THE DETERMINATION OF MILLENIAL SCALE EROSION RATES USING COSMOGENIC ANALYSIS OF ^{10}Be IN THE SHENANDOAH NATIONAL PARK

A Progress Report Presented

by

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to

The Faculty of the Geology Department

of

The University of Vermont

Accepted by the Faculty of the Geology Department, the University of Vermont, in partial fulfillment of the requirements for the degree of

Master of Science specializing in Geology

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Abstract

My research investigates the erosional history of the Blue Ridge Province of the Appalachian Mountains in the Shenandoah National Park. Using the isotope ^{10}Be for cosmogenic nuclide analysis, I will determine erosion rates in the Park on the timescale of 10^3 – 10^6 and investigate whether Hack's (1960) model of *dynamic equilibrium* and steady state behavior are applicable to the geomorphic processes that are operating in the park. I am also testing Matmon et al.'s (2003b) observation that the concentrations of ^{10}Be vary between different grain sizes.

All 16 samples analyzed so far contain significant amounts of ^{10}Be (> $3.59 * 10^5$ atoms/g), which can be modeled to suggest erosion rates somewhat lower than others have measured in the Appalachians (4 to 14 m/My). ^{10}Be analysis of 4 sediment samples separated into four grain different grain sizes (0.25 – 0.85 mm, 0.85 – 2 mm, 2 - 10 mm, > 10 mm) allows me to test for grain size dependence of nuclide concentration. Two samples show a monotonic decrease in ^{10}Be concentration with increasing grain size. The third follows the same trend except for the largest two grain size fractions. The fourth sample shows no distinct trend. The differences in ^{10}Be concentrations are not great, ~23%, indicating that grain size has little consistent effect on measured ^{10}Be concentration and thus modeled erosion rates. With these results it appears that lithology does influence erosion rates, but with only n = 4, I cannot yet make concrete conclusions about this analysis. Taking the modeled values as is, granite (13.8 m/My) and siliciclastic rocks (11.9 m/My) seem less stable in this weathering environment than quartzite (5.6 m/My) and basalt (4.3 m/My).

1.0 Introduction

Understanding the dynamic nature of the Earth's surface, the form of the land surface, the processes that create it and how the landscape has changed over time is fundamental to geomorphology. For decades, geomorphologists have sought to understand the relationships between erosion rates (both physical and chemical, e.g. Riebe et al., 2001, 2003), climate (Harris and Mix, 2002), and topography and lithology (Hack, 1960). The Appalachian Mountains have been the subject of intense study for decades because of the interest in understanding the geomorphic processes that occur in mountain ranges following orogenic events (Miller and Duddy, 1989; Pazzaglia and Brandon, 1996; Naeser, 2001, 2005; Matmon et al., 2003a, 2003b; Reuter et al., 2003, 2004, 2005; Morgan, 2004). Of particular interest in the Appalachians is the paradox that exists in the continued existence of mountainous topography tens to hundreds of millions of years after orogenic events ceased (Pazzaglia and Brandon, 1996).

I am investigating the relationship between erosion rate, lithology, slope, basin area and grain size and compare my results with Hack's (1960) model of *dynamic equilibrium* and steady state behavior which predicts that erosion rates should be independent of lithology; less resistant lithologies will have shallow slopes and more resistant lithologies will have steeper slopes. My study will add to the understanding of the processes involved in the changing landscape of the Blue Ridge Mountains within the Shenandoah National Park (Fig. 1), one of the most heavily visited in the east, with approximately 2 million visitors per year. So far, my data show that the Park is eroding only slowly (4.3 to 13.8 m/My) and that erosion rate varies by lithology in contrast to Hack's model.

2.0 Progress To Date

2.1 *GIS Analysis of the Shenandoah Park Landscape*

Using ArcGIS I generated a list of drainage basins that included criteria such as basin size, location, lithology, mean slope, and elevation range (Table 1). These basins were delineated using several GIS layers including: DEM's (Digital Elevation Models) of the park along with bedrock geology that provided an overall picture of the physiography and principal bedrock formations found within the park, National Hydrography Datasets (NHD) that provided the stream layer, digital contour maps (DRG) that were overlayed to provide a visual confirmation of streams and a digital layer of the National Park Boundary.

Once the basins were delineated, and the desired criteria were established, I was able to choose sample sites of sufficient basin size to allow for adequate mixing of sediments within the basin, while sampling basins that represent a variety of average slopes, elevations, and lithologies. I carried these maps and data to the field with me so that based on field access, I could chose alternate basins if field conditions, such as access limitations, prevented me from sampling certain basins.

2.2 Sample Collection

In the fall of 2005, I collected 4 samples (Fig. 2, Table 2) (broken into four grain size splits: 0.25 – 0.85 mm, 0.85 – 2 mm, 2 - 10 mm, > 10 mm), and this past summer a further 36 samples (Figs. 3a and 3b, Table 2) from active river or stream channels within or near to the boundaries of the park (Fig. 1). The amount of sediment I collected this summer was based on the results of samples collected in the field in the fall of 2005. For all the quartz-rich lithologies ~ 0.5 - 1 kg of sample was sufficient to carry out the lab processes to isolate ^{10}Be. The majority of samples were wet sieved in the field to the 0.25 – 0.85 mm size fraction, which is a suitable size for processing in the lab.

2.3 Lab Work

Quartz was isolated at UVM using protocols outlined at http://www.uvm.edu/cosmolab/lab/whatwedo.html. A brief synopsis of the process is as follows: the quartz is cleaned in the mineral separation lab via a process of etching in HCl, and HF/ HNO_3; a density separation is performed that removes heavy minerals such as magnetite and ilmenite. The clean quartz is then tested for its purity and ^{10}Be is isolated using standard lab procedures (http://www.uvm.edu/cosmolab/lab/whatwedo.html) by Jennifer Larsen. The ^{10}Be is then measured using accelerator mass spectrometry (AMS) at the Lawrence Livermore Laboratory.

3.0 Data

Over the spring semester of 2006, I processed the initial 16 samples gathered in the fall of 2005. These samples comprised the four grain size splits of the four lithologies found within the boundaries of the Shenandoah National Park. Following isolation of ^{10}Be in the cosmogenic lab at UVM, the samples were taken to Lawrence Livermore National Laboratories where they were measured on the accelerator mass spectrometer (AMS) in order to determine the $^{9}Be/^{10}Be$ ratio. Once this ratio was determined, the concentration of ^{10}Be in each sample is known. These concentrations can then be normalized using the altitude-latitude scaling function of Lal (1991) and erosion rates modeled using methods presented in Bierman and Steig (1996).

4.0 Results

Table 1 shows measured ^{10}Be concentrations and modeled erosion rates of the first 16 samples collected and processed. The granite samples displayed a monotonic decrease in ^{10}Be concentration with increasing grain size (3.59 x 10^5 to 2.34 x 10^5 atoms/g) which map to erosion rates between from 14 to 22 m/my. The basalt sample shows a similar trend with ^{10}Be concentrations decreasing with grain size from 1.03 x 10^6 to 8.09 x10^5 atoms/g (corresponding to erosion rates of 4.3 to 5.6 m/My). The quartzite samples show decreasing ^{10}Be concentrations in the three smaller grain sizes (7.44 x 10^5 to 5.06 x 10^5 atoms/g), but at increase in the >10mm grain size fraction (6.18 x 10^5 atoms/g). Modeled erosion rates for quartzite range from 6 to 8 m/My. The siliciclastic ^{10}Be concentrations show no pattern with grain size and give model erosion rates of 8 to 13 m/My.

5.0 Discussion

5.1 Grain Size Analysis

The analysis of ^{10}Be concentrations on grain has yielded some interesting results. Of the four samples collected to investigate this relationship, 2 of them display a monotonic inverse relationship between grain size and ^{10}Be concentration similar to that seem by Matmon et al.

(2003b) in the Great Smokies (sandstone) and Brown et al. (1995) in Puerto Rico (granite). The granite and basalt samples display a decrease in ^{10}Be concentrations with increasing grain size (Fig.4, Table 1). Of the other samples, the quartzites also appears to follow this trend, except for a slight increase in ^{10}Be concentration in the >10 mm grain size split. The siliciclastic samples show no correlation between ^{10}Be concentrations and grain size. In conclusion then, there is some grain size effect but it is not consistent between lithologies. In the context of previous research, 2 of my initial samples display similar relationships to those found by Matmon et al. (2003b) (Fig. 4, Table 1.) That is that cosmogenic nuclide concentrations vary systematically with grain size: smaller grains have higher ^{10}Be concentrations than larger ones; larger clasts only survive short transport distances. With n = 4 I cannot draw definitive conclusions as to the validity of the Matmon model. Brown et al. (1995) in Puerto Rico attributed the grain size relationship he found to deep excavation of large clasts by landslides. Although landslides do occur in the central and southern Appalachians, they rarely occur in the same location and are often associated with major storms (Morgan et al. 1997). During my field season this summer I did not see much evidence of landslides being a major component in the geomorphic processes operating in the Park, due to the intense vegetation that covers the slope and renders them stable.

5.2 Erosion Rates vs Lithology

Hack's *dynamic equilibrium* suggests the landscape is in a steady state and that all elements of the landscape erode at the same rate; less resistant lithologies will have shallow slopes and more resistant lithologies will have steeper slopes. My initial results suggest that there appears to be a relationship between ^{10}Be-modelled erosion rates and lithology for these samples (Fig. 6), contradicting Hack's (1960) theory that suggests that erosion rate is not influenced by lithology. It remains to be seen if this preliminary trend will be as robust when I have the remainder of my data. My data reveals that quartzite and basalt are, in Hack's terminology, the most resistant, and that granite and siliciclastic are the least resistant (Fig. 6). The lack of micas and mafics in the quartzite could explain the stability of this lithology. Granite has the highest erosion rates and slopes (Figs. 5 and 6), and although it is relatively stable in arid regions (Bierman and Nichols, 2004), and less so in humid regions (Durgin, 1997). So, these erosion rates for granite are not unreasonable in a region where the average annual rainfall within the park is ~ 1500 mm per year.

In conclusion, initial data suggest that lithology affects basin-scale erosion rates in Shenandoah Park and that grain size has little effect on ^{10}Be concentration in this area. The cosmogenically-determined erosion rates (0.25 – 0.85 mm) in Shenandoah Park for granite (12.3 m/My), basalt (4.3 m/My), quartzite (5.6 m/My) and siliciclastic (11.9 m/My) are similar to or lower than those reported elsewhere in the Appalachians, including those of Matmon et al. (2003b), 25 to 30 m/My for meta-sandstone in the steep Great Smoky Mountains, and those of Reuter et al. (2004), 4 – 54 m/My in Susquehanna River basin for shale, sandstone, and schist

Fig. 7). My data is also of a similar magnitude to long-term erosion rates determined using other techniques. The short term cosmogenic erosion rates (10^4 yrs) I measured in the Blue Ridge of Shenandoah Park are consistent with long term rates (>10^7 yrs) estimated using U/Th/He near the Blue Ridge Escarpment by Spotila et al. (2004), 11 to 18 m/My, and using fission tracks in the southern Appalachians by Naeser et al. (2005), 20 m/My. This consistency suggests long-term rates of erosion of the region are steady and are reflected by the cosmogenic data.

5.0 Future Work

5.1 Statistical Analysis

Once I get results for my remaining samples from Livermore Laboratory, I will normalize ^{10}Be concentrations using the altitude-latitude scaling function of Lal (1991) and model erosion rates using methods presented in Bierman and Steig (1996). Erosion rates will be analyzed with respect to lithology, slope, and grain size; the grain size analysis having already been completed. I will test the significance of erosion rate change as a function of slope and basin size to test the hypothesis that isotope concentration (set by the erosion rate) is a function of slope. I intend to do this first in order to remove the effect of slope and basin size. Then, I will complete a one-way ANOVA analysis for the four lithologies in order to test for significant differences in erosion rates between the lithologies, and finally, I will contrast the four erosion rates of the lithologies to see if there are any differences between them, which will enable me to test Hack's theory of *dynamic equilibrium*.

5.2 Timeline

For the full timeline of my future work see Table 3.

Figures and Tables

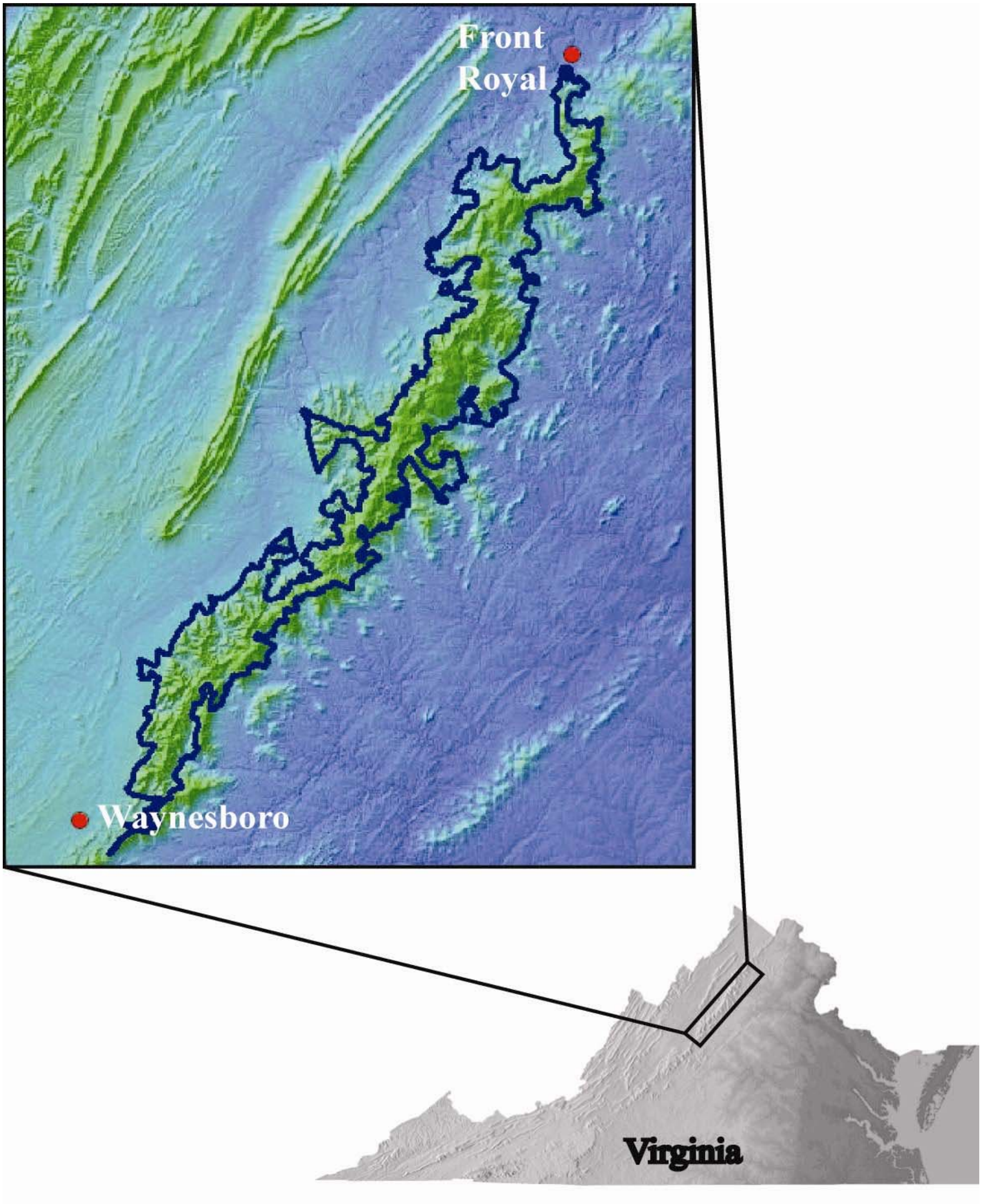


Figure 1. Location Map of the Shenandoah National Park

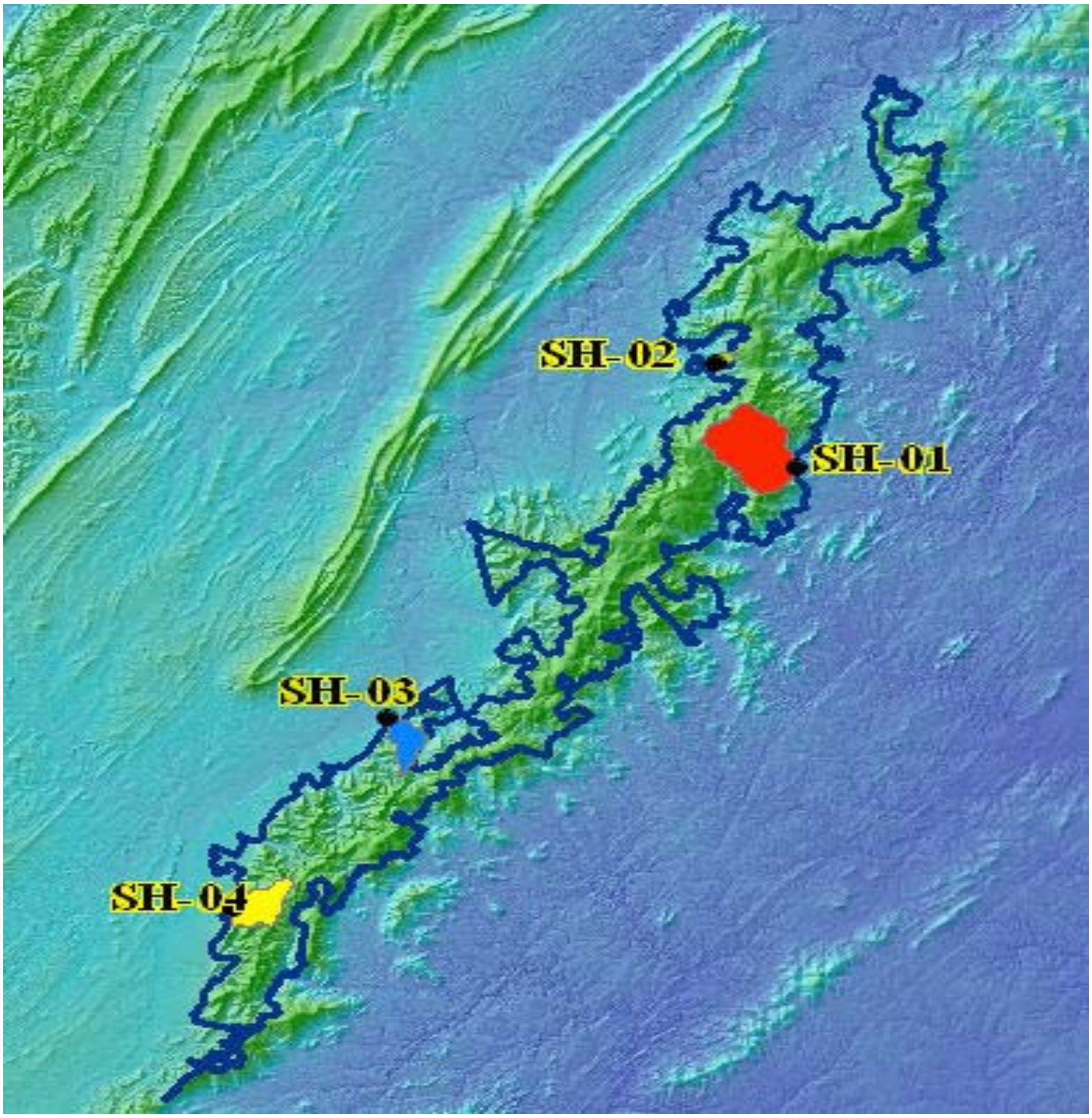


Figure 2. Map showing the initial sites and basins sampled in Shenandoah National Park in the fall of 2005. SH-01: Granite, 40 km^2 basin, avg. slope 18˚, erosion rate = 14 m/My; SH-02: Basalt, 1 km^2 basin, avg. slope 14˚, erosion rate = 4 m/My; SH-03: Quartzite, 9.3 km2 basin, avg. slope 18˚, erosion rate = 6 m/My; SH-04: Siliciclastic, 23 km^2 basin, avg. slope 23˚, erosion rate = 12 m/My. Dark blue line is the Shenandoah National Park Boundary.

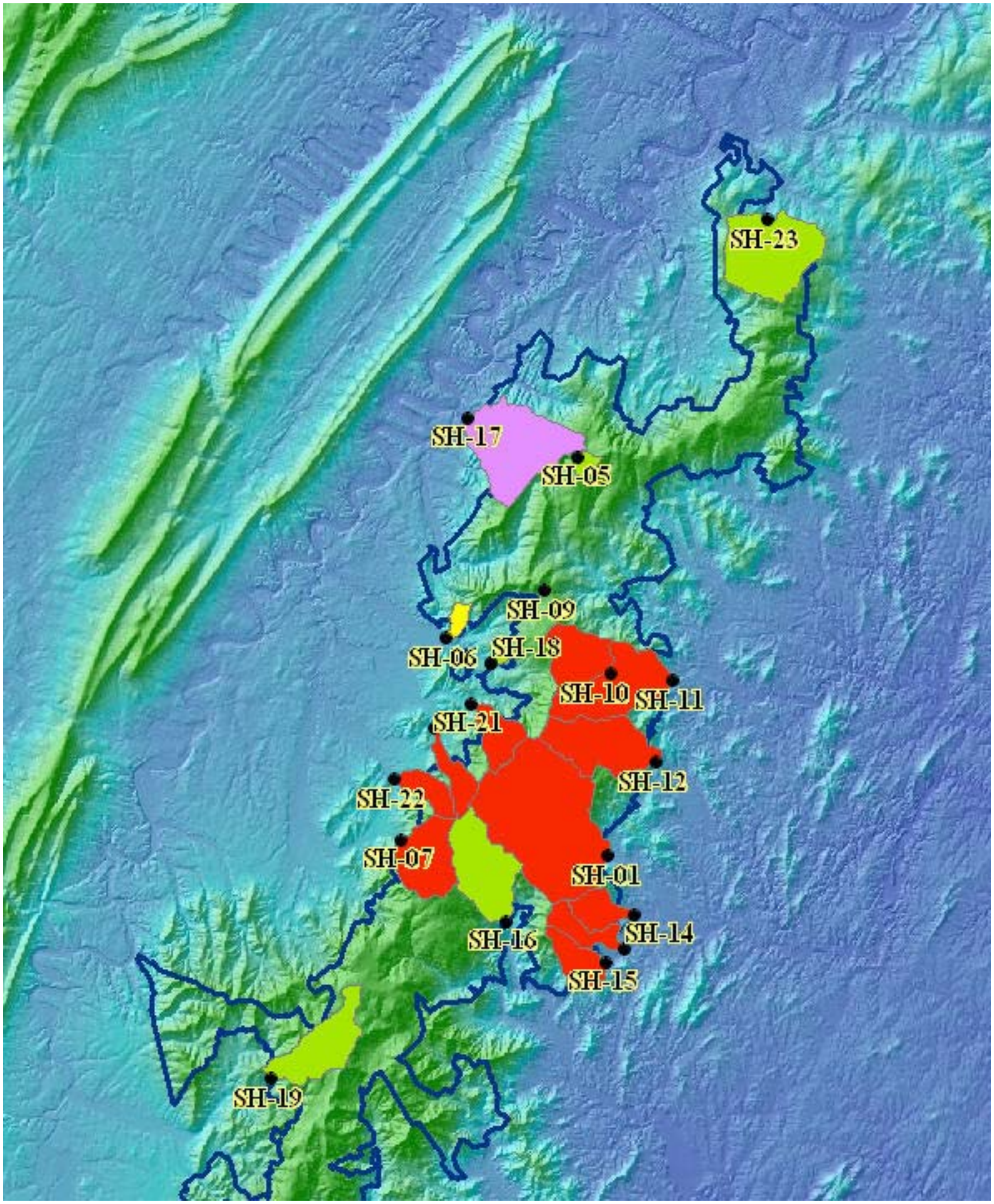


Figure 3a. Map showing all the sample sites and associated delineated basins in the northern part of the Shenandoah National Park. Granite = red basins; Basalt = green basins; Siliciclastic = yellow basin. For details of basin area, slope and associated erosion rates see Tables 1 and 2. Dark blue line is the Shenandoah National Park Boundary.

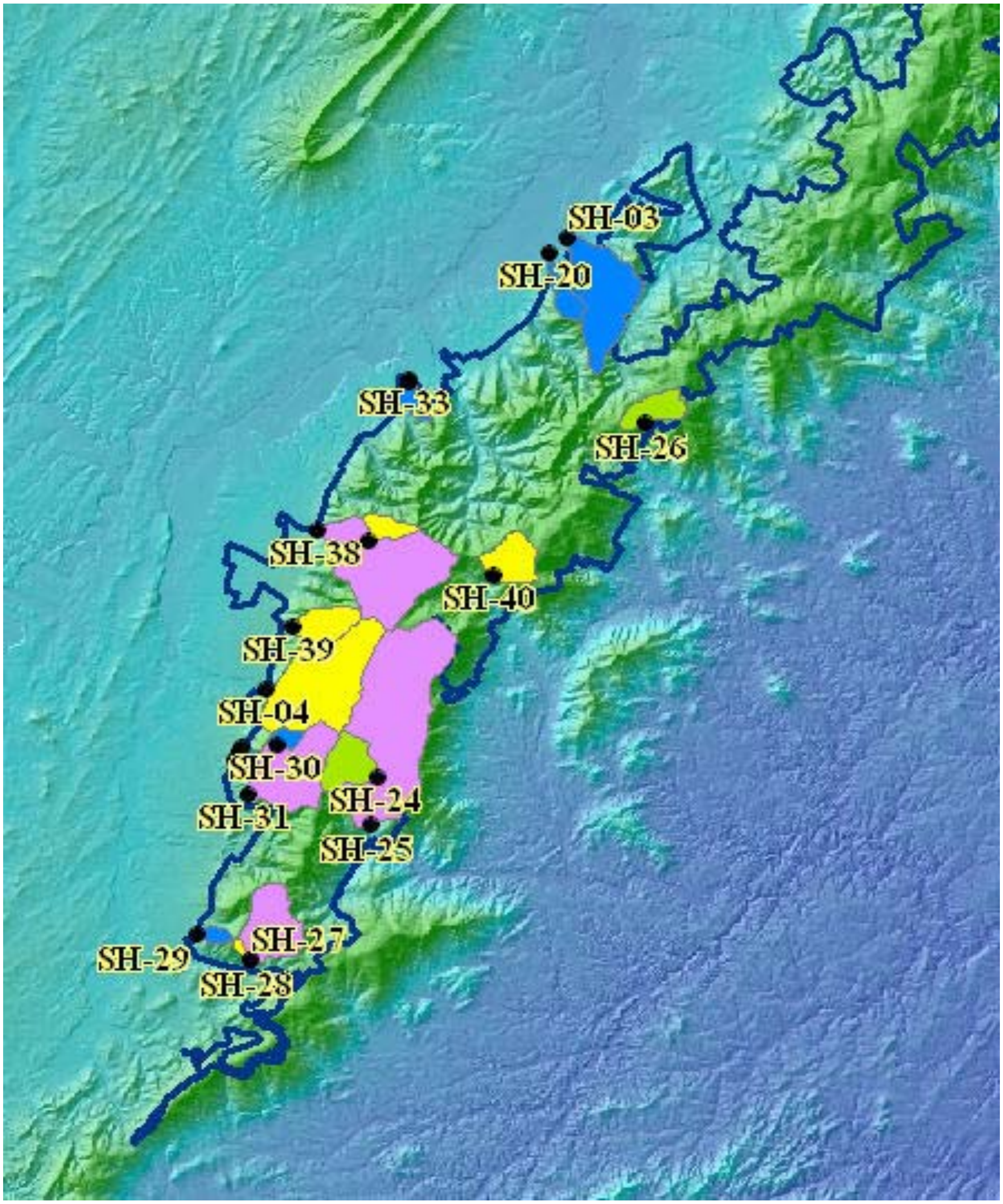
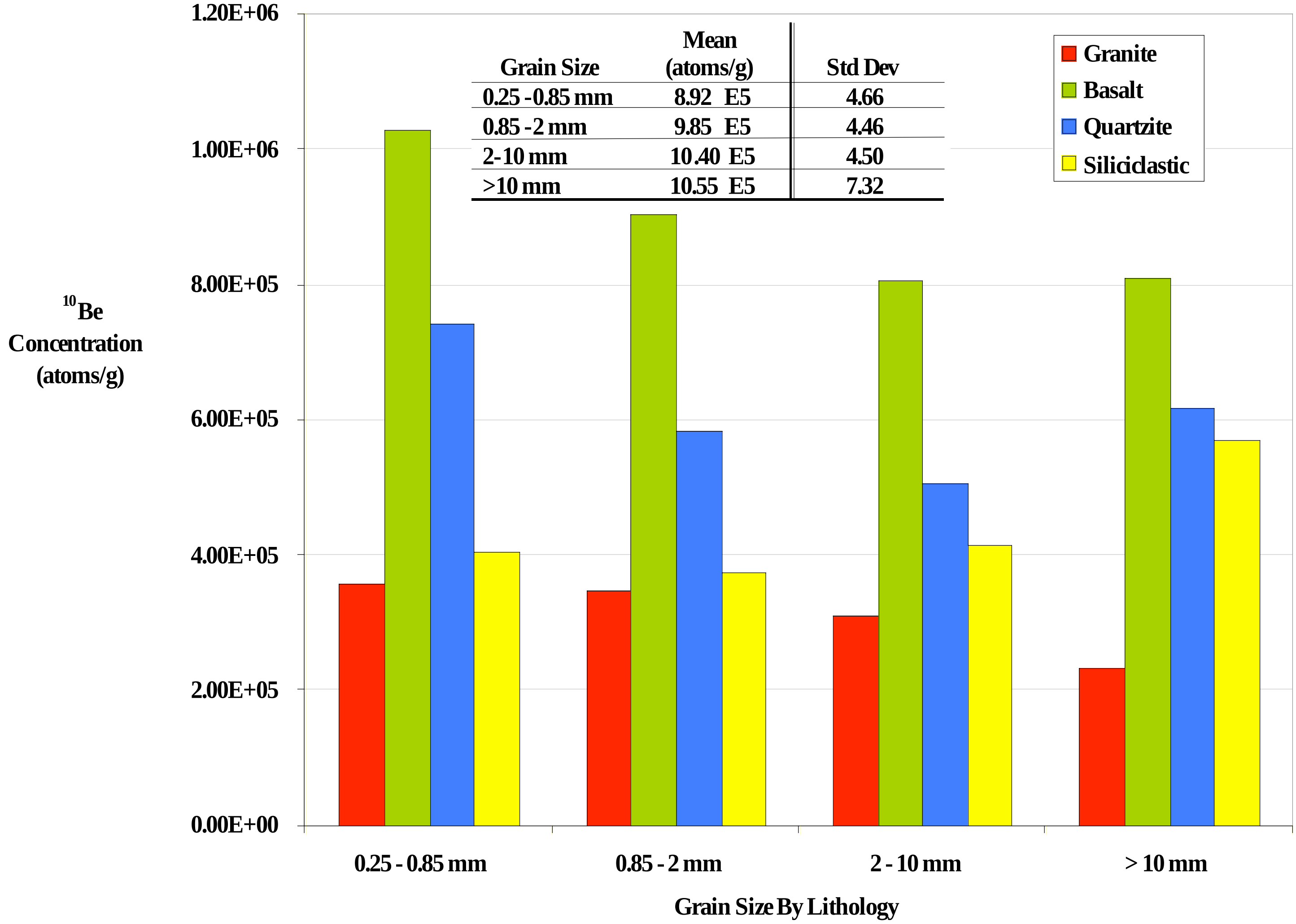


Figure 3b. Map showing all the sample sites and associated delineated basins in the southern part of the Shenandoah National Park. Basalt = green basins; Siliciclastic = yellow basins; quartzite = blue basins; Multilithology = purple basins. For details of basin area, slope and associated erosion rates see Tables 1 and 2. Dark blue line is the Shenandoah National Park Boundary.



Grain Size	Mean (atoms/g)	Std Dev
0.25 - 0.85 mm	8.92 E5	4.66
0.85 - 2 mm	9.85 E5	4.46
2-10 mm	10.40 E5	4.50
>10 mm	10.55 E5	7.32

Figure 4. Grain size splits by lithology are shown here along with corresponding ^{10}Be concentrations. The inset table details the mean ^{10}Be concentrations in each grain size split as well as the associated standard deviation.

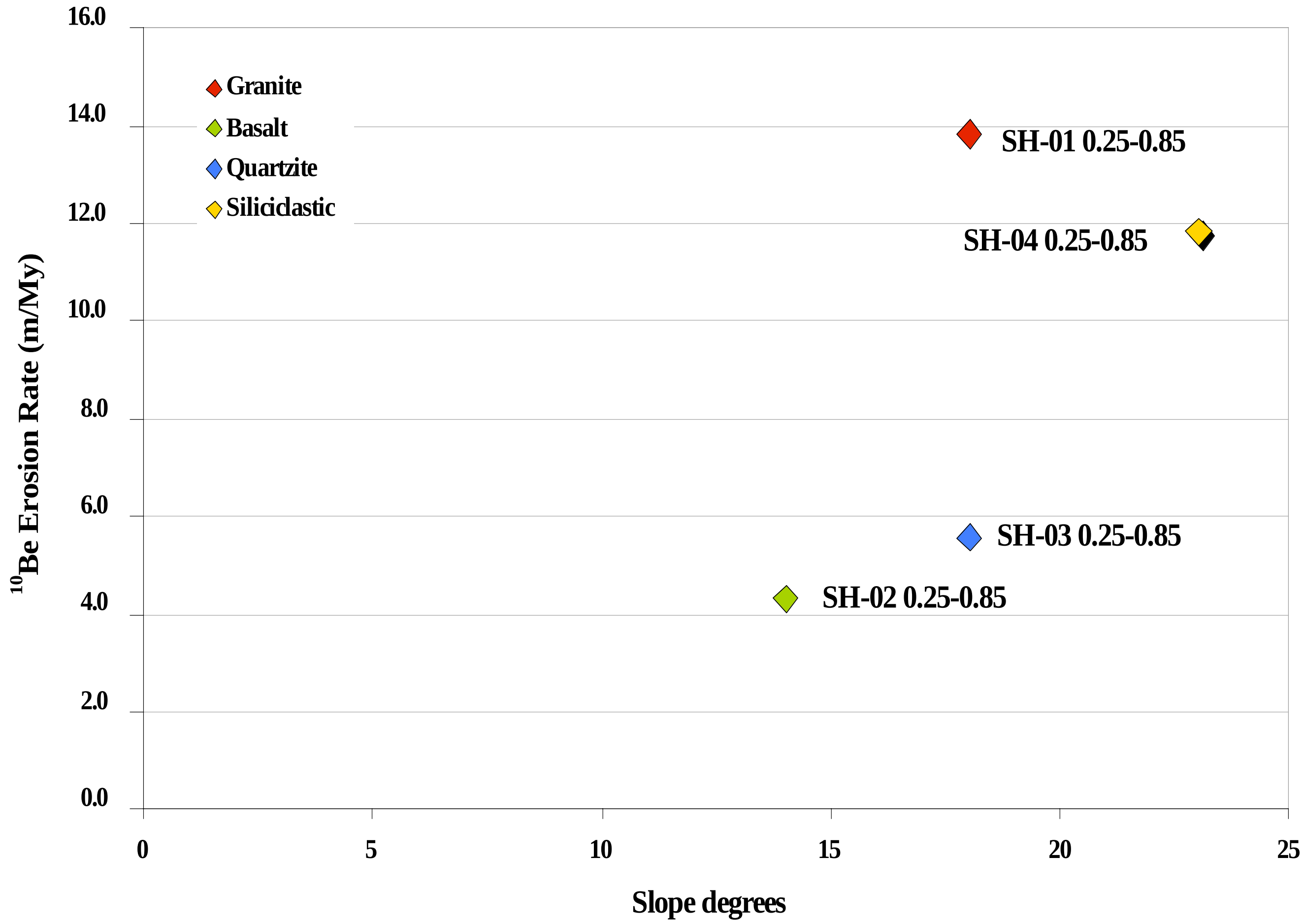


Figure 5. The erosion rates of the first four sampled lithologies are displayed against the mean average slope of each basin sampled. The erosion rate vs. slope data is plotted for the 0.25 - 0.85 mm grain size fraction.

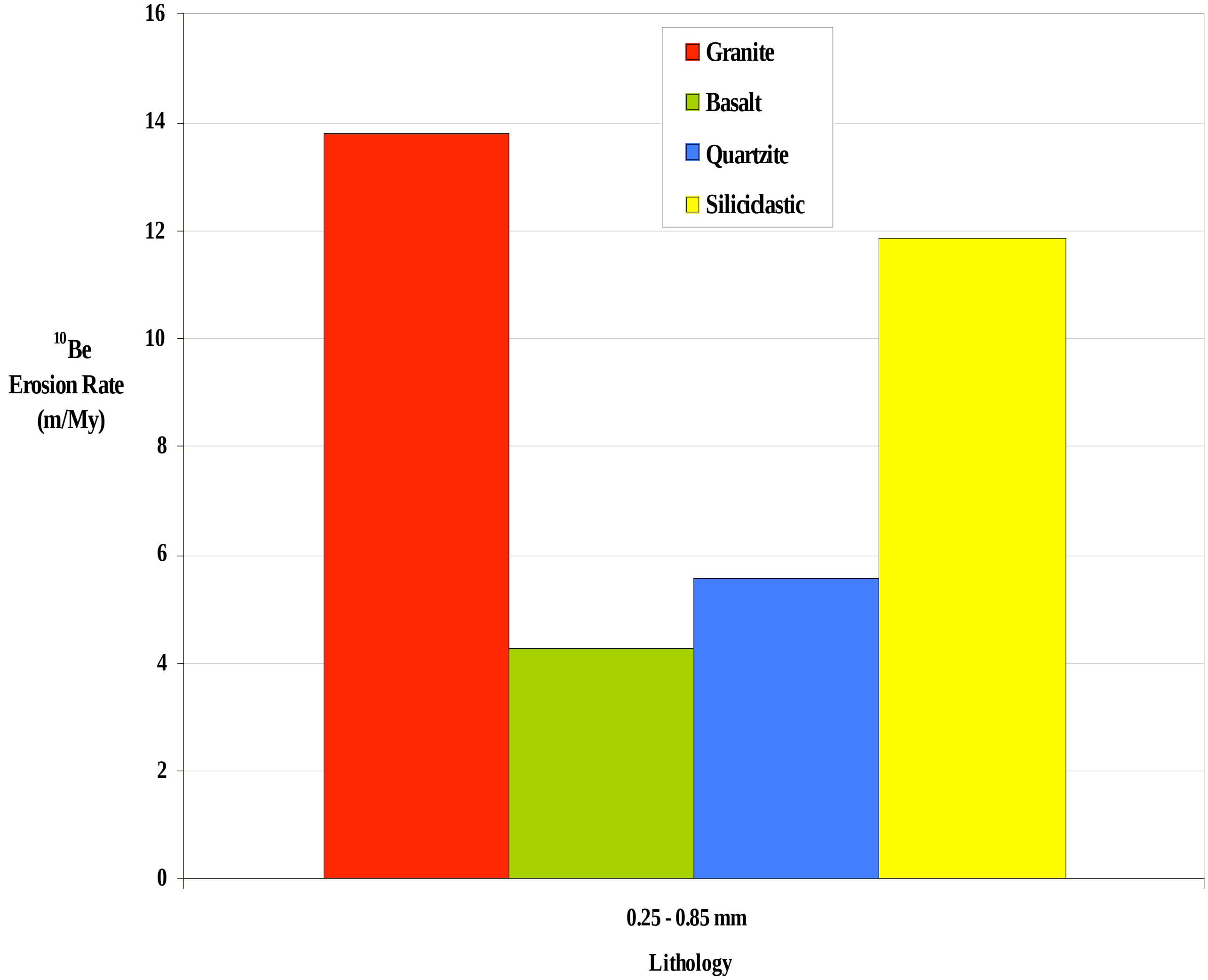


Figure 6. Erosion rates of the initial four samples in the 0.25 - 0.85 mm grain size split vs. lithology.

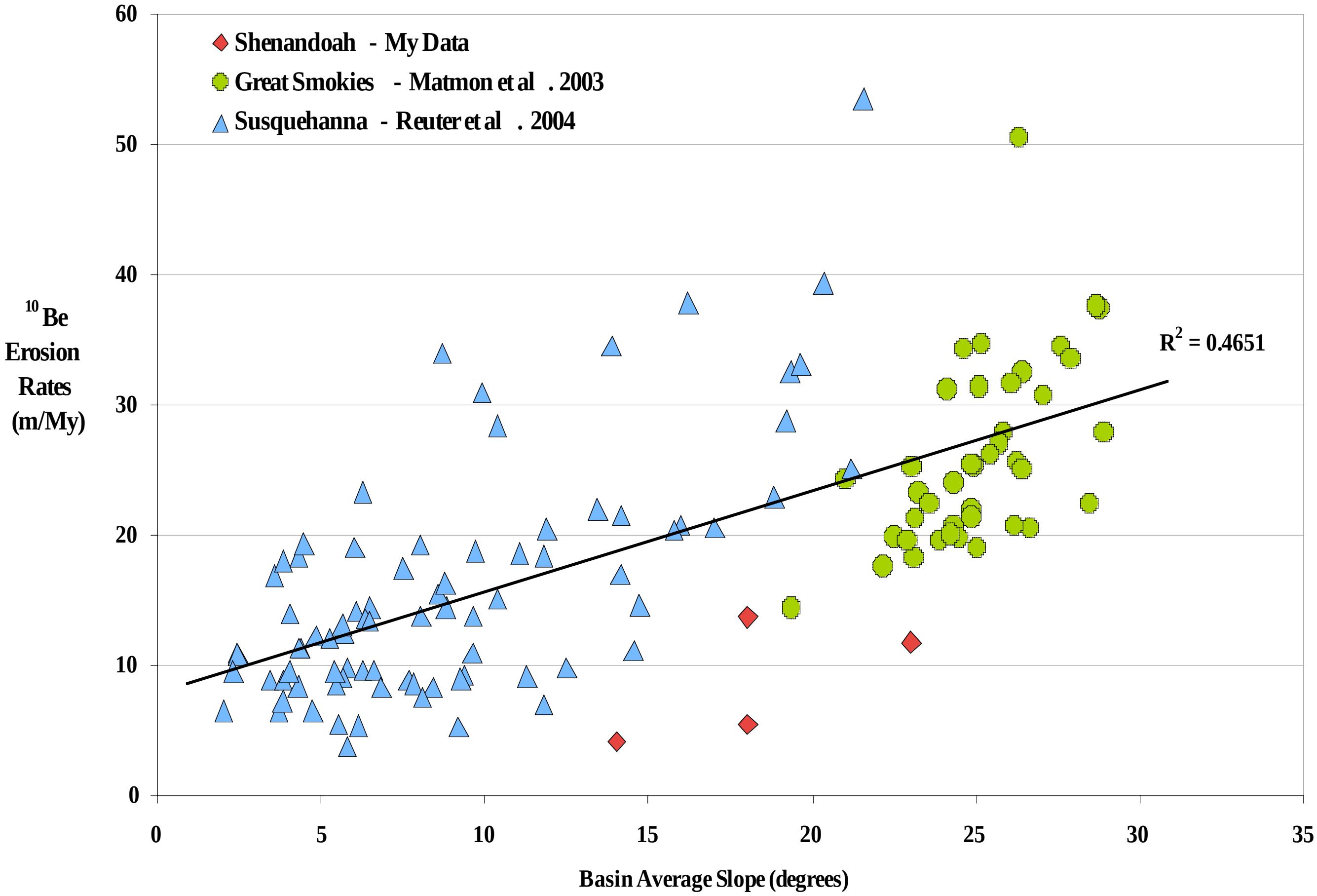


Figure 7. ^{10}Be Erosion Rates in the Appalachians. The data shown are the erosion rates vs. average basin slope from the Susquehanna River Basin (Reuter at al. 2004); the Great Smokey Mountain National Park (Matmon et al. 2003) and my initial data from the Shenandoah National Park.

Table 1. ^{10}Be Concentrations and Erosion Rates of Grain Size Splits

Lithology	Slope °	Mean elevation (m)	Basin Area (km^2)	^{10}Be Concentrations (atoms/g)	10Be model e (m My-1)
Granite					
SH01 .25-.85	18	631	39.6	3.59E+05	13.8
SH01 .85-2	18	631	39.6	3.49E+05	14.3
SH01 2-10	18	631	39.6	3.10E+05	16.1
SH01 >10	18	631	39.6	2.34E+05	21.4
Basalt					
SH02 .25-.85	14	549	1.0	1.03E+06	4.3
SH02 .85-2	14	549	1.0	9.06E+05	5.0
SH02 2-10	14	549	1.0	8.08E+05	5.6
SH02 >10	14	549	1.0	8.09E+05	5.6
Quartzite					
SH03 .25-.85	18	457	9.3	7.44E+05	5.6
SH03 .85-2	18	457	9.3	5.84E+05	7.2
SH03 2-10	18	457	9.3	5.06E+05	8.4
SH03 >10	18	457	9.3	6.18E+05	6.8
Siliciclastic					
SH04 .25-.85	23	610	12.7	4.06E+05	11.9
SH04 .85-2	23	610	12.7	3.75E+05	12.9
SH04 2-10	23	610	12.7	4.17E+05	11.5
SH04 >10	23	610	12.7	5.69E+05	8.4

Table 2. Sample Locations

Lithology	Sample #	Coordinates NAD 83 UTM 17		Elevation (feet)	Slope °	Basin Area km^2	Quad
		Easting	Northing				
BASALT	SH-02	730091	4282755	1200	14	1.0	Thornton Gap
	SH-05	734721	4293571	2100	11	1.5	Thornton Gap
	SH-09	732865	4286590	2300	13	6.4	Thornton Gap
	SH-16	730811	4269239	1200	15	13.9	Old Rag Mountain
	SH-19	718300	4261025	1720	17	11.7	Fletcher
	SH-23	744848	4306000	900	14	18.7	Chester Gap
	SH-24	697551	4226600	1600	21	3.6	Browns Cove
	SH-26	708069	4241014	2200	15	2.6	Swift Run
SILICICLASTIC	SH-04	693189	4230180	1400	23	12.7	Crimora
	SH-06	727619	4284094	1480	21	1.5	Luray
	SH-27	692551	4219150	1540	21	0.3	Waynesboro East
	SH-37	697182	4236207	1520	23	1.5	McGaheysville
	SH-39	694228	4232723	1680	26	3.0	Crimora
	SH-40	702060	4234803	1600	16	3.3	Browns Cove
GRANITE	SH-01	736324	4272684	800	18	39.6	Old Rag Mountain
	SH-07	725233	4273513	1560	23	10.6	Big Meadows
	SH-08	727035	4279401	1220	20	4.3	Luray
	SH-10	736495	4282213	1050	18	9.5	Thornton Gap
	SH-11	739752	4281853	740	18	24.1	Washington
	SH-12	738857	4277575	960	17	14.0	Old Rag Mountain
	SH-13	737679	4269600	720	17	4.7	Old Rag Mountain
	SH-14	737188	4267845	720	17	4.6	Old Rag Mountain
	SH-15	736216	4267136	800	18	5.8	Old Rag Mountain
	SH-21	728957	4280649	1320	22	5.6	Thornton Gap
	SH-22	724850	4276706	1080	21	4.3	Big Meadows
QUARTZITE	SH-03	704974	4248555	1080	18	9.3	McGaheysville
	SH-20	704275	4247989	1100	20	1.7	McGaheysville
	SH-29	690397	4220154	1600	16	0.7	Waynesboro East
	SH-30	693633	4227895	1960	18	0.8	Crimora
	SH-32	698743	4242670	1240	12	1.1	McGaheysville
	SH-34	691885	4227255	1600	21	0.5	Crimora
	SH-35	692083	4227608	1720	21	0.3	Crimora
	SH-36	692204	4227789	1760	23	0.2	Crimora
MULTI	SH-17	728841	4295614	600	17	20.0	Bentonville
	SH-25	697272	4224629	1600	19	25.3	Browns Cove
	SH-28	692528	4219091	1500	18	5.9	Waynesboro East
	SH-31	692472	4225882	1800	21	8.6	Crimora
	SH-33	698786	4242809	1500	12	1.2	McGaheysville
	SH-38	695213	4236654	1360	22	15.0	Grottoes

Table 3. Timeline

Spring 2006	Initial quartz processing and sample preparation Thesis proposal preparation Preparation of GIS database and selection of further sample sites Initial samples brought to Lawrence Livermore National Laboratory (LLNL) for processing
Summer 2006	Further sample collection (May - June) Quartz processing of second sample set (June – October) Analyze ^{10}Be data from initial samples Write abstract based on initial data for presentation at the Geological Society of America (GSA) Annual Fall Meeting
Fall 2006	Present poster of initial data at GSA Progress Report Further processing of second sample set
Spring 2007	Take second sample set to LLNL for AMS analysis Data analysis of AMS results (Feb/Mar)
Summer 2007	Start writing thesis
Fall 2007	Complete thesis Prepare papers for journal submissions (including invited GSA special paper- Geology and Related Studies of Shenandoah National Park and Vicinity, Virginia) Present final work at GSA annual meeting Defend Thesis

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