A Topographic and Lithologic Analysis of the Kittatinny Ridge and Their Implications for Appalachian Erosional History

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A Topographic and Lithologic Analysis of the Kittatinny Ridge and Their Implications for Appalachian Erosional History

by

David Carl Sharpe

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Abstract:

The eastern-most ridge of the Appalachian Mountains, Kittatinny Ridge, extends from New York State south to West Virginia. The ridge is composed of erosion-resistant quartzite conglomerate throughout (Shawangunk Formation, Tuscarora Formation) underlain by sandstone, siltstone, slate and shale (Martinsburg Formation, Juniata Formation). The relatively consistent lithology of the Kittatinny Ridge makes it ideal for analyzing how variations in climate, glacial history and other topographic influences have impacted long-term erosion along the ridge. This project analyzed the lithologic consistency and topography of the Kittatinny Ridge at different locations and what geomorphological implications the results might have. Rock samples of the Shawangunk and Tuscarora Formations were collected at various locations along the ridge in New York, New Jersey, Pennsylvania and West Virginia. These samples were tested using a Scanning Electron Microscope (SEM) for bulk composition and porosity to determine erodability. Schmidt hammer measurements were also taken at the various collecting sites to determine rock hardness. River longitudinal profiles and their valley hypsometries were measured to determine long-term erosion amounts along the ridge. This was done using geographic information system (GIS) ArcMap v. 10.1 to delineate the ridge and determine valley and river geometries. One-third arc second digital elevation models (DEMs) were downloaded from the National Map, and standard hydrologic GIS procedures (sinks filled, flow direction determined, flow accumulation calculated, stream networks identified, and watersheds generated) were followed to determine watershed areas and river networks.
Analysis of the Shawangunk and Tuscarora samples indicate that they are lithologically similar when compared to other rock types. Northern samples yielded a porosity of 1.15% and southern samples yielded a porosity of 1.67%. Schmidt hammer data revealed that the rock samples of Shawangunk are slightly harder than samples of the Tuscarora. GIS results suggest that there were higher erosion rates along the southern extent of the ridge. River long profiles and hypsometries show differences, with southern watersheds being more concave. This could be from an influence of the ridge’s glacial history, structural differences, or recent topographic rejuvenation from mantle upwelling. There was a data gap between New Jersey and West Virginia where samples were not collected due to distance and time. Future work includes sampling from these missing latitudes along the Kittatinny Ridge.
A TOPOGRAPHIC AND LITHOLOGIC ANALYSIS OF THE KITTATINNY RIDGE
AND THEIR IMPLICATIONS FOR APPALACHIAN EROSIONAL HISTORY

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science

by

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Montclair, NJ
August 2015
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# Table of Contents

1. **Introduction/Background**.................................................................................................1  
   1.1 Appalachian History ......................................................................................1  
   1.2 Influence of Rock Erosion...............................................................................4  
   1.3 Measuring Erosion Rates................................................................................8  
   1.4 Project Goals.................................................................................................9  

2. **Methodology**..............................................................................................................11  
   2.1 Sample Collecting..........................................................................................11  
   2.2 Sample Analysis............................................................................................12  
   2.3 GIS Analysis..................................................................................................15  

3. **Results**.......................................................................................................................17  
   3.1 Porosity..........................................................................................................17  
   3.2 Schmidt Hammer...........................................................................................18  
   3.3 Concavity Index............................................................................................19  
   3.4 Hypsometries.................................................................................................20  

4. **Discussion**..................................................................................................................21  
   4.1 Lithologic Comparison.......................................................................................21  
   4.2 GIS Topographic Analysis...............................................................................23  
   4.3 Implications.....................................................................................................24  
   4.4 Limitations and Data Gaps..............................................................................29  
   4.5 Future Work.....................................................................................................30  

5. **Conclusion**..................................................................................................................31  

6. **References**..................................................................................................................32  

7. **Figures and Tables**....................................................................................................36
List of Figures

Figure 1: Appalachian Mountain Physiographic Provinces.............................................36
Figure 2: Geologic Map of Pennsylvania..........................................................................37
Figure 3: Wisconsinan Glaciation Map............................................................................38
Figure 4: New York Sampling Location..........................................................................39
Figure 5: New Jersey Sampling Location.........................................................................40
Figure 6: West Virginia Sampling Location......................................................................41
Figure 7: New York Porosity Example............................................................................42
Figure 8: West Virginia Porosity Example.....................................................................43
Figure 9: GIS River and Watershed................................................................................44
Figure 10: Hypsometry Example......................................................................................45
Figure 11: River Long Profile Diagram............................................................................46
Figure 12: Latitude vs. Porosity........................................................................................48
Figure 13: Latitude vs. Rebound Number........................................................................50
Figure 14: New York River Long Profiles.......................................................................56
Figure 15: New York DEM..............................................................................................57
Figure 16: New Jersey River Long Profiles......................................................................58
Figure 17: New Jersey DEM...........................................................................................59
Figure 18: Pennsylvania (NE) River Long Profiles.........................................................60
Figure 19: Pennsylvania (SW) River Long Profiles.........................................................61
Figure 20: Pennsylvania DEM.........................................................................................62
Figure 21: West Virginia River Long Profiles..................................................................63
Figure 22: West Virginia DEM.........................................................................................64
Figure 23: Latitude vs. Concavity Index

Figure 24: New York Hypsometries

Figure 25: New Jersey Hypsometries

Figure 26: Pennsylvania (NE) Hypsometries

Figure 27: Pennsylvania (SW) Hypsometries

Figure 28: West Virginia Hypsometries

Figure 29: Latitude vs. Hypsometry

Figure 30: Porosity vs. Rebound Number
List of Tables

Table 1: Porosity Results.................................................................................................47
Table 2: Schmidt Hammer Results..................................................................................49
Table 3: New York GIS Results......................................................................................51
Table 4: New Jersey GIS Results....................................................................................52
Table 5: Pennsylvania (NE) GIS Results........................................................................53
Table 6: Pennsylvania (SW) GIS Results........................................................................54
Table 7: West Virginia GIS Results................................................................................55
Table 8: GIS Data: State Averages..................................................................................73
1. Introduction/Background

1.1 Appalachian History

The Appalachian Mountains are one of the oldest mountain ranges in the United States with a complicated history of mountain building events, or orogenies, and the deposition of new rocks from the erosion of older ones. The initial orogeny of the Appalachians, the Grenville, occurred about a billion years ago (Stanley and Luczaj, 2009). Since then several more tectonic events (the Taconic Orogeny of the Ordovician, the Acadian Orogeny of the Devonian and the Alleghenian Orogeny of the Carboniferous) have uplifted the Appalachians while erosion has been wearing them down to what we see today (Stanley and Luczaj, 2009).

The Appalachians are divided into four distinct provinces (Figure 1: Appalachian Mountain Physiographic Provinces). The crystalline provinces include the Piedmont and the Blue Ridge Mountains on the eastern side of the Appalachians (Hatcher, 2010). The Piedmont is a gently rolling topographic transition between the flatter Atlantic Coastal Plain and the Blue Ridge and Valley and Ridge provinces to the west. The rocks in this province consist of highly weathered various igneous and metamorphic rocks of Proterozoic and Paleozoic ages that formed from various episodes of orogenies and continental rifting (Hatcher, 2010). The Blue Ridge province is to the west of the Piedmont but only extends from Georgia to southern Pennsylvania. This province mostly consists of Proterozoic aged igneous and metamorphic rocks from the Grenvillian Orogeny that were thrusted over rocks of the Valley and Ridge province to the west (Hatcher, 2010). The sedimentary Appalachians are to the west and consist of the Valley and Ridge province and the Appalachian Plateau (Hatcher, 2010). The Valley and Ridge
is mostly composed of varying sedimentary rock layers deposited during the Paleozoic. These sedimentary layers were compressed during the Alleghenian Orogeny in the late Paleozoic, folding and faulting them. The Appalachian Plateau is very similar to the Valley and Ridge Province with the main difference being low amplitude folding and almost flat laying rocks versus the tight, high amplitude folding of the Valley and Ridge (Hatcher, 2010).

The Valley and Ridge province derives its name from the sedimentary rock formations within it that vary in durability and susceptibility to weathering. This difference creates valleys where the rock type is friable and more easily eroded and ridges where the rock type is stronger and more resistant. The Kittatinny Ridge is the eastern-most prominent ridge of the Valley and Ridge province and is generally considered the start of the Appalachian Mountains in New York, New Jersey and Pennsylvania (Witte and Monteverde, 2012). The Kittatinny Ridge is locally referred to as other names, but for the purposes of this paper the ridge will be referred to as the “Kittatinny Ridge.” This ridge is composed of a hard, erosion-resistant quartzite conglomerate of the Shawangunk and Tuscarora Formations extending from the Catskill region of New York to southern West Virginia and Virginia. A notable characteristic of this ridge is the number and size of exposed bedrock outcrops along it (McBride, 2014).

The Shawangunk Formation is early Silurian in age and composed of a quartz rich pebble conglomerate with interbedded layers of sandstone. It is roughly 400 meters in thickness and is the backbone to the Kittatinny Ridge (Epstein, 2010). The Shawangunk Formation extends from just north of New Paltz, NY down through New Jersey and partly in to Pennsylvania. The Shawangunk Formation was deposited in a clastic wedge
of quartz-rich braided-river sediment transgressing to a shallow marine environment. Uplift from the Taconic Orogeny during the Silurian allowed for fast flowing water and a lot of eroding sediment to be deposited in river valleys and coastal environments (Epstein, 2010; Bennington, 2008). The Late Ordovician-aged Martinsburg Formation is a slatey greywacke and lies unconformably below the Shawangunk creating the southeast slope of the Kittatinny Ridge (Epstein, 2010). The Shawangunk is dipping roughly 30° to the northwest in most parts of New Jersey and eastern Pennsylvania. The tilting of the Shawangunk is due to the Alleghenian Orogeny that created the supercontinent Pangea and is responsible for the tight folds of the Valley and Ridge province (Bennington, 2008).

The Silurian Tuscarora Formation in central Pennsylvania and West Virginia is lithostratigraphically equivalent to the Shawangunk Formation. The Shawangunk transitions into the Tuscarora near the Swatara Gap in Pennsylvania where Swatara Creek cuts through the Kittatinny Ridge (Figure 2: Geologic Map of Pennsylvania). The Tuscarora was deposited after the Ordovician Taconic Orogeny as the rivers crossing the eroding mountains carried sand and gravel down to alluvial fans and beach environments within the Appalachian Valley basin (Barnes et al., 2014). More sediment of various sources was continually deposited on top of the Tuscarora Formation throughout the Paleozoic until Africa collided with North America resulting in the Alleghenian Orogeny (Barnes et al., 2014). Even though this is the same collision event that tilted the Shawangunk Formation in New York and New Jersey, the Tuscarora Formation had much greater deformation. The kink band structures and fold thrust belts that broke up the Tuscarora resulted from this collision, as thick pieces of the sedimentary bedrock
were pushed over each other and tilted in an en echelon decollement (Faill, 1969; Kulander, 1986). In Pennsylvania the Tuscarora Formation is between 150 and 200 meters thick and is composed of varying quartz-arenite, sandstone, and quartz-conglomerate units with some interbedded layers of grey shale and it is the most basal unit of the Silurian underlain by the Juniata Formation of the Ordovician (Cotter, 1983). The Tuscarora is folded and faulted throughout central Pennsylvania with prominent outcrop exposures at Tuscarora Mountain, Hawk Mountain and Blue Mountain (Barnes et al., 2014). The Tuscarora continues south into Maryland, Virginia and West Virginia and is exposed as part of the well-known Seneca Rocks attraction and has many outcrops along North Fork Mountain in West Virginia.

1.2 Influences of Rock Erosion

Rock outcrop erosion rates and relative topographic relief depend on three main factors: tectonic setting, rock type and the local climatic regime (Portenga and Bierman, 2011). Each of these three main influences on erosion can be subdivided into their own respective influences. Climate is a highly important factor in determining erosion rates. Climate is influenced by latitude and elevation and has impacts such as annual precipitation, temperature fluctuations, glaciation, extent and type of vegetation cover, and chemical weathering rates which all determine how much erosion can occur and at what rate (Portenga and Bierman, 2011). Considering that the east coast of North America is currently a passive tectonic margin, tectonic setting is not an obvious influence on erosion at this study site (at least for the last several tens of millions of years), which eliminates one variable of erosion.
Rock type is very important in determining how erodible a rock is. Crystalline rock tends to be a much harder rock to erode as many mountain ranges such as the Sangre de Christo range in Colorado or the Sierra Nevada range in California are capped with rocks such as granites or gneisses (Lindsey, 2010; Henry, 2009). Sedimentary rocks can be resistant to erosional forces as well such as prominent exposures like the Bighorn Mountains in Wyoming and the Dinaric Alps in southern Europe (KellerLynn, 2011; Hughes, 2011). A rock’s resistance to weathering and its durability depend mainly on its mineral composition, grain/crystal size, pore space and how well cemented or fractured the rock is (Cooke and Doornkamp, 1974; Anderson and Anderson, 2010).

A region’s glacial history could also have a major influence on the topographic features of its landscape. Some landscape’s topography is directly impacted by the ice moving through and over it, whereas others could be affected by the large amounts of flooding that occurs after an ice dam breaks or when glacial ice melts (Hanson, 2012; Song, 2012). Advancing glaciers can bulldoze valleys deeper and wider, permanently changing the shape of the river valley. Regions that have undergone long periods of glacial advances and retreat are quite different than ones without (Anderson and Anderson, 2010). Evidence of glaciers can be seen in more pronounced topographic relief, classic ‘U’ shaped valleys and striations left behind on bed rock, although all of these are not always observed together. The most recent and most influential glacial period in the northeast began in the Pleistocene Epoch, about 1.6 million years ago. Numerous glacial advances and retreats since have shaped the valleys and ridges of New York, New Jersey and northern Pennsylvania down to just south of the Delaware Water Gap (Isachsen et al., 1991) (Figure 3: Wisconsinan Glaciation Map). Valleys located
beyond the extent of the last glacial maximum (the Wisconsinan Glaciation) would not have experienced equivalent erosional histories as the valleys within the glacial boundary. This difference in glacial history would change the topography of the landscape and, subsequently, how its rivers move through it.

Glaciers not only cause physical alterations to a landscape by moving through them, but the immense weight of the glacial ice can depress the Earth’s crust. This in turn raises the crust around the area being forced down by the glacier’s weight. Since the recession of the Wisconsinian glacial maximum that reached as far south as New Jersey and northern Pennsylvania the weight of the ice has been lifted off of the Earth’s crust and has been returning to equilibrium. This phenomenon is known as glacial isostatic adjustment (GIA) (Sella, 2007). When a landscape returns to equilibrium, the land that was once under glacial ice rebounds and the land surrounding it will eventually subside. Sella et al. (2007) used GPS to track the motions of glacial isostatic adjustment. The GPS data revealed that much of the GIA was occurring in northern Canada, specifically around the Hudson Bay region, but rebound was occurring as far south as the New York and New Jersey area. A “hingeline” was drawn to separate the regions of North America that were rebounding and subsiding. Most places south of New Jersey demonstrated significant subsidence which clearly corroborates the extent of the last glacial maximum (Sella et al., 2007)

Overall, the east coast of North America is a passive tectonic margin as there is no active plate boundary or any significant tectonic forcing aside from glacial isostatic adjustment. Without tectonic activity or large magmatic upwelling there are no leading forces to drive uplift or any other type of topographic change to the Appalachian
Mountains. One theory about the controls on topographic relief is dynamic equilibrium, and in this scenario there is no net change in erosion or uplift and the topography is controlled by the erosional resistance of the rock. The erosion rates of a landscape should be relative to the rock’s resistance to erosion (Matmon et al., 2003). Rocks with a stronger resistance will create greater topographic relief compared to rocks of weaker resistance.

However, studies by Gallen et al. (2012) and Liu, (2014) have suggested that portions of the Appalachian Mountains are not in dynamic equilibrium, uplift is occurring faster than erosion, and recent (i.e., Miocene) topographic rejuvenation may have transpired. Gallen et al. (2012) used LiDAR (Light Detection And Ranging) DEMs to find retreating knickpoints in rivers and the timing of their appearance in the Cullasaja River basin. Their results indicate that the landscape is undergoing recent rejuvenation and that the topography may not be as passive as presumed. Using geodynamic models of mantle buoyancy, fluctuations of increasing sedimentation in the Gulf of Mexico and erosion in particular parts of the Appalachians, Liu (2014) was able to model surficial elevation change and isostatic adjustment of the Appalachians. Liu has also concluded that the Appalachians are not in a state of dynamic equilibrium and that after the Miocene topographic relief has increased. Similarly, Gallen et al. (2012) states that topography has increased by 150% in the Cullasaja River basin since the Miocene.

Topographic rejuvenation has also been studied by Rowley et al. (2013) along the coastal plains from Virginia to Florida. They used sedimentary rocks deposited in a marine environment during the Pliocene that have experienced warping and displacement of 60 meters combined with mantle convection simulations to model the dynamic
topography. Their models show evidence of topographic rejuvenation and distortion during the last 3 Ma. Rowley et al. (2013) concluded that these results are an implication of mantle dynamics and are partially a result of glacial isostatic adjustment.

1.3 Measuring Erosion Rates

There are many tools and methods used to calculate surficial erosion rates. Measuring the concentration of $^{10}$Be in a rock is one method to calculate rates of erosion (Portenga and Bierman, 2011; Sullivan et al., 2007; Reuter, 2005). $^{10}$Be is produced when surface rock is exposed to cosmogenic rays, and that exposure can be calculated by measuring the concentration of $^{10}$Be (Portenga and Bierman, 2011). Simplified, lower erosion rates produce higher concentrations of $^{10}$Be. Optically Stimulated Luminescence (OSL) is another method of measuring erosion (and possibly deposition) rates by measuring the amount of charge that is present on a mineral when exposed to sunlight. The amount of charge is dependent on how long the sediment was buried after exposure (Murray, 2002). Once the sediment is exposed again to sunlight the amount of charge on the sediment resets. The age of the sediment’s burial can be calculated by measuring the amount of charge present and how deep it was buried (Wallinga, 2002).

Erosion amount can also be measured qualitatively by examining topographic characteristics such as river longitudinal profiles. Also called river long profiles, they are a measure of a river’s change in elevation over distance. River long profiles can reveal how strongly or weakly eroded a particular landscape of interest is. A strongly eroded landscape will generally have a more concave profile shape whereas a convex profile shows a weakly eroded landscape (Zaprowski, 2001). Hypsometries are similar to river long profiles, but instead measure a watershed’s elevation distribution over its area.
Hypsometries are useful in demonstrating the incising power and history of a river system across its entire watershed rather than just the river channel itself. Using Geographic Information Systems (GIS), watershed hypsometries and river long profiles of the Kittatinny Ridge can be created to determine the extent of erosion. The GIS method is the most economical and appropriate approach for this study, allowing large geographic areas to be compared relatively quickly.

1.4 Project Goals

The goal of this study is to determine how lithologically similar the Shawangunk and Tuscarora Formations are across various geographic locations and if these formations have the same durability to weathering forces as measured by their surface topography. I achieved this goal by examining the lithologic properties of the rocks and determining how the ridge’s topography varies spatially. The questions posed to answer during this study are related to the lithologic characteristics and geomorphic history of the Kittatinny Ridge. How similar are the formations in the northern extent of the study area to the rocks in the southern extent? If the formations are lithologically similar, are there differences in the surface morphology of the Kittatinny Ridge? Is the surface morphology of the Kittatinny Mountains representative of the long-term (~1x10^6 years) erosion rates of the Northern Appalachians, including the possible influence of climate and/or rejuvenated tectonic activity along this supposed “passive” margin? Can these results provide support to other studies of similar interest?

To answer these questions I measured and compared the rock hardness of various outcrop exposures of the Shawangunk and Tuscarora Formations using a Schmidt Hammer. I collected and compared rock samples of the Shawangunk and Tuscarora
Formations by using an optical microscope and an SEM to determine composition and porosity. I have analyzed longitudinal river profiles and river watershed hypsometries at various locations along the Kittatinny Ridge, in both the Shawangunk and Tuscarora Formations, using ArcGIS. The methodology and results of this study are included in the following sections.
2. Methodology

2.1 Sample Collecting

Rock samples of the Shawangunk and Tuscarora Formations were taken at several locations along the ridge. The sampling sites in New York were near Mohonk Preserve outside of New Paltz and Minnewaska State Park, while New Jersey samples were collected at High Point State Park and the Delaware Water Gap. In West Virginia the sampling sites were along North Fork Mountain in Spruce Knob/Seneca Rocks National Forest. Figures 4, 5 and 6 show the map locations where the samples were collected.

The collecting locations were chosen based on prominent ledge-forming outcrops within the Shawangunk and Tuscarora Formations. The locations were chosen based on sufficient outcrop exposure and relatively easy access (i.e., adjacent to or within a reasonable hike from a main road). Prominent exposures of high topographic relief indicate strong rock durability and resistance to erosion (at least compared to other local rocks with lower relief). The samples were collected at random locations at each study site and as a group encompassed as much of the outcrop as possible to reduce possible sampling bias. In the field I used a standard 22 oz. rock hammer, an 8 lb. sledge hammer, goggles, masking tape for labeling, and a notebook.

One tool that can be used to differentiate between the hardness of two rocks is called the Rebound Hammer, or Schmidt Hammer, named after the Swiss engineer who invented it, Ernst Schmidt. The Schmidt Hammer uses a steel rod and spring to strike a hard substance with a known force. The distance the hammer rebounds is recorded by a slide indicator on the outside of the hammer and measures the elasticity or hardness of the material it strikes on a scale from 10-100 and this value is referred to as a rebound.
number (Day, 1980). The Schmidt Hammer was originally intended for engineering projects that would need to determine the hardness of different types of concrete and cement (Cemex USA, 2013). Geologists use the Schmidt Hammer to compare the hardness of two similar types of rocks or different types of rocks and make interpretations of rock lithology, composition or how fractured a rock is (Day, 1980). It can be used to help geomorphologists quantitatively analyze how varying rock type can influence topographic relief. Although there are many factors influencing the accuracy of the Schmidt Hammer, such as angle of impact, surface texture and even temperature, precautions can be taken to ensure consistent results to be compared (Viles et al. (2010); Cemex USA, 2013).

Multiple (15 – 30) Schmidt hammer measurements were taken on various sections of the rock outcropping at each sampling site to test for rock hardness. The hammer measurements were calibrated with the Schmidt hammer standard block, which has a known rebound number of 80. The difference between the observed rebound measurement and the value of the standard block was then used to adjust field measurements. The rebound number measured 70 on the Schmidt hammer standard block so all field measurements were calibrated by adding 10. The measurements at each location were averaged for a single representative hardness value of that location.

2.2 Sample Analysis:

After fieldwork, samples were taken back to the lab for further processing. Rocks were cut with a rock saw into thin-section ready pieces and sent to Spectrum Petrographics in Washington State for thin section production. Four samples were collected from New York and two of those were sent for thin section preparation. Two
samples were collected from New Jersey and one of those was sent for thin section production. Six samples were collected from West Virginia and three of those were sent for thin section production. The thin sections were prepared to a 30 micron thickness with a microprobe finish. A total of eight thin sections were processed and analyzed.

The Scanning Electron Microscope (SEM) is a highly versatile instrument that can be adapted for multidisciplinary use. The SEM uses a tungsten filament to produce an electron beam that interacts with the desired specimen to produce characteristic electrons and x-rays. These characteristic electrons and x-rays are collected to generate micro- to nanometer scale images. Backscatter electron microscopy (BSE) will display a grayscale image where brightness is determined by atomic number of the element the electron beam is interacting with (Reed, 2005). The BSE can be used to analyze rock samples for mineral composition and the amount of pore space. Minerals will vary in brightness based on elemental composition and pore space will appear black where there is no electron interaction (Pope, 1995).

Initial analyses of the thin sections were performed with an optical microscope to determine mineral assemblages. The thin sections were then carbon coated using a Denton Vacuum Desk IV carbon coater and prepped for a microprobe analysis. Following the methodology of Pope (1995), the pore space of each thin section was measured by the percentage of black pixels in a grayscale image collected by the backscatter detector on the Scanning Electron Microscope (SEM). The black pixels are interpreted to be empty space between mineral grains (porosity). A Hitachi S-3400N Scanning Electron Microscope (SEM) with a Bruker X Flash Detector 4010 was used to analyze the eight thin sections. SEM conditions included a 15 keV, an emission current
of ~145, a probe current of 70.7 and the filament was set to 91. A magnification of 15x was used and the ABCC tool was used to adjust the brightness and contrast on each image capture. Nine image captures were used on each thin section at an 80 second slow capture rate at 2560 image size. Figures 7(A) and 8(A) show a New York thin section image capture example and a West Virginia thin section image capture.

The grayscale images were exported to a tiff or jpeg file and analyzed in ArcMap 10.1. Each image was converted to an integer raster file using the ‘Int’ tool in spatial analyst. This function enabled the attribute table to be opened to get values and counts. The images were changed to a ‘stretched’ display to obtain 8-bit grayscale values between 0 and 255 (0 = black; 255 = white). A conditional command was used to change all values of less than 1 (black) to a value of 1 and everything else to a value of 0. This command converted all of the pixels into two values (pore space and mineral space) to be calculated into a percentage. Zero was used to ensure that only the darkest pixels were being used and to not introduce bias in choosing a pixel value cutoff. Figures 7(B) and 8(B) show porosity raster files of a New York and West Virginia image capture. The results of the nine images for each thin section were averaged and the averaged value was used to represent the percent porosity of each rock sample.

The mineralogy of the thin sections was determined in combination with optical microscopy and SEM. An Axioscop 40 and AxioCam MRC at 5x magnification were used to determine mineralogy and capture images of the thin section mineralogy. The mineralogy determination was confirmed with Bruker x-ray analysis on the SEM. Multipoint capture was used in the center of each mineral to reduce the amount of x-rays being generated at mineral boundaries.
2.3 GIS analysis:

To determine potential variations in erosion, ArcGIS was used to generate river long profiles and hypsometric curves of watersheds along the Kittatinny Ridge. One-third arc second (approximately 10x10 m pixels) digital elevation maps (DEMs) were downloaded from the USGS National Map database in UTM projection. ArcMap 10.1 was used to view and work with the DEMs. These DEMs were used to calculate watershed areas of low-order streams draining the Kittatinny Ridge using standard GIS techniques in Spatial Analyst. The ‘fill’ tool was used to fill in any sinks and make hydrologically-continuous DEMs, followed by the ‘flow direction’ tool to calculate flow direction. The ‘flow accumulation’ tool was used to calculate flow accumulation. The ‘slope’ tool was used to calculate the slope values of the DEMs. The ‘conditional’ tool was used to set accumulation values of 5,000 cells (approximately 0.5 km²) or greater to ‘1’ and everything below to ‘no value.’ In ArcMap a polygon shapefile was created to outline the base of the ridge at the steepest slope value. For the New York, New Jersey and Pennsylvania DEMs a magnification of 10,000 was used to view and determine the base of the slope. Rivers from the conditional 5,000 layer that crossed the line at the base of the slope were used in this study. A minimum cutoff value of approximately 400 meters in length was used to pick rivers that crossed the shapefile line. Those chosen rivers were delineated in ArcInfo from the point that crossed the shapefile line using the ‘watershed’ command. For the West Virginia DEM a smaller conditional value of 1,000 accumulation cells was used and rivers could not be chosen based on a shapefile outline of the base of the ridge. The ‘slope’ tool did not reveal a characteristic delineation of the
ridge and therefore a different methodology had to be used. Coverages of the watersheds were created using the ‘gridpoly’ command. DEMs of the watersheds were created using the ‘arc latticeclip’ command. Figure 9 shows an example of one river and its watershed along the Kittatinny Ridge in Pennsylvania. The elevation data of each watershed DEM was exported to text files and processed in Microsoft Excel.

River long profiles (elevation over distance of the stream channel) of each river were created in ArcMap and exported to MS Excel. The elevation data for each watershed was normalized to itself in MS Excel and used to create hypsometric curves (land area over elevation) to display variations of valley shapes along the ridge. The river long profile data was normalized and plotted in MS Excel to display differences in profile shapes. Hypsometric values of each river were taken at the proportion of area above median elevation (Figure 10). Concavity indices were created by using the formula

$$\frac{(0.5-A)}{0.5}$$

where \( A \) = the area between the normalized river long profile and the 1:1 slope, a slightly modified version of Zaprowski (2005) (Figure 11).
3. Results:

3.1 Porosity

Nine images of each thin section’s pore space were taken in backscatter electron (BSE) view on the SEM. The nine photos were processed in ArcMap and pore space percent was exported to Excel and then averaged. The porosity results are included in Table 1. Rock sample NJ-1A had an average pore space percent of 1.90. The lowest measured pore space percent of the nine NJ-1A images was 0.38 and the highest measured pore space percent was 4.16. Rock sample NJ-1B had an average pore space percent of 1.44. The lowest measured pore space percent of the nine NJ-1B images was 0.44 and the highest measured pore space percent was 2.83. NY-1 had an average pore space percent of 0.96. The lowest measured pore space percent of the nine NY-1 images was 0.42 and the highest measured pore space percent was 1.56. Rock sample NY-2 had an average pore space percent of 0.29. The lowest measured pore space percent of the nine NY-2 images was 0.11 and the highest measured pore space percent was 0.80. WV-2 had an average pore space percent of 1.46. The lowest measured pore space percent of the nine WV-2 images was 0.71 and the highest measured pore space percent was 2.22. Rock sample WV-3A had an average pore space percent of 1.03. The lowest measured pore space percent of the nine WV-3A images was 0.52 and the highest measured pore space percent was 2.53. WV-3B had an average pore space percent of 2.59. The lowest measured pore space percent of the nine WV-3B images was 1.08 and the highest measured pore space percent was 4.01. Rock sample WV-6 had an average pore space percent of 1.60. The lowest measured pore space percent of the nine WV-6 images was 1.22 and the highest measured pore space percent was 2.16. The average pore space
percent of samples in the northern states is 1.15 and the average pore space percent of samples in the southern states is 1.67 (Table 1: Porosity Results). The average porosities of the NY-NJ samples and the WV samples were found to be statistically different with a T-test (\( p < 0.01 \)). Examples of the porosity result images are included in Figures 7 and 8. Porosity was plotted against latitude and is included in Figure 12.

### 3.2 Schmidt Hammer

Schmidt hammer measurements were taken along the Shawangunk and Tuscarora Formations during sampling trips. Table 2 shows the results of the measurements taken and are grouped by sampling locality. 15-30 measurements were taken at each site, averaged, and then plotted by their latitude. Two sets of measurements were taken near the Mohonk Preserve in New York. At latitude 41.7351° N an average measurement of 54.30±7.14 standard deviation was recorded. At latitude 41.7372° N an average measurement of 58.15±5.40 was recorded. Three sets of measurements were taken at High Point in New Jersey. At latitude 41.3072° N an average measurement of 51.86 ±6.93 was recorded. At latitude 41.3083° N an average measurement of 56.32±7.62 was recorded. At latitude 41.3239° N an average measurement of 63.71±8.91 was recorded. Two sets of measurements were taken at the Delaware Water Gap in New Jersey. At latitude 40.9687° N an average measurement of 50.93±13.20 was recorded. At latitude 40.9681° N an average measurement of 50.13±12.01 was recorded. Four sets of measurements were taken on the Tuscarora Formation along the North Fork Mountain in West Virginia. At latitude 38.9770° N an average measurement of 41.13±3.89 was recorded. At latitude 38.9729° N an average measurement of 34.67±6.08 was recorded.
At latitude 38.7167° N an average measurement of 49.70±6.69 was recorded. At latitude 38.7196° N an average measurement of 41.45±3.39 was recorded. The Schmidt hammer measurements were plotted against latitude (Figure 13: Latitude vs. Rebound Number). There is a slightly positive correlation between rebound number and latitude.

3.3 Concavity index

The New York river profiles had an average concavity index of -0.06±0.21 standard deviation (all expression of variance will be standard deviation), at an average latitude of 41.70° N. New Jersey had the lowest average concavity index of -0.38±0.17 at average latitude 41.23° N. The Pennsylvania study area was split into two DEMs and analyzed separately due to the large raster file size. The northeast Pennsylvania river profiles had an average concavity index of 0.00±0.09 at average latitude 40.60° N and the southwest Pennsylvania river profiles area had an average concavity index of 0.09±0.09 at average latitude 40.08° N. The West Virginia river profiles had an average concavity index of 0.32±0.07 at average latitude 38.82° N. A positive concavity index indicates a concave profile shape and a negative concavity index indicates a more convex profile shape. The concavity index results for each state are included in Tables 3-7 and the river long profiles with their respective DEMs are included in Figures 14-22. Concavity index was plotted against latitude and is included in Figure 23. There were more concave profiles at lower latitudes and more convex profiles at higher latitudes. New York had some concave but mostly convex profiles. The New Jersey profiles were all convex. Pennsylvania had little variation in profile shapes and was generally neither concave nor convex. The West Virginia profiles were all concave.
3.4 Hypsometries

Tables 3-7 show the hypsometric values of the watersheds grouped by state. Again, the northern Pennsylvania and southern Pennsylvania results were grouped separately. The northern Pennsylvania watershed data showed the highest average area above median elevation (AAME) value of 0.84±0.04, but a New Jersey watershed had the highest individual AAME value of 0.97. The watersheds from West Virginia show the lowest average AAME with a value of 0.36±0.04. The hypsometric profiles of each state are included in Figures 24-28. There appears to be a decrease in AAME trending southward which can be seen in Figure 29.
4. Discussion

The initial postulation of this study indicated a lithostratigraphic equivalence between the Shawangunk and Tuscarora Formations. This study attempted to substantiate how lithologically similar the two formations were and if they could be used to assess long term (~\(10^6\) years) erosional differences that vary spatially. The determination of the Shawangunk and Tuscarora Formations’ lithologic equivalence and their geomorphic implications could be used further understand the complex geologic and geomorphic history of the Appalachian Mountains.

4.1 Lithologic Comparison

An analysis of rock samples collected from New York, New Jersey, Pennsylvania, and West Virginia was completed to test the lithologic equivalence. Pore space and composition were analyzed with the SEM and compared between each of the samples. The results showed a very high percentage of quartz throughout all of the samples, but what minimally varied between the samples was the amount of macro pore space, displayed in Table 1. The samples from New York and New Jersey yielded an average pore space of 1.15% which is slightly less than the 1.67% average pore space that the samples from West Virginia yielded. Bernet et al. (2007) analyzed the diagenesis of quartz arenites in southern New York, including a sample of the Shawangunk conglomerate. Its porosity was approximately 0.9%, only 0.25% less than the average of my New York and New Jersey samples and 0.06% less than NY-1 which yield a porosity of 0.96%. The West Virginia samples had a slightly higher porosity but are close to the results of Manger (1963) that stated a sample of the Tuscarora in West Virginia ranged between 0.9-1.5% porosity.
When the porosity results of this study are compared with known porosity values of similar and dissimilar rock types, the 0.52% difference between the northern and southern rock samples seem negligible. While the difference measured here was statistically different, the difference is minimal compared to the measured ranges of other rock samples. McWhorter and Sunada (1977) calculated the porosity of various rocks and sediment to acquire a range for their respective types. Most of their results yielded porosity ranges above the measured porosity averages for the northern and southern rock samples. Basalt, a common igneous rock, has a porosity range of 3-35% and schist, a common hard metamorphic rock, has a porosity range of 4-49% (McWhorter and Sunada, 1977). Some examples of sedimentary rocks that were analyzed included a medium-grained sandstone with a porosity ranging between 14 and 49% and a limestone that ranged between 7 and 56% porosity. When these rocks and their porosity ranges are compared to the porosities of the Shawangunk and Tuscarora samples there is strong evidence that these samples have unusually low porosities and the 0.52% difference is minimal.

Macro pore space was quantified at a millimeter scale on the SEM-BSE at a magnification of approximately 15x. Micro pore space was not quantified in this study but based on initial investigation of the pore space some of the thin sections had microfractures visible at higher magnifications. The micro pore space within the rock samples could alter the measured porosity between the samples. The resolution of the SEM shows only what is present at the magnification being used. If a higher magnification of 100x or greater were to be used more images would need to be captured to equal the same amount of surface area covered at 15x magnification. The micro pore space
revealed at a scale of micrometers could have yielded different porosity results and can be a consideration for future work. Although, it is possible that the micro-fractures within the thin sections could be a result of the grinding and polishing that is necessary for thin section production.

Schmidt Hammer measurements indicated that the rocks in New York and New Jersey were harder than the rocks in West Virginia. A correlation can be made between the hardness of the rocks in the north and their low pore space and the lower hardness of the rocks in the south and their relatively high pore space (Figure 30: Porosity vs. Rebound Number). The rocks of the Shawangunk Formation in the north are slightly harder than the Tuscarora Formation in the south. The variation in rock hardness between the northern and southern study sites could be a result of weathering. The Schmidt hammer measurements were taken at the surface on various parts of the exposed outcrops. The results of these measurements could be influenced by how much surface weathering each sampling location has experienced. It is possible that the Tuscarora Formation in West Virginia experienced more weathering than the Shawangunk Formation in New York and New Jersey which would yield a lower rebound number.

4.2 GIS Topographic Analysis

The northern states' concavity index averages are lower (-0.38 for New Jersey and -0.06 for New York) than the southern states (0.39 for West Virginia and 0.09 for southern Pennsylvania), meaning the southern states had more concave long river profile shapes (Tables 3-7). The river long profile shapes progressively get more concave from north to south (Figures 14-22). River long profiles are a qualitative measure of topographic equilibrium. Concave river long profiles tend to indicate that erosion has
overcome the resistance of rock type and/or tectonic uplift or rebound (Knighton, 2014). Initially, based on the concavity index results of the study areas it appears that more erosion has occurred in southern watersheds compared to the northern watersheds. The river long profiles in figures 10-18 support this observation as the profiles become more concave progressing south. Hypsometric profiles in figures 24-28 show a similar trend to the river long profiles although slightly disharmonious as hypsometries are a measure of a watersheds elevation over an area which influences their shape. Pennsylvania has a higher average hypsometric value than both New Jersey and New York (Table 8: GIS Data: State Averages) which are farther North. These higher hypsometric values could indicate that the Pennsylvania watersheds are a part of an incised plateau.

4.3 Implications

One significant control on topographic relief and erosional histories of a region is its glacial history. Glaciers have impacted the Northeastern United States many times during the Quaternary, with the most recent glacial maximum occurring just over 20,000 years ago and extending as far south as central Pennsylvania and New Jersey (Isachsen, 1991) (Figure 3: Wisconsinan Glaciation Map). Evidence of glaciation in New York, New Jersey and Pennsylvania can be seen in end moraines, glacial till, striations, pronounced U-shaped river valleys, and erratic boulders, miles from their source. Glacial advances cover mountains, valleys and everything in between, potentially drastically changing their landscapes. It is possible that the pronounced convex river long profile shapes seen in the New York, New Jersey, and northern Pennsylvania (Figures 14, 16, and 18) were exaggerated by advancing glacial ice. The softer rock of the Martinsburg Formation that underlies the Shawangunk Formation and the Bloomsburg red beds of the
northwest slope of the Kittatinny Ridge would have been significantly eroded by the Wisconsinan glaciation leaving the more resistant quartzite sandstone conglomerate at a higher relief to the valley floor. The gently sloping streams measured along the Tuscarora Formation in southern Pennsylvania and West Virginia (Figures 19 and 21) are more representative of river valley erosion and not that of a glacial valley.

Geologically-recent topographic rejuvenation may have influenced the way the Appalachian landscape has evolved (Gallen et al. 2012; Liu 2014). Isostatic uplift can increase erosion and exaggerate the processes of landscape evolution. Miocene rejuvenation in the southern Appalachians due to mantle upwelling could have had an influence on the river profile shape observed in West Virginia but it is unknown if the mantle upwelling extended to the northern Appalachians. If the mantle upwelling was distributed equally throughout the Appalachians then the resulting uplift would not significantly influence this study as the effects would be applied equally across the northern and southern study areas. However, an unequal distribution of mantle upwelling could attribute to the plateau-like hypsometries that were seen in Pennsylvania. Rowley et al. (2013) revealed that mantle upwelling may not have been equally distributed and that Virginia has experienced a significantly higher topographic rejuvenation in the last 3 Ma. The increased topographic rejuvenation in this region could have attributed to more incised river valleys if river incision was able to overcome the rate of uplift. A relatively higher uplift rate in Pennsylvania could explain the more convex hypsometries and the less convex river long profiles if the river incision was equal to or higher than the uplift.

Isostatic rebound due to deglaciation in the northern Appalachians could also have increased the relative amount of uplift. In addition to the possible spatial...
distribution of mantle upwelling, the northern Appalachians are rebounding from the last glacial maximum (Sella et al., 2007) which means that relative uplift rates in New York, New Jersey and northern Pennsylvania are higher than the uplift rates of the non-glaciated states. These variations in uplift rates could have had influence over the river long profiles measured in this study. River profile concavity is directly related to the balance between incising and uplift (Knighton, 2014). The more convex profiles of New Jersey and New York could be the result of faster uplift rates in this region. This scenario seems unlikely as results from Gallen et al. (2012) and Rowley et al. (2013) conclude that the southern Appalachians have experienced the most topographic rejuvenation and that glacial isostatic adjustment was not as great of a contributor as mantle upwelling. It is possible that mantle upwelling was strongest in the southern study area, which could account for the increased incision results, and that the convex river long profiles and hypsometries of the northern study area were singularly the result of exaggerated glacial valley relief. The results from the topographic analysis in this study could help support other studies investigating the dynamic topography within the Appalachians.

The Shawangunk and Tuscarora may be lithologically similar but the two formations have experienced dissimilar tectonic and climatic histories. Geographically, exposures of the Shawangunk Formation along the Kittatinny Ridge are continuous and have only experienced moderate tilting of the beds. On a topographic map the Kittatinny Ridge can be followed quite easily from New York through New Jersey and into Pennsylvania. It is in central Pennsylvania after the Shawangunk transitions into the Tuscarora where it becomes difficult to follow the Kittatinny Ridge continuously and where the topographically high exposures of the Tuscarora are known by various other
local names. The change in geographic distribution of the Tuscarora Formation can be linked to the unique geologic/tectonic history of central Pennsylvania and West Virginia. During the Alleghenian orogeny and the collision between North America and Africa, the Tuscarora sandstone was a part of a fold thrust belt that pushed thick blocks of sedimentary bedrock on top of each other en echelon (Faill, 1969; Kulander, 1986). The faulting and folding of the Tuscarora in central Pennsylvania and West Virginia may have thinned and weakened it, increasing incision. The divergent structural histories of the Shawangunk and Tuscarora Formations may be a factor in the varying results of the longitudinal profiles and hypsometries.

Topography within the Appalachian Mountains have been uplifting, eroding, depositing new rock and uplifting again in cycles long before glaciers, and recent topographic rejuvenation have had its part in shaping the Kittatinny Ridge to what we see today. There is no definite way of knowing the variables and forces influencing the erosion of the Appalachians. Although, studies by Roden and Miller (1989) and Steltenpohl and Kunk (1993) reveal roughly how long the rocks in the Appalachians today have been exposed near the surface. Using apatite fission-track thermochronology Roden and Miller (1989) studied ash beds in the Valley and Ridge province of Pennsylvania to determine the cooling and unroofing of the rocks in the region. They determined that these rocks began their unroofing shortly after the Alleghenian Orogeny (285-270 Ma). It is unknown what factors of erosion affected the Kittatinny Ridge between its initial surfacing and the cycles of glaciation and mantle upwelling in the last few million years.
Erosional histories are difficult to determine because erosion often erases the history geologists are trying to understand. Sediment can reveal much information about the history of a mountain range, a river, a valley. Depending on how much sediment is present one could possibly calculate how much had eroded, its source, and what kind of processes brought it there. Geologists can study sediment to interpret the stories it is trying to tell about where it came from, how it got there and what forces were acting on it such as fluvial, glacial, or tidal (Stefanon et al., 2012). What is more difficult is discerning the intricate properties of the original rock they are derived from. Once a rock has been eroded it is difficult to impossible to get quantitative results on the mineralogy, pore space, or hardness of that rock. This is what makes studying erosional histories so challenging. For this study we were only able to study and measure the rocks that are present today. What kind of rock from the Tuscarora and Shawangunk Formations was there before it eroded away? The answer to that question could have had a significant impact on erosion along the Kittatinny Ridge. For the purposes of this study I am going to infer that the rock that has been eroded away had all been of similar type to what is there presently.

Rock samples of the Shawangunk Formation were collected in the Mohonk Preserve and Minnewaska State Park in New York, as well as High Point, New Jersey. Schmidt hammer measurements were also taken at these locations as well as the Delaware Water Gap in New Jersey. These locations were chosen because of exposed outcrops and their travel convenience from the Montclair State University area. A weekend sampling event took place at North Fork Mountain in West Virginia in order to obtain rock samples and Schmidt hammer measurements. Due to travel distance and
time, much of the Shawangunk Formation and Tuscarora Formation was not sampled or measured in the field. This data could have been helpful in creating a more reliable relationship between rock hardness and pore space. The relationship between porosity and rebound number (Figure 30) shows a negative correlation, as porosity decreases the rebound number increases and vice versa. Using this relationship in coincidence with the river long profiles measured in ArcMap, we can infer the pore space and rock hardness of the Kittatinny Ridge where samples were not collected.

4.4 Limitations and Data Gaps

The field data was collected sporadically when time was available and weather permitted between September 2014 and March 2015. Snow cover and access to the desired sampling locations made data collecting difficult during the winter. Much of the Kittatinny Ridge through Pennsylvania and West Virginia is too far from Montclair State University to make frequent sampling trips. This limited the amount of rock samples analyzed and was limited to the one sampling trip to North Fork Mountain, West Virginia for the southern data.

Some watersheds were removed from the study and therefore their respective river long profiles and hyspometries were not included in the results. The watersheds removed include watershed numbers 5, 6, 7, 10, 13, 15 and 18 from New Jersey, and numbers 1, 2 and 11 from Pennsylvania (NE). These watersheds did not meet the updated criteria for selecting rivers to be analyzed. Either these rivers were too short in length to be analyzed or did not accurately represent the Kittatinny Ridge well enough.
4.5 Future Work

More samples could be collected between New Jersey and West Virginia to gain a better distribution of porosity and hardness data. Schmidt hammer data could be collected on both fresh rock surfaces and weathered ones to acquire a quantitative comparison of rock weathering from location to location. Micro pore space could be analyzed at a higher SEM magnification in addition to the macro pore space to gain a more accurate porosity measurement of each sample. Mineralogy was confirmed qualitatively but a more quantitative measurement of mineralogy and cementation could be completed in the future to compare to other studies’ data like Bernet (2007). Rock density and specific gravity is another method that could be used to compare samples of Shawangunk and Tuscarora.

Climate data could be acquired for New York, New Jersey, Pennsylvania and West Virginia to look for precipitation rates and other weathering factors that might influence the rebound numbers and the morphology of each study area. Schmidt hammer measurements could be taken on both fresh rock and weathered rock to try to acquire a quantitative measure of weathering influence.
5. Conclusion

This project sought to test the lithostratigraphic equivalence of the Shawangunk Formation in New York, New Jersey and eastern Pennsylvania with the Tuscarora Formation in central Pennsylvania and West Virginia, the backbone of the Kittatinny Ridge, in order to further understand its geomorphic history. The SEM analysis of Shawangunk and Tuscarora samples revealed that they are approximately compositionally equivalent, with the porosities of the northern samples are within 0.52% of the southern samples. The minor difference in porosity between northern and southern rock samples can be considered negligible when compared to much larger ranges in porosity for other rock types. Schmidt hammer measurements revealed that the rock samples in New York and Jersey are slightly harder than the rock samples collected in West Virginia, but more data can be collected for these sites comparing fresh rock to weathered rock hardness. River long profiles and hypsometries generated for watersheds within New York, New Jersey, Pennsylvania and West Virginia displayed a higher concavity trending south. The more convex profiles in New York, New Jersey and eastern Pennsylvania are most likely the result of exaggerated relief due to glacially carved valleys parallel to the Kittatinny Ridge. The more concave profiles in the southern study areas are most likely attributed to the higher influence of topographic rejuvenation focused around Virginia. The rivers in these affected areas would have higher incision in response to the uplifting topography. The results collected from this study could help support future studies of topographic rejuvenation and glaciation in the Appalachian Mountains.
6. References


Figure 1: Appalachian Mountain Physiographic Provinces. The Kittatinny Ridge is on the eastern border of the Valley and Ridge province. Modified from Stoffer, 2015.
Figure 2: Geologic Map of Pennsylvania. The Silurian aged rocks outline where the Shawangunk and Tuscarora Formations are located. The red circle roughly represents where the Shawangunk transitions into the Tuscarora. Modified from Barnes et al. (2014).
Figure 3: Wisconsinan Glaciation Map. The blue arrow is pointing to the farthest extent of the Wisconsinan Glaciation in Pennsylvania. Modified from Isachsen (2000).
Figure 4: New York Sampling Location (red circle). The site is west of New Paltz, NY. Captured from Google Maps.
Figure 5: New Jersey Sampling Location (red circle). The site is at High Point, NJ. Captured from Google Maps.
Figure 6: West Virginia Sampling Location (red circle). The site is located southwest of Petersburg, WV, along North Fork Mountain. Captured from Google Maps.
Figure 7: New York Porosity Example. Sample NY-1 showing 0.42% porosity. (A) Image capture from the SEM. (B) Pore space raster image from ArcMap. This image capture from the NY-1 sample had one of the lowest measured porosities of the images analyzed.
Figure 8: West Virginia Porosity Example. Sample WV-3B showing 4.01% porosity. (A) Image capture from the SEM. (B) Pore space raster image from ArcMap. This image capture from the WV-3B sample had the highest measured porosity of the images analyzed.
Figure 9: GIS River and Watershed. Example of a river (highlighted in teal) and its watershed (outlined in red) along the Kittatinny Ridge in Pennsylvania produced from GIS.
Figure 10: Hypsometry Example. A hypsometry showing that ~84% of the basin area is above the median elevation. Modified from Zaprowski (2005).
Figure 11: River Long Profile Diagram, showing concavity index calculation. Modified from Zaprowski (2005).
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<th>Sample ID</th>
<th>Average Porosity (%)</th>
<th>Standard Deviation</th>
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<td>South</td>
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Table 1: Porosity Results.
Figure 12: Latitude vs. Porosity.

Latitude vs. Porosity

\[ R^2 = 0.2188 \]

Latitude

Porosity (%)

38.5 39 39.5 40 40.5 41 41.5 42

North Fork Mt.

High Point
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<th>State</th>
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Table 2: Schmidt Hammer Results.
Figure 13: Latitude vs Rebound Number.
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</table>

Table 3: New York GIS Results.
### New Jersey GIS Results

<table>
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<tr>
<th>WS#</th>
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<th>Concavity Index</th>
<th>Hypsometry (Portion of Area above elevation)</th>
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Table 4: New Jersey GIS Results
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<th>Concavity Index</th>
<th>Hypsometry (Portion of Area above elevation)</th>
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</thead>
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Table 5: Pennsylvania (NE) GIS Results.
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<th>Concavity Index</th>
<th>Hypsometry (Portion of Area above elevation)</th>
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</thead>
<tbody>
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<tr>
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Table 6: Pennsylvania (SW) GIS Results.
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<th>Hypsometry (Portion of Area above elevation)</th>
</tr>
</thead>
<tbody>
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</tr>
</tbody>
</table>

Table 7: West Virginia GIS Results.
Figure 14: New York River Long Profiles (colored lines) and a 1:1 line (black line). The majority of the lines are above the black 1:1 line, meaning that most of the watersheds were generally convex.
Figure 15: New York DEM. New York's watersheds are included along the ridge.
Figure 16: New Jersey River Long Profiles (colored lines) and a 1:1 line (black line). The majority of the lines are above the black 1:1 line, meaning that most of the watersheds were generally convex.
Figure 17: New Jersey DEM. New Jersey's watersheds are included along the ridge.
Figure 18: Pennsylvania (NE) River Long Profiles (colored lines) and a 1:1 line (black line). The majority of the lines are approximately equal to the black 1:1 line, meaning that most of the watersheds generally show no concavity.
Figure 19: Pennsylvania (SW) River Long Profiles (colored lines) and a 1:1 line (black line). The majority of the lines are approximately equal to the black 1:1 line, meaning that most of the watersheds generally show no concavity.
Figure 20: Pennsylvania DEM. Pennsylvania’s watersheds are included along the ridge.
Figure 21: West Virginia River Long Profiles (colored lines) and a 1:1 line (black line). The majority of the lines are below the black 1:1 line, meaning that most of the watersheds were generally concave.
Figure 22: West Virginia DEM. West Virginia's watersheds are included along the ridge.
Concavity Index

Latitude vs. Concavity Index

Figure 23: Latitude vs. Concavity Index. Concavity decreases with increasing latitude.
Figure 24: New York Hypsometries. The curves are generally convex, with most of the watersheds' areas located at higher elevations.
Figure 25: New Jersey Hypsometries. The curves are generally convex, with most of the watersheds' areas located at higher elevations.
Figure 26: Pennsylvania (NE) Hypsometries. The curves are generally convex, with most of the watersheds' areas located at higher elevations.
Figure 27: Pennsylvania (SW) Hypsometries. The curves are generally convex, with most of the watersheds' areas located at higher elevations.
Figure 28: West Virginia Hypsometries. The curves are generally concave, with most of the watersheds’ areas located at lower elevations.
Figure 29: Latitude vs. Hypsometry for the studied watersheds. The hypsometric values generally increase to the north.
Figure 30: Porosity vs. Rebound Number. The rebound number from the Schmidt Hammer decreases with increasing porosity.
<table>
<thead>
<tr>
<th>State</th>
<th># of Watersheds</th>
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<th>Average Concavity Index</th>
<th>StDev</th>
<th>Average Hypsometry</th>
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Table 8: GIS Data: State Averages.