Detecting landscape response to perturbations by climate and base level in central Pennsylvania using *in-situ* ^{10}Be and ^{26}Al

A Thesis Progress Report Presented

by

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to

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I. INTRODUCTION

1.1 Objective

My project is a cosmogenic isotopic investigation of rates of landscape change in Pennsylvania. I am supported by the Susquehanna Shale Hills Critical Zone Observatory (SSHCZO), an NSF-supported, interdisciplinary organization of scientists who study processes within the 'critical zone', the area spanning from the bedrock/soil interface to the top of the tree canopy. As part of the SSHCZO geomorphology research group, I am interested in the transport and development of regolith, the weathered, unconsolidated material on top of rock. An understanding of regolith formation is fundamental to the study of soils, landforms, and the cycling of life-sustaining nutrients through the critical zone (Brantley et al., 2007).

The SSHCZO is located in central Pennsylvania, a complex Appalachian landscape that has been shaped largely by glacial/interglacial cycles (Braun, 1989; Clark and Ciolkosz, 1988), and changes in base level (elevation relative to sea level) over time (Pazzaglia and Gardner, 1993; Mills, 2000; Hancock and Kirwan, 2007; Miller et al., 2013). My project touches upon many different topics, but my central research question is: how have changes in climate and base level influenced the development and transport of regolith in Pennsylvania? To address this, I am measuring the cosmogenic nuclides ^{10}Be and ^{26}Al, isotopes produced by the bombardment of cosmic rays, in order to infer rates of regolith transport and residence time in rocks, sediments, and soils south of the last glacial maximum boundary in Pennsylvania.

My project begins at Garner Run, a SSHCZO-operated hillslope site, where I investigate rates of regolith formation and transport, contributing to an interdisciplinary analysis of this site. Then, in order to have a more complete vision of the geomorphic processes that have shaped this region as a whole, I expand my focus to two end-member sites—the boulder field at Hickory Run State Park, which has been greatly influenced by past climate (Smith, 1953; Wilson, 2013), and

Young Womans Creek, a tributary to the West Branch Susquehanna River, a region that is responding to a fall in base level in the Cenozoic (Miller et al., 2013). Isotopic analyses of these three sites will (1) contribute to current discussion of regolith generation and flux rates at the SSHCZO, (2) elucidate the exposure age and history of an enigmatic periglacial feature (Hickory Run), and (3) analyze the spatial distribution of erosion rates in a watershed that is responding base level changes through fluvial incision (Young Womans Creek). See fig. 1 for locations of all study sites.

Since my thesis proposal presentation, my sampling strategy at Garner Run has been clarified, and my work there has been expanded to measure meteoric ^{10}Be (produced in the atmosphere) in addition to in-situ ^{10}Be (produced inside the crystal matrix of quartz particles). I have also made progress by completing fieldwork and sample collection at all 3 sites, and by competing quartz isolation and purity testing on the majority of my samples. For clarification of analyses and sample types at each site, refer to table 1 in the appendix.

1.2 A Note on Meteoric ^{10}Be

Meteoric ^{10}Be is used similarly to in-situ ^{10}Be to measure the residence time (Pavich et al., 1984) and downslope transport (Monaghan et al., 1992; Jungers et al., 2009) of regolith. Produced by collisions of cosmic rays with oxygen and nitrogen in the atmosphere, meteoric ^{10}Be is removed from the atmosphere through rainfall or dry aerosol deposition, ultimately adhering to reactive surfaces the soil (Willenbring and von Blanckenburg, 2010). My measurements of ^{10}Be inventories in quartzite-derived Garner Run soils will provide a comparison dataset to West et al. (2013), who used meteoric ^{10}Be inventories to quantify regolith transport and residence times at the original shale-underlain SSHCZO site.

1.3 Implications of My Research

Garner Run: The SSHCZO originated as just one site, Shale Hills, a small, first-order, shale-underlain catchment in the Shavers Creek watershed. Researchers at Shale Hills studied the rates and mechanisms of regolith transport, aided by the fact that the bedrock there is homogenous Silurian Rose Hill shale. In order to understand the generation and behavior of regolith from other lithologies, the SSHCZO has expanded its focus to Garner Run, a nearby catchment underlain by Tuscarora Quartzite. Analyses at the Garner Run site will enable us to determine whether two proximal, first-order catchments in the Shavers Creek watershed with different lithologies have developed over similar timescales, or whether their modes of regolith formation and transport differ significantly. My work will also contribute to the overall discussion of erosion rates, hillslope transport of regolith, and landscape evolution in the Appalachians (i.e. Bierman and Portenga, 2011; Jungers et al. 2009; West et al., 2013).

Hickory Run: Periglacial features, such as boulder fields, are ubiquitous in Pennsylvania (Braun, 1989; Clark and Cilokosz 1988). My research at Hickory Run is the first attempt at quantitatively constraining the age of an Appalachian boulder field, and will give insight into the age and formation of these enigmatic features. Culturally, my work will add to the knowledge that the Pennsylvania Department of Conservation and Natural Resources has of this National Natural Landmark, which researchers and laypeople alike have puzzled over for many years.

Young Womans Creek: By studying fluvial terraces and stratigraphy around the Susquehanna River basin, others have suggested that Pennsylvania is responding to a fall in base level that most likely began in the Cenozoic (Pazzaglia and Gardner, 1993; Mills, 2000; Miller, 2013). However, the rate at which this transient wave of incision is migrating into the uplands has only recently been studied through measurements of *in-situ* ^{10}Be (Miller et al., 2013), and on a large scale. By sampling intensively in a small watershed I will be able to calculate rates of fluvial incision on a finer scale, yielding a high-resolution dataset that will shed light onto the pace of landscape response to this perturbation.

II. PROGRESS: SPRING 2015 THROUGH SEPTEMBER 2015

2.1 Fieldwork

In May 2015, I spent one week in Pennsylvania in which I presented my research plans at the SSHCZO annual 'All Hands' meeting and conducted sampling at Hickory Run State Park and Young Womans Creek with Paul Bierman, Nicole West, Eric Kirby, and Molly Bruno. I returned to State College in July 2015 to obtain soil samples from the SSHCZO repository at Penn State University, and to collect hillslope boulder samples and stream sediments at Garner Run.

Garner Run: Hillslope soils, boulders, and stream sediments

Since my progress report, I better defined my sampling strategy at Garner Run. This first-order watershed in Huntingdon County, PA is bounded by Leading Ridge to the south and Tussey Mountain to the north (fig. 2, fig. 3). My work here will include analyses of meteoric (n=4) and in-situ (n=4) ^{10}Be inventories in amalgamated soil pit samples from Leading Ridge (3 pits) and Tussey Mountain (1 pit). These soils were sampled in 10 cm increments by SSHCZO researchers.

In the field, I sampled small boulders (<1m diameter) in 30-meter-long hillslope-parallel transects adjacent to each soil pit on Leading Ridge, with the intent of amalgamating all boulders into one sample per transect (n=3). I sampled the boulders most representative of average boulder size on the ridge (fig. 4), and took measurements, photographs, and notes on any prominent features of each boulder (n=15 boulders per transect). I also collected stream sediments (n=2) in Garner Run immediately adjacent to my bottommost hillslope boulder transect, wet sieving to the 850-250 µm fraction (fig. 5).

Hickory Run: boulders and tors

At Hickory Run boulder field, I sampled boulders in transects across the main body of the field (fig. 6, fig. 7) and in the surrounding forest (n=43) and on tor-like outcrops (weathered bedrock) northwest of the field (n=5) (fig. 8), which some believe to be the source rock of the field. We sampled the uppermost few centimeters of each rock and recorded the dimensions, sample thickness, coordinates, notable features, and lithology of each boulder.

Young Womans Creek: stream sediments

We selected sample locations in the right and left hand branches of Young Womans Creek that reflected the distribution of slopes found within subbasins (fig. 9). Over the course of two days, I traveled around the watershed, collecting samples immediately below stream junctions (n=17) (fig. 10). Stream sediments were wet sieved in the field to the 850-250 µm fraction for *in-situ* analysis, and coordinates of each feature were recorded along with a photographs and notes on the morphology of each stream.

2.2 Sample Preparation

I crushed and amalgamated each Garner Run soil profile in order to get one representative sample from each pit, removed 50 g of each for meteoric ^{10}Be analysis, and then sieved each sample to the 850-250 µm fraction for *in-situ* analysis. I also crushed all Leading Ridge boulder samples and weighed out 100 g of each boulder to produce one amalgamation per transect (n=3). Hickory Run rock samples (n=52) were crushed and sieved individually, and I washed and dried all Young Womans Creek (n=17) and Garner Run (n=2) stream sediments.

2.3 Laboratory Work: Quartz Separation

In order to measure *in-situ* ^{10}Be and ^{26}Al, I must isolate the quartz from my samples. To do this, I performed a series of acid etchings. I etched my samples for a minimum of two days in hot HCl, which removes grain coatings, weathered material, and meteoric ^{10}Be. Then, to break down all minerals other than quartz, I subjected my samples to three 24-hour ultrasonic etchings in a hot, dilute mixture of HF and HNO_3, and one final week-long etch in a very weak mixture of HF, HNO_3, and HCl. I have completed all quartz separation on Hickory Run and Young Womans Creek samples, and Garner Run samples are in progress. Once quartz is isolated, I use ICP to test for common impurities such as aluminum and titanium. By mid-September 2015 I had separated all quartz from my samples and completed quartz purity testing.

2.4 Geospatial Work

In addition to the physical and chemical preparation of 82 samples, I have worked to create GIS point layers and .kmz files in Google Earth for sample locations at each of my field sites, linking to photographs and descriptions that can be shared with colleagues. I have also used eCognition feature extraction software to analyze trends in the orientation, roundness, and size of blocks at Hickory Run boulder field (fig. 11), which I will use to create a poster at the annual GSA conference in October.

2.5 Results from Fieldwork and Updated Hypotheses on Hickory Run

During my recent fieldwork, I made many new observations on the boulder field at Hickory Run. While surveying the boulders in the field, we observed an audible and sometimes visible groundwater network, with streams in the nearby forest disappearing underneath boulders in the main body of the field. I suspect that this underground network of water may have facilitated the transport of boulders through the breakup of blocks by frost action and the sliding of boulders by solifluction (freeze-thaw-induced creep) under cold periglacial conditions.

In the southern reaches of the field, we observed small, beveled, polished cobbles fitted together beneath larger boulders (fig. 12). This inverse grading was only visible due to manmade pits in a few areas, so we could not discern whether this stratigraphy was similar for the entire field. The small subsurface cobbles were often a reddish color, possibly stained by iron oxides. The topmost blocks were frequently lighter (perhaps bleached by exposure to the atmosphere), and some had lichen growing on top. The texture of boulders in the field varied considerably from the north to the south, with massive, angular boulders dominating the northern reaches of the field. I hypothesize that the presence of larger clasts at the top of the field and smaller, more weathered clasts at the base of the field indicates a sense of downslope transport, and that exposure ages in the southern reaches of the field will be older. If this is true, then I should see a spatial correlation between ^{10}Be exposure age and distance down the long axis of the field. Hickory Run has commonly been attributed to the Last Glacial Maximum (LGM), but due to the extent of the field, the weathering of boulders, and the cosmogenic analyses of Wilson et al. 2008, who demonstrated that relict periglacial block streams in the Falkland Islands are considerably older than previously thought (up to 700-800 ky), I hypothesize that ^{10}Be measurements will show a history that extends over multiple glacial/interglacial cycles, with many blocks pre-dating the LGM.

On the margins of the field, we noticed that the surrounding forest is encroaching, with forest duff slowly filling in the interstices between blocks. I hypothesize that forest blocks may have been the first to cease movement, and may have more complex, and possibly older ages than blocks in the main body of the boulder field.

In the forest, 1 km northwest of the boulder field, there is a ridgeline of weathered sandstone tors, which some have hypothesized to be the source rock of the field (Smith, 1953; Geyer, 1969). However, I am skeptical of this assumption, as there are very few tors on the ridgeline and there are no visible trails of large blocks leading down to the field. It is possible that this material does exist, but is now concealed by soils. If the tors did, in fact, contribute to the boulder field, then I would hypothesize that the tors have younger ^{10}Be exposure ages, as they would have been more recently exposed than the boulders in the main body of the field. I also hypothesize that the ages of these tors may be coeval with the LGM, as this is when the cessation of boulder-producing conditions may have occurred.

III. FUTURE WORK

3.1 Laboratory Work

After the lab is re-commissioned in late October 2015, I will extract *in situ* ^{10}Be from my samples, and I will also analyze Garner Run amalgamated soil samples (n=4) for meteoric ^{10}Be. I will analyze ^{10}Be at the Livermore National Laboratory and ^{26}Al in a subset of Hickory Run samples at Purdue University in early winter. If results from ^{26}Al analysis show complex burial histories, then I will run more boulder samples for ^{26}Al. I will analyze data and begin writing manuscripts in spring 2016. By early 2016, I will have completed all isotopic measurements, which will enable me to complete my thesis by early fall 2016 (table 2).

3.2 Further Work

In addition to completing extractions for meteoric ^{10}Be and *in-situ* ^{10}Be and ^{26}Al, I will continue geospatial work on my study sites. For Hickory Run, I will refine my eCognition rule set for boulder extraction, and visualize trends in boulder orientation on a poster at the 2015 GSA conference in October. I will also continue with MATLAB and ArcMap analyses of stream profiles and basins in Young Womans Creek, which will allow me to compare my measured erosion rates to channel steepness and zones of incision in the watershed. For my Garner Run samples, I will work on modeling hillslope regolith transport with the help of Nikki West, a fellow SSHCZO researcher and postdoctoral fellow at the Georgia Institute of Technology.

Appendix

Table 1. Analyses planned at each study site. I will perform 78 measurements for *in-situ* ^{10}Be and 4 measurements for meteoric ^{10}Be.

Site	Description	Measurements	n
Garner Run, Rothrock State Forest, near State College, PA	SSHCZO-operated hillslope catena	*In-situ* ^{10}Be in boulders transects on Leading Ridge, (15 boulders per transect)	3
		In-situ ^{10}Be in amalgamated soil samples from 3 pits on Leading Ridge, 1 on Tussey Ridge	4
		Meteoric ^{10}Be in amalgamated soil samples from soil pits.	4
		In-situ ^{10}Be in Garner Run stream sediments	2
Hickory Run State Park, Kidder, PA	Boulder field	*In-situ* ^{10}Be, ^{26}Al in rock samples from field and adjacent forest	52
Young Womans Creek, North Bend, PA	Watershed	*In-situ* ^{10}Be in stream sediment samples at junctions.	17

Table 2. Anticipated timeline for M.S. thesis project.

Time Period	Tasks to Complete
Fall 2015	-Finish final HF/HNO_3 etches, purity testing -Dissolve quartz for *in situ* ^{10}Be and ^{26}Al analysis -Processing for meteoric ^{10}Be -Present Hickory Run poster at GSA
Winter 2015	-Start writing introduction, continue background and methods -Measure ^{10}Be at Lawrence Livermore National Laboratory and ^{26}Al at PRIME
Spring 2016	-Data analysis -Begin writing discussion
Summer 2016	-Finish writing
Fall 2016	-Defend thesis

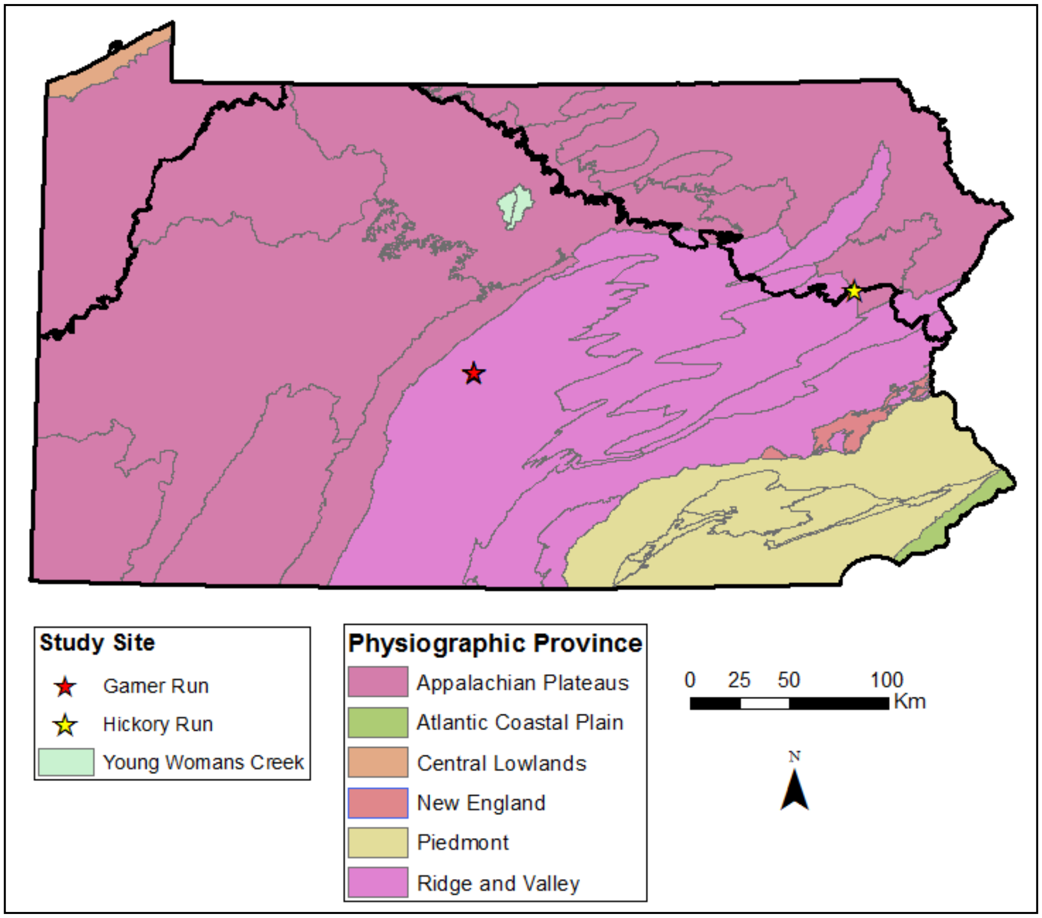

Figure 1. Locations of study sites in relation to physiographic provinces and LGM boundary (dark black line). Hickory Run (yellow star) and Young Womans creek (green polygon) are just south of the glacial boundary in the Appalachian Plateaus province. Garner Run (red star) is in central Pennsylvania in the Ridge and Valley province.

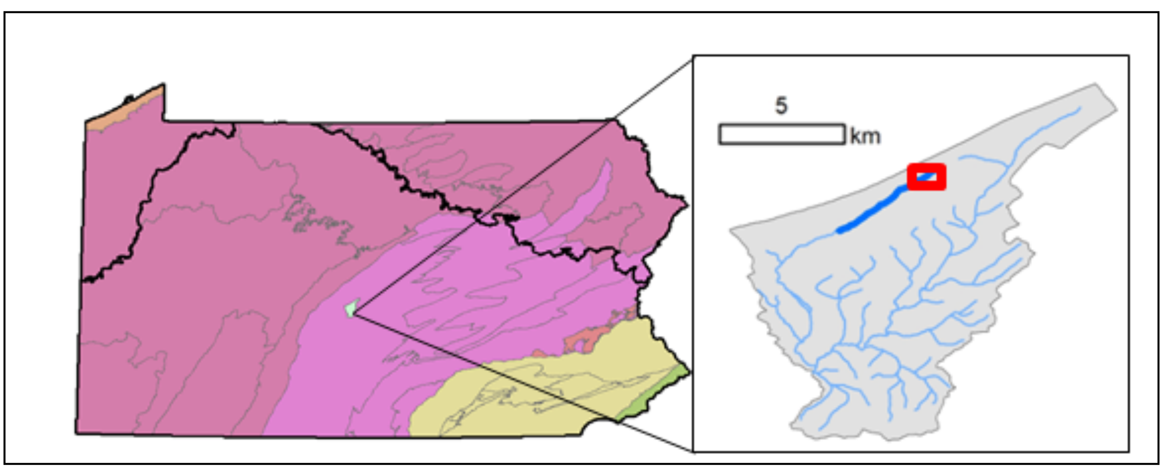

Figure 2. Garner Run is in the northern reaches of Shaver's Creek watershed in the Susquehanna River Basin.

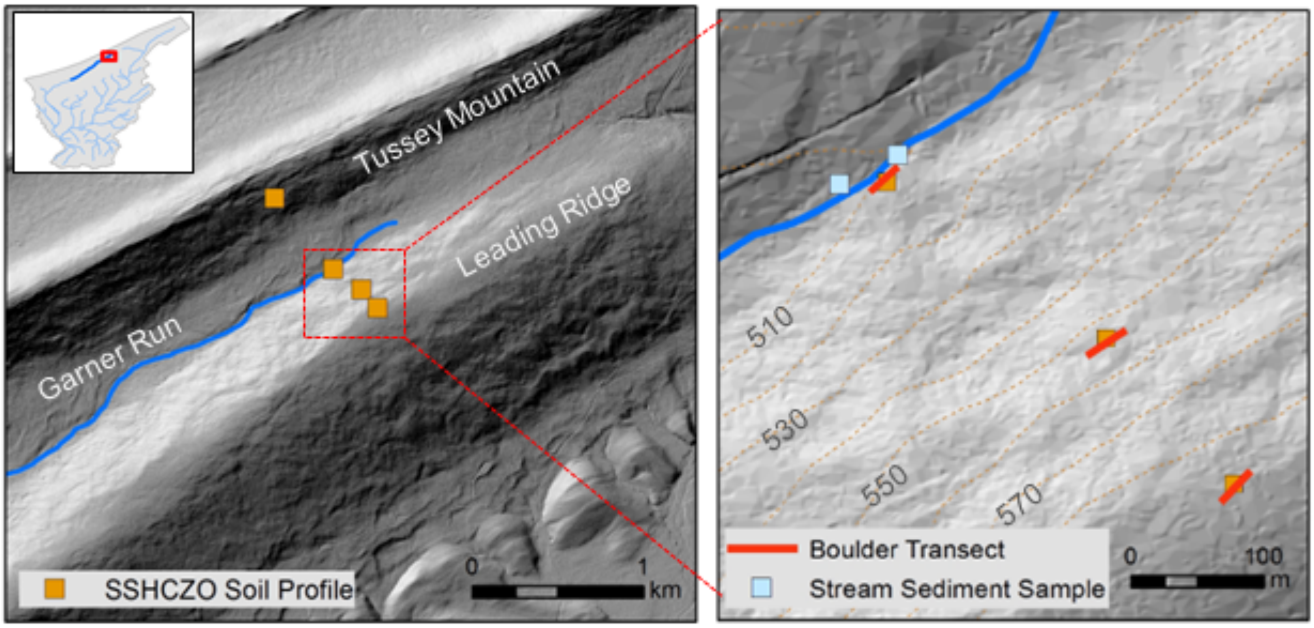

Figure 3. Location of Garner Run soil profiles, stream sediment samples, and boulder transects. There are 3 soil profiles on Leading Ridge and 1 on Tussey Mountain (left). In July 2015 I sampled 3 amalgamated boulder transects and collected 2 stream samples on Leading Ridge (right).

Figure 4. Typical Tuscarora quartzite boulder sampled on Leading Ridge at Garner Run site.

Figure 5. Sampling stream sediments at Garner Run. Sediments were sieved to the 850-250 µm fraction in the field. The streambed is shallow, ~3 m wide, and covered in quartz sand and angular quartzite cobbles.

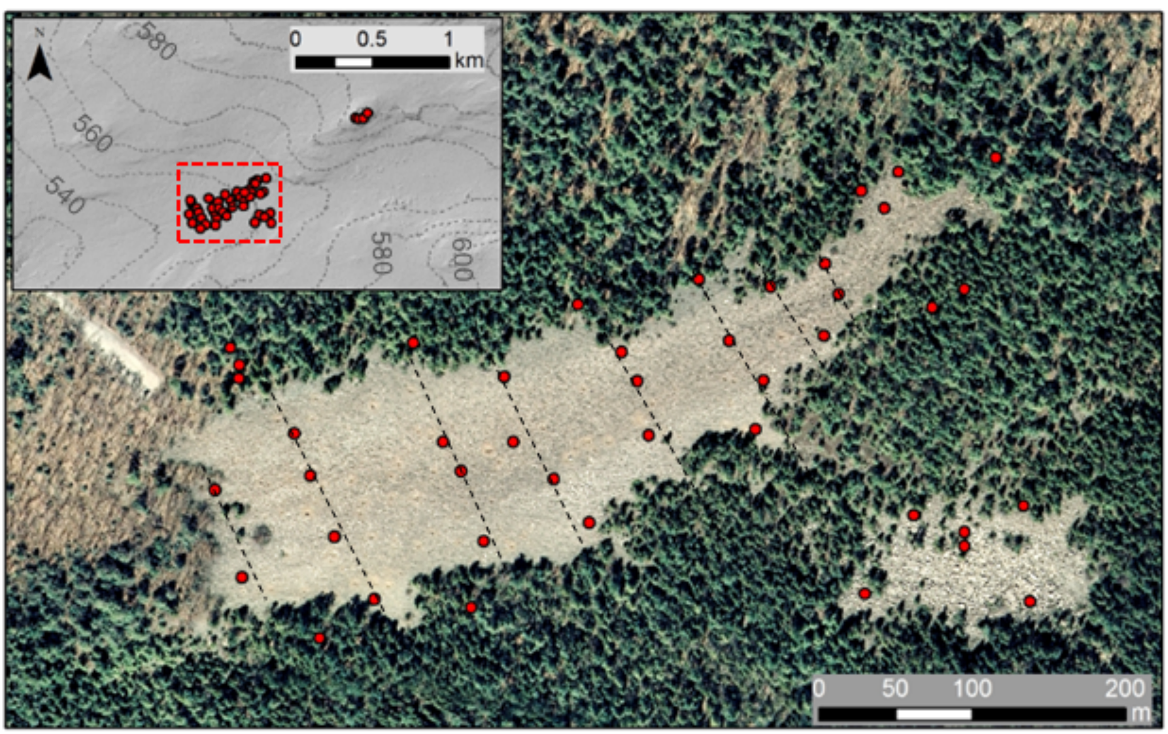

Figure 6. Local topography (inset) and locations of sample sites at Hickory Run State Park. Red dots represent sample sites, dotted black lines indicate transects.

Fig. 7. Ground view of Hickory Run boulder field, standing at the southwest end of the field looking north.

Figure 8. Tor-like bedrock in the forest 1 km northwest of Hickory Run boulder field.

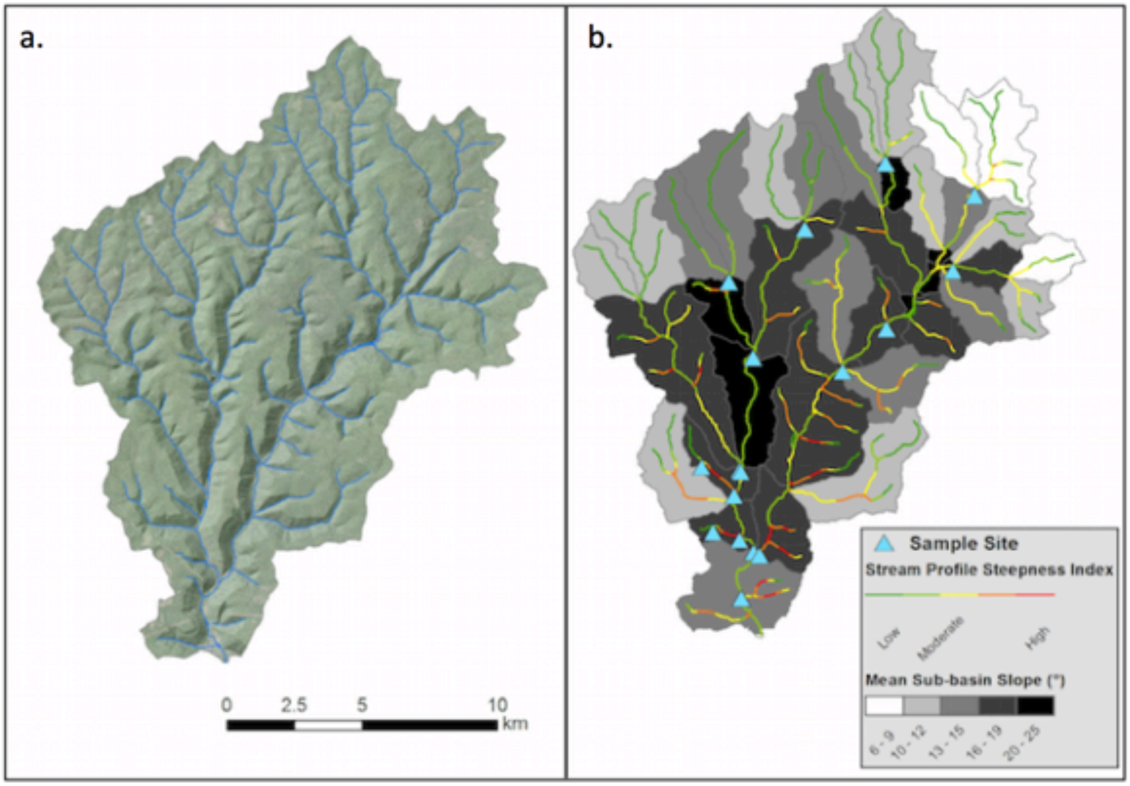

Figure 9. (a) Hillshade view of Young Womans Creek watershed (U.S. Geological Survey, 2015). (b) Watershed divided into subbasins shaded by mean slope, streams displayed by normalized steepness index (generated with the methods of Whipple et al., 2007). The steepest reaches (red lines) are the areas with the greatest fluvial incision into the landscape.

Figure 10. Sampling stream sediment in Young Womans Creek.

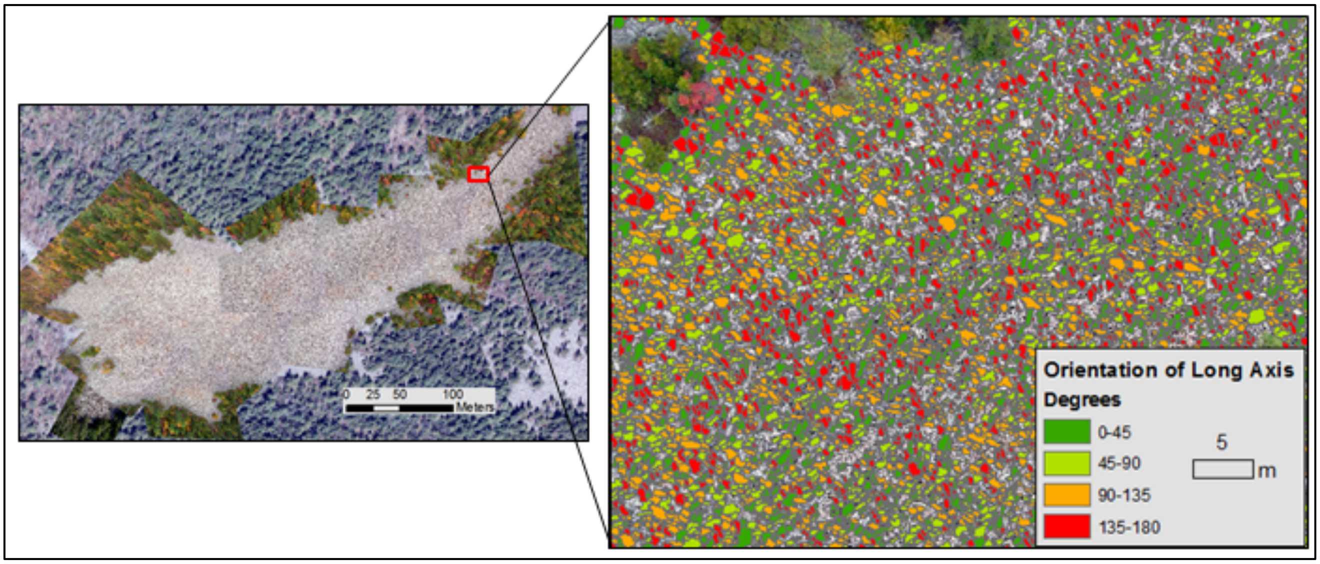

Figure 11. ECognition identifies boulders at Hickory Run and exports information on the area and orientation of the long axis (pictured) of each object (imagery courtesy of Noel Potter, Dickinson College).

Figure 12. Small, polished cobbles beneath larger boulders at Hickory Run boulder field.

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