Fracture spacing within forested sites is thus substantially greater than the grassland sites, causing forested blocks to have greater volume on average. Based on these numbers, expected block volumes and shapes can be estimated (Table 1). Blocks are expected to be smallest and least cubic for the slopes under the Threemile Limestone ledge (approx. 961 10^3 cm^3 vs. 3,302 10^3 cm^3 and 55% vs 88% resp.), especially for the flatter of the two slopes (106 10^3 cm^3 and 44%).

Hardness values of the ledges show initial hardness values vary between 45 and 51 units and are not significantly different between the two limestone units ($p < 0.01$) or among the four slopes (Table 1).

Table 1. - Means and standard deviations of properties of the ledge of detachment across all sites.

		Threemile Limestone, grassland		Cottonwood Limestone, forest	
Ledge properties	Unit	Flat (24°)	Steep (31°)	Flat (25°)	Steep (30°)
Number of observations		5	5	5	5
Layer thickness	cm	15 (± 2)	46 (± 9.1)	69 (± 24)	94 (± 23)
Ledge width	cm	102 (± 37)	174 (± 10)	167 (± 49)	135 (± 11)
Fracture spacing	cm	69 (± 20)	107 (± 6)	171 (± 55)	105 (± 23)
Expected block volume	cm^3	106 10^3	856 10^3	1970 10^3	1332 10^3
Expected block cubiness	%	44%	66%	79%	97%
Ledge hardness	Rebound value	51 (± 8)	45 (± 13)	50 (± 16)	47 (± 12)

Block properties

Flat and steep Threemile (grassland) hillslopes held 189 and 156 DLBs, respectively, while the flat and steep Cottonwood (forest) hillslopes held 91 and 86 DLBs, respectively. More blocks were observed in the grassland sites because they have longer slopes than the forested sites (approx. 25m vs 15m, resp.). DLBs in forested hillslopes are higher than DLBs in grassland hillslopes (16 ± 13cm vs. 12 ± 13cm, $p < 0.01$). DLBs in forested hillslopes also have larger surface area than DLBs in grassland hillslopes (15.2 ± 21 10^{-2} m^2 vs. 11 ± 19 10^{-2} m^2, $p = 0.02$). Thus, calculated block volumes in the forested hillslopes are substantially larger than grassland DLBs (50 10^{-3} m^3 vs. 36.2 10^{-3} m^3). The largest DLB volumes were found in the steeper slope sites, with the steep Threemile (grass) site having the largest block volumes (68.8 10^{-3} m^3). Blocks located in Cottonwood (forest) sites were more cubic than blocks located in Threemile (grass) sites (51 ± 24% vs. 43 ± 23%, $p < 0.01$, Figure 11).

Therefore, DLB volumes do not meet our expectations based off the ledge of detachment expected block volumes. Expected block volumes were substantially greater than observed DLB volumes on all four slopes (cf. Table 1,Table 2). Block cubiness values in the Threemile (grass) sites were near what was expected, but blocks in the Cottonwood (forest) sites were less cubic than expected (Table 1).

Block volumes in steeper sites were also substantially larger than in flatter sites (61 ± 13 10^{-3} m^3 vs. 23 ± 10 10^{-3} m^3, $p < 0.01$). Blocks on steep slopes were more cubic blocks than blocks on flatter sites (53 ± 23% vs. 39 ± 22%, $p < 0.01$) (Figure 11).

DLBs in the Threemile (grass) sites have similar relative block slopes (relative to the hillslope steepness) than DLBs in the Cottonwood (forest) sites (5 ± 12.5° vs. 4 ± 15.7°, $p = 0.44$). Relative block orientations are similar across all Threemile and Cottonwood sites (35 ± 37° vs. 32 ± 42°, $p = 0.35$).

DLBs in the steeper slopes (both grassland and forest) have greater relative block slopes (relative to the hillslope steepness) than DLBs in the flatter sites (6.9° ± 13 vs. 2.7° ± 14, $p <0.01$). Relative block orientations are also greater in steeper slopes than in flatter slopes (44 ± 48 vs. 25 ± 26, $p < 0.01$).

Out of the total 524 DLBs observed, 263 DLBs were large enough to conduct hardness tests. Grassland DLBs were harder than forest DLBs (48 ± 6 vs. 41 ± 7.4, $p < 0.01$) (Table 2). DLBs on flat slopes were harder than blocks under the steeper slopes (48 ± 7 vs. 43 ± 7, $p < 0.01$). This is consistent with flatter ledges also having greater hardness values (Figure 11). Hardness values of DLBs on the Threemile (grass) slopes mirror the hardness values to their ledge of detachment, while DLBs on Cottonwood (forest) slopes are softer than the ledge of detachment (48 ± 6 vs. 41 ± 7, $p < 0.01$).

Table 2. - Detached Limestone Block (DLB) properties and standard deviations

		Threemile Limestone layer		Cottonwood Limestone layer	
DLB Properties	Unit	Flat Grass	Steep Grass	Flat Forest	Steep Forest
Observations		189	156	91	86
Height	cm	7.72	17.98	14.73	18.29
Surface area	10^{-2} m^2	6.0	17.1	14.4	16
Volume	10^{-3} m^3	8.9	68.8	52	47.6
Cubiness	%	35	52	48	54
Block slope	°	-3.65	-6.63	-0.73	-7.46
Block orientation	°	13.01	-5.23	3.96	5.6
Hardness observations		77	85	44	57
Hardness	Rebound Value	51.8 (± 5.3)	45.1 (± 5.9)	43.1 (± 6.8)	39 (± 7.3)

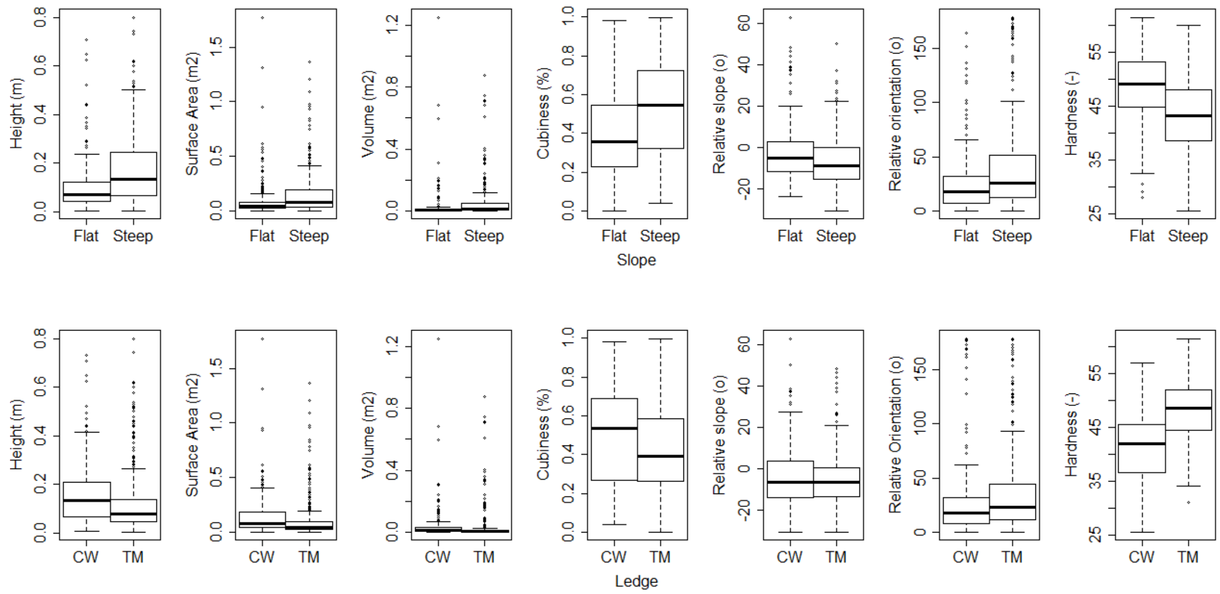

Figure 11. - Box plots showing block properties for both slope types (top row) and both lithologies (bottom row). Cottonwood (CW) and Threemile (TM) layers.

Table 3. - ANOVA test results showing probability that block properties are not affected by vegetation type / lithology and slope steepness.

Variable	Vegetation / Lithology	Slope Steepness
Classes	Forest/Grass Threemile/Cottonwood	Flat / Steep
Hardness	<0.01	<0.01
Height	<0.001	<0.01
Surface Area	0.02	<0.01
Volume	0.19	<0.01
Relative block slope	<0.001	<0.01
Relative block orientation	0.35	<0.01

Change in DLB properties with distance downslope from ledge

The impact of distance downslope from a rock ledge was investigated using the distance to the ledge as independent numerical variable in regression analysis. DLB height decreases as DLBs move downslope in all locations (-0.005 m/m), based on the entire four slope dataset ($p < 0.01$). The most substantial height loss was on the flat Threemile (grass) slope (-0.013 m/m). DLB surface areas also decreased across all slopes (-0.007 m^2/m, $p < 0.01$), with the flat Threemile (grass) slope having the most loss (-0.018 m^2/m). As a result, volumes of DLBs also decrease with distance downslope on all slopes (-0.003 10^{-3} m^3/m, $p < 0.01$), with the flat

Threemile (grass) slope having the fastest loss (-0.009 10^{-3} m^3/m, $p < 0.01$). DLB cubiness changes significantly with distance downslope on all slopes, except for the steep Cottonwood slope ($p = 0.4$). DLBs on the flat Threemile (grass) and Cottonwood (forest) slopes become more cubic with distance from slope. While DLBs on the steep Cottonwood (forest) slope became less cubic with distance downslope.

Relative block steepness increases significantly with distance downslope on the flat Threemile, and the steep Cottonwood slopes ($p < 0.01$, $p = 0.02$, resp.)~~.~~ Relative block orientation increases significantly with distance downslope in the steep Cottonwood (forest) slope ($p = 0.02$, Figure 12).

Hardness values increase with increasing distance downslope for the entire dataset (0.27 rebound value/m, $p < 0.01$). However, only the steep Threemile (grass) slope individually has the most significant change in hardness with distance downslope (0.3 rebound value/m, $p < 0.01$), while the other three slopes did not show significance with hardness changes with distance downslope.

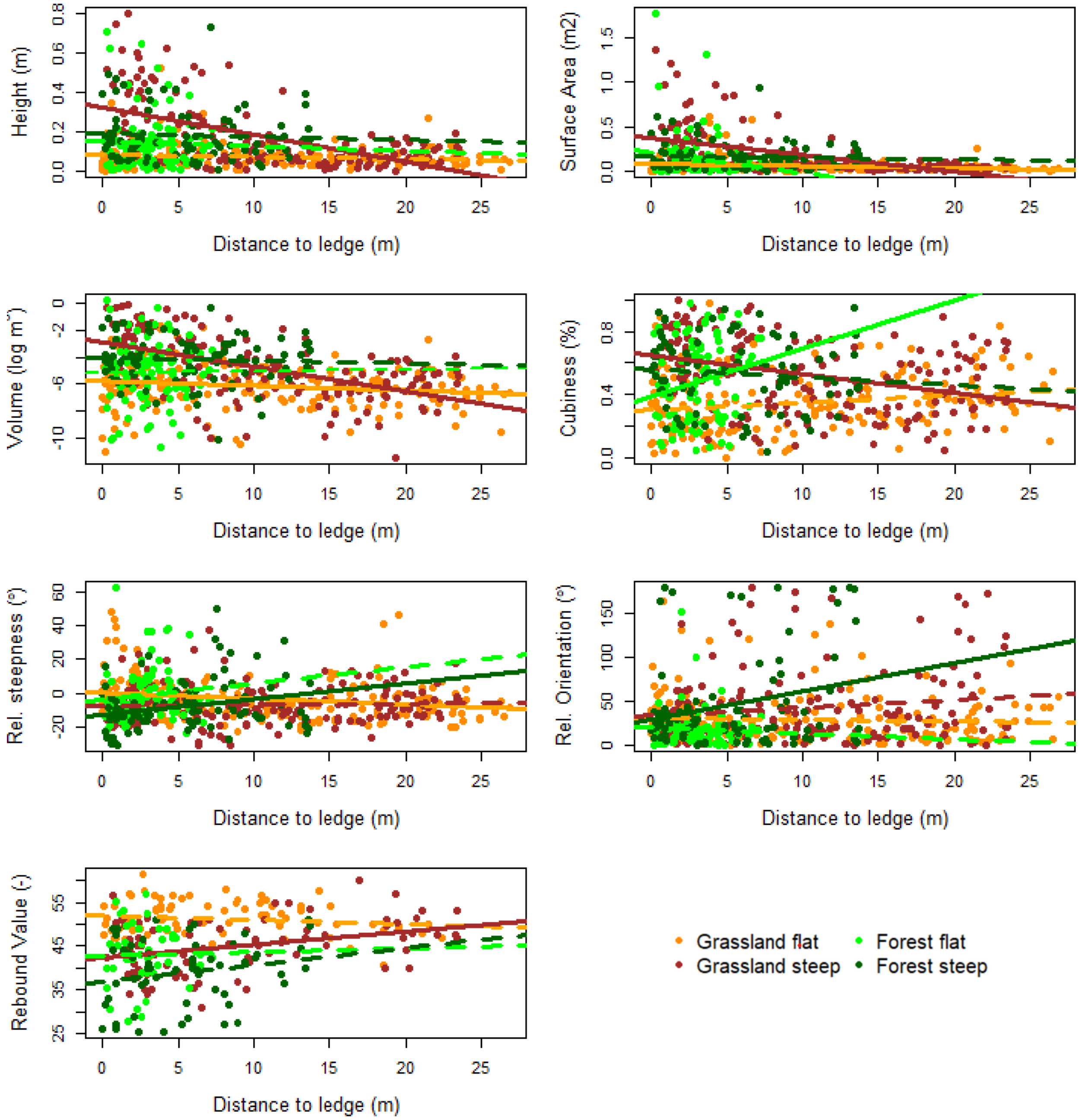

Figure 12. - Scatterplots of DLB properties as a function of distance from the ledge of detachment. Colors refer to the four studied hillslopes. All lines reflect linear models with distance to ledge, with solid lines reflecting significant relations, and dashed lines reflecting no significance

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Block detachment

Through quantitatively comparing the two point clouds of the Scenic Drive road cut one year apart, areas of increased weathering can be observed. Below are three figures that highlight specific areas of erosion. The comparisons are between point clouds created from photo datasets comprised of ~1000 photos per visit. Photos were taken in November for both the 2018 and 2019 datasets. Losses of shale were outlined by the red boxes, while the limestone losses were outlined by golden boxes. Figure 13 shows an overview image of the entire site in the upper half, while the lower half of the figure is the first set of comparison photos. While the next two figures (Figure 14 and 15) show comparisons on the top and bottom image.

The material that experienced the most erosion was shale, which was expected due to the high erodibility of shale compared with limestone. However, limestone losses were also visible, but in substantially smaller quantities and losses were spatially clustered in the upper section of the road cut. The first comparison image (Figure 14, A) shows shale (red boxes) being eroded most substantially directly underneath limestone layers. Limestone layers in the image showed limited change, however, the two golden boxes show two locations of limestone detachment. The next comparison image showed no signs of limestone erosion, but substantial shale erosion can be observed in the red boxes (Figure 14, B).

The next sets of comparisons once again capture the loss of limestone. All limestone detachment in the images occurs in limestone layers that are interacting with roots. The lower limestone units show no visible signs of erosion, even though these limestone layers are thinner than the higher limestone layers (Figure 15, A). Therefore, it seems that freeze thaw, or dissolution is being caused by root infiltration, thus, leading to block erosion and detachment in the upper layers nearest vegetation.

Figure 13. One point cloud, which are a product of >1000 photos per time sequence of the roadcut at Scenic Drive, visually indicating the kind of erosion that happened over a one-year timespan when compared with another point cloud of the same location. The blue color in the image shows NO DATA areas that Cloud Compare could not generate.

Figure 14. Comparisons of two point clouds, from November 2018 and 2019. Red boxes outline losses of shale. Golden boxes outline losses of limestone.

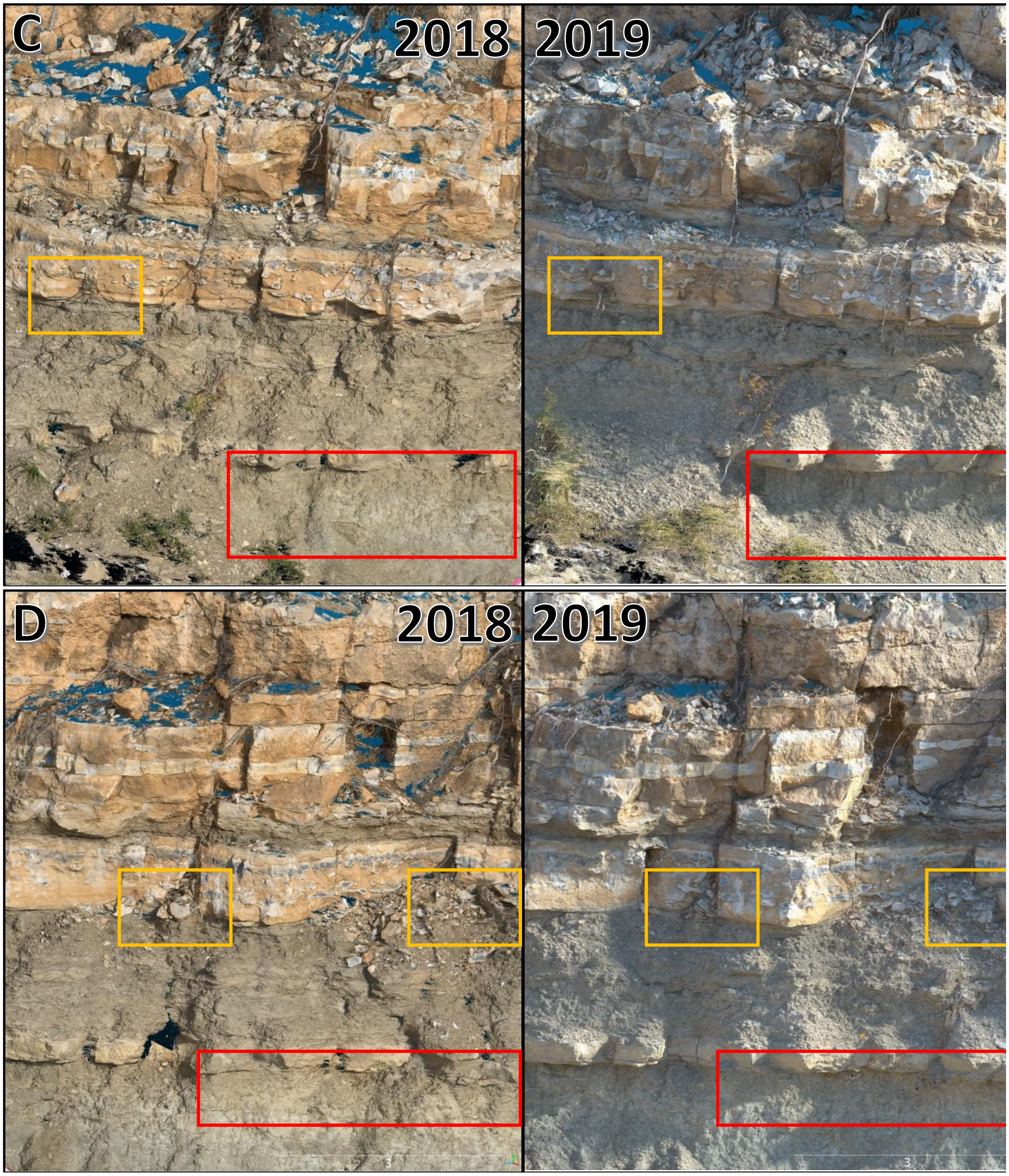

Figure 15. Comparisons of two point clouds, from November 2018 and 2019. Red boxes outline losses of shale. Golden boxes outline losses of limestone.

Discussion

While the two sets of sites at Konza Prairie varied in lithology, vegetation and slope steepness, commonalities were discovered in all site locations. Firstly, addressing my **first hypothesis**: regardless of vegetation type, DLB size was expected to decrease with distance downslope due to weathering processes. This was supported by a significant negative regression ($p < 0.01$), indicating that weathering over time affects blocks regardless of lithology, vegetation or slope steepness (Dunn. et al, 1964). The rate of reduction in DLB size, however, is not equal among all four slopes, with lower flatter slopes and slopes under Threemile limestone ledges experiencing greater reductions. The strongest reductions were on the flatter Threemile slope: -0.0005 m^3/m, whereas the average reduction across all four hillslopes was -0.003 m^3/m (Figure 12).

Konza Prairie has been measured to lose calcite mass at a rate of ~540 kg/ha/yr (Macpherson et al., 2008). Combining this with our observed rates of volume loss, would allow for a calculation of a maximum rate of block movement down from the ledge, expressed in m/yr. However, this calculation would require us to assume for the moment all of the following: that dissolution rate does not change with distance from the ledge, that dissolution only happens on the surface, that dissolution is spatially constant, and that Konza prairie exclusively consists of slopes like the ones in this study**.** These assumptions are certainly not remotely correct. At the very least, Macpherson et al among others find that dissolution happens mainly in the CO_2 rich subsurface and affects mostly windblown loess deposits instead of limestone blocks. Therefore, any estimate of block movement rate using denudation rates will first require quantification of all the assumptions.

The **second hypothesis** was that block hardness values increase with distance from the ledge. Indeed, taken together, all DLBs in the study appeared to be hardening as indicated by higher hardness values observed with increasing distance downslope ($p < 0.01$). However, on closer inspection, this apparent relationship turns out to be an artefact of the fact that blocks in forest are softer from the time of detachment (average hardness = 42) and on average closer to their ledge than grassland blocks (average hardness = 48). The second hypothesis was therefore rejected. The **third hypothesis** was that the change in DLB hardness values with increasing distance downslope would vary based on slope lithology. To answer the third hypothesis, taken separately, neither the Threemile (grass) blocks nor the Cottonwood (forest) blocks significantly harden with increasing distance from the ledge ($p = 0.19$, $p = 0.75$, resp.), even though the estimated coefficient of hardening is substantial in both cases (Grass = 0.09 m^{-1}, Forest = 0.07 m^{-1}). Therefore hypothesis #3 must be rejected for the moment.

Hypothesis 3 was proposed because I believed there would be more case hardening in grassland sites due to the difference in microclimates between grasslands and forests within Konza Prairie. Grasslands would experience faster evaporation after rainfall, leading to a larger fraction of water evaporating rather than infiltrating. Even though the hardening rates between vegetations were not statistically significant, grass sites did show slightly more hardening over time. These inconclusive rates of case hardening join values from literature range from months to thousands of years per meter transported downslope (Dorn, 2004), highlighting the need for further research in this area.

The **fourth hypothesis** focused on whether tile-shaped blocks (with low cubiness) on grassland slopes have a steepness and orientation more closely mirroring the slope they are located on than cube-shaped blocks (with high cubiness) on forested slopes (Table 2,Figure 12). This was hypothesized due to trees potentially acting as mobilizers of block transport. However, both relative orientation and relative block steepness showed no connection to slope vegetation and therefore no connection to slope lithology ($p = 0.36$, $p = 0.44$, resp.). Thus, the hypothesis was rejected. The **fifth hypothesis** was that DLBs on steeper hillslopes are less likely to have similar orientation and steepness to the slope on which they reside. This was expected because blocks on steeper slopes would be more likely to tumble rather than slide. This hypothesis was accepted because steeper slopes in both the Threemile (grass) and Cottonwood (forest) locations showed larger relative block orientation than that of the flatter slopes (relative orientation of blocks on both flat slopes together = 22.3°, relative orientation of blocks on both steep slopes together = 43.5°). In addition, blocks on the steep Cottonwood (forest) slope had significantly larger relative block orientation with increasing distance from the ledge (3.2°/m, $p < 0.02$). Conversely, blocks on the flat Threemile (grass) slope even had smaller relative block orientation with increasing distance from ledge (-0.18°/m, $p = 0.46$)(Table 2,Figure 11).

These findings are broadly consistent with higher rates of tumbling on steeper hillslopes, despite the fact that block shapes differ strongly between the steep Threemile and steep Cottonwood hillslopes, and despite the fact that these hillslopes are hardly steeper than the flatter hillslopes (30° vs. 25°). This points to an unusual dependence of the transport process on slope steepness. There may be a threshold slope steepness beyond which slow tumbling dominates block transport and before which, creep and other processes dominate.

The **sixth hypothesis** focused on the interactions between limestone and shale layers, specifically, that for the limestone layers to detach, removal of the underlying shale must first take place. Observations of the photosets gathered one year apart at the Scenic Drive outcrop, did indeed highlight the weathering process that is playing out beneath the surface. As expected, most weathering occurred in the shale layers. However, small blocks of limestone were detached throughout the road cut. A substantial amount of limestone block erosion occurred in the upper section of the site, where there was no clear undercutting by shale. This may be due to root, and thus water infiltration in the layers nearest the vegetation. Water infiltration then leads to freeze thaw or dissolution, both of which can cause erosion within the limestone layers.

Implications

Results of this study highlight the need for further research into rates of block transport downslope in landscapes derived from mixed lithologies. Natural landscapes and artificial features (such as roadcuts) both experience similar weathering treatments if located within a small spatial area. Observing the artificial area that showcases the weathering uninhibited by vegetation and soil cover allows researchers to witness weathering of layers with much greater ease and considerably less monetary expenditure. While a natural setting may take thousands of years to weather layers, an exposed roadcut greatly alters the temporal scale of weathering. Through measuring dimensions of surficial blocks transporting downslope and using this data with other available proxies such as water calcite concentration, we can determine dissolution rates via mass loss, and from there we are able to make estimates of block movement due to values of distance and time both being available.

Moving forward, samples of slope residing blocks may be taken in a series downslope to be dated using cosmogenic nuclide dating, depending on the chemicals present in specific rock types. Limestone contains the cosmogenic nuclide Chlorine-36, which provides the time a block was exhumed. Once blocks become exposed to the sky the accumulation of cosmogenic nuclides begins and that is the signal that can be observed to determine how long the block has been present on the surface. By conducting this sampling strategy on numerous blocks along a transect of a hillslope, researchers can determine the ages of blocks through finding the difference in years of exposure. This work would then facilitate the creation of time and distance plots that would provide insight about rates of downslope transport.

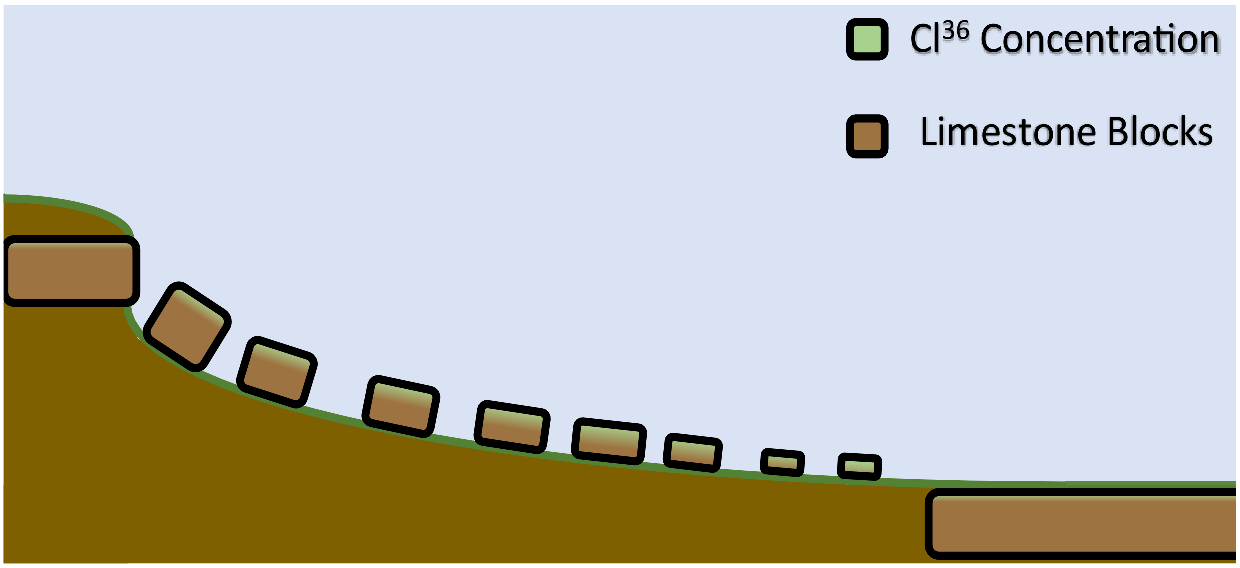

Figure 16. Sketch showing the expected increasing concentration of cosmogenic nuclide with increasing distance downslope

Recommendations

By studying natural settings near anthropogenic features (road cuts, quarries, etc.), we can also get ideas about how human activity accelerates erosion. Studying these features is a cost-effective method to test and observe heterogenous lithologies different weathering rates, and how that in turn influences hillslope morphology. Without the need for heavy equipment to reveal underlying bedrock this methodology can used in areas to provide low-cost analysis of local terrain. Specifically, roadcuts are useful due to their commonality, which allows for researchers to observe processes that act on bedrock. Glimpses into heterogenous lithology can show interplay between rock layers to highlight potential processes or mechanisms at play. Quarries can also provide information into underlying bedrock.

Conclusions

In conclusion, the ledge of detachment, vegetation, and slope steepness have significant effects on hillslope residing blocks. The ledge of detachment, determines block height, and starting hardness. This causes the ledge of detachment to be the most significant determinant of block properties. The extent to which vegetation influences block weathering could not be determined due to the two vegetations originating from different ledges. Slope steepness did however have influence over the transportation of the DLBs, and whether tumbling can occur. Surprisingly, vegetation may have had a minimal impact on

DLB properties, aside from the effects of creep in the grassland sites which seemed to aid in moving the blocks downslope through the mass movement of the entire slope.

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