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

A Thesis Proposal Presented
by
Jane Duxbury
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The following members of the Thesis Committee have
read and approved this document before it was circulated
to the faculty:

____________________________ Dr. Paul Bierman (Advisor)

____________________________ Dr. John Aleong (Chair)

____________________________ Dr. Gregory Druschel

____________________________ Dr. Milan Pavich

Date Accepted: ______________________

Abstract

This research will investigate 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 years. I will 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 will also test Matmon et al.'s (2003b) observation that the concentrations of ^{10}Be vary between different grain sizes. This research builds upon the recent and ongoing studies investigating the ancient Appalachian Mountains as distinct landforms, specifically the continued topographic relief of the Blue Ridge Mountains.

As this study is being completed within a national park, I will also be able to disseminate data and information relating to the Park's natural resources such as management of sediments and the role of human impact on erosion as a part of informal science education of the general public.

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; 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 will investigate the relationship between erosion rate, lithology, slope, basin area and grain size and compare this 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, one of the most heavily visited in the east, with approximately 2 million visitors per year. The data and information generated by this study will thus provide opportunities for informal science education of the general public.

2.0 Physical Setting

The Appalachian Mountain belt stretches from Newfoundland, Canada in the northeast, south to Alabama (Rodgers, 1970). It is divided into four geologic provinces that, from east to west are, the Piedmont (foothills), the Blue Ridge, the Valley and Range, and the Appalachian Plateau. The Appalachian Mountains resulted from the deformation of Paleozoic and Precambrian basement rocks by three main orogenic events beginning in the Paleozoic Era: the Taconic, Acadian and Allegheny orogenies (Rodgers, 1970). The Taconic orogeny, which began in the Ordovician period, represents terrane collisions with North America and is noted for the thrusting and faulting that occurred mainly in the northern portion of the Appalachians (Pavlides, 1968). The Devonian period Acadian orogeny occurred as the Iapetus Ocean was closing, and the Afro-European and North American plates were colliding (Harris, 1990). This orogenic event was centered in New England and southern New York and included thrusting, folding, metamorphism and granitic intrusions. The Allegheny orogeny occurred in the southern Appalachians during the Pennsylvanian period, and folding, thrusting, metamorphism, and intrusions characterized it from Pennsylvania south to Alabama.

Shenandoah National Park (Figs. 1, 2a) is situated within the Blue Ridge Mountains between Fort Royal in the north and Rockfish Gap in the south, near Waynesboro, VA (Gathright, 1976). The park covers an area of ~780 km^2 through parts of eight counties, is approximately 110 km in length and its width varies between 5 and 10 km. The highest point of the Blue Ridge Mountains within the park is Hawksbill, which stands 1,235 m high above the low-lying Piedmont Province to the East and the Shenandoah Valley to the west (Kiver et al., 1999). The Potomac River crosses the Blue Ridge to the north at Harpers Ferry, and the James and Roanoke Rivers cross to the south. There are also two wind gaps, Thornton and Powell, which mark the path of ancient stream courses (Kiver et al., 1999). Mountaintops and slopes are heavily vegetated and soil covered, and the mean annual rainfall is 100 to 150 cm per year.

The Blue Ridge Mountains in Virginia are the northward plunging, western limb of an anticlinorium, which was formed as the result of complex folding events (Morgan, 2004). The core of the anticline is composed of igneous, metamorphic, and sedimentary rocks. The end of the Paleozoic Era completed the main faulting and folding connected with the Appalachians. Major thrusting was a feature of the Alleghenian orogeny in the late Paleozoic, when the crystalline rocks of the Blue Ridge were thrust westward over younger sedimentary rocks, creating a linear feature, an overturned anticline. The broad regional area of the Blue Ridge experienced uplift and arching, which supplied sediment to the Mesozoic basins, and the Blue Ridge may have been eroded to near sea level during this period (Morgan, 2004).

There are four principal rock types within the park: Quartzites, granites, siliciclastics and metabasalt. These rock types are represented by a variety of units of different ages: Precambrian - Old Rag Granite, the Pedlar Formation (granodiorite), Swift Run Formation (quartzites, conglomerates and siliceous slates), the Catoctin Formation (flood basalt); Cambrian – the Chilhowee Group composed of the Weverton Formation (conglomerate, sandstone and phyllite), the Hampton (Harpers) Formation (phyllite) and the Erwin (Antietam) Formation (quartizite) (Gathright, 1976). These are all overlain by lower Cambrian Tomstown Dolomite (Morgan, 2004).

3.0 Techniques for Estimating Erosion Rates

Several techniques, including cosmogenic nuclides, thermochronology and sediment yields, allow understanding of landscape change through a quantitative assessment of erosional rates.

3.1 Cosmogenic Nuclides

Analysis of rock and sediment to determine the concentration of cosmogenic nuclides has become an important tool for understanding landscape evolution since the 1980's via the utilization of high-sensitivity noble gas (Craig and Poreda, 1986; Kurz, 1986) and accelerator mass spectrometers (AMS) (Elmore and Phillips, 1987). AMS allows measurement of rare radio isotopes, such as those produced by the interaction of rock and soil and cosmic rays, which build up predictably over time and can be utilized for exposure dating (Craig and Poreda, 1986; Kurz, 1986; Elmore and Phillips, 1987; Bierman, 1994). Cosmogenic isotopes situated in near-surface rock such as ^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al and ^{36}Cl, have been used to ascertain sediment generation (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996), transport (Nichols et al., 2002, 2003, 2005) and deposition rates (Clapp, 2001, 2002; Nichols, 2002, 2005), and when these isotopes are integrated with interpretive models the resulting information can be used to determine the rate at which the landscape has changed over timescales of 10^3 to 10^6 years (Bierman and Nichols, 2004).

Of specific utility for this study is the cosmogenic isotope ^{10}Be because it is the longest-lived of the radioactive isotopes mentioned above and is easily measured in quartz (Bierman et al., 2002). It is also a mineral which is widely distributed on Earth's surface and can relatively easily be separated from other minerals because of its low reactivity with various acids (Kohl and Nishiizumi, 1992). ^{10}Be is produced in situ as a result of spallation, the interaction of cosmic rays with target nuclei that are split by incoming, high-energy, fast cosmic ray neutrons

(Bierman, 1994; Lal, 1998). Lal and Peters (1967) first suggested that ^{10}Be could be a functional label for sediment transport processes and erosion because of its physical and chemical properties. Nuclide concentrations in rock are dependent and on latitude and altitude (Nishiizumi et al., 1989). In simple terms, quartz grains in basins that are eroding slowly have a high concentration of ^{10}Be because they have been exposed to cosmic-ray bombardment longer than quartz grains in fast eroding basins.

Several assumptions underlie the translation of measured isotopic abundances into erosion rates via conceptual and mathematical models (Bierman, 1994). These assumptions include: steady state erosion (assuming erosion is constant and continuous, e.g. rate of uplift and erosion remain unchanged over time) and no-inheritance (boulders and sediments processed have no prior cosmogenic dosing). The interpretive method assumes that the isotopic concentration of all sediment being generated and transported out of a basin is constant over time.

3.2 Thermochronology

Thermochronology allows the measurement of the rates at which deeply buried rocks approach the surface as exhumation proceeds (Reiners, 2006). Noble gas and fission-track thermochronometric systems have a range of closure temperatures, which make them sensitive to exhumation through a range of crustal depths (1 -10 km) (Reiners, 2006). Knowing the geothermal gradient and the closure temperature sets a beginning point from which to calculate erosion/unroofing rates. An erosion rate can be determined because both depth of unroofing and time since passing the closure isotherm are known. Three thermochronological methods currently in use include ^{40}Ar/^{39}Ar, (U-Th)/He, and fission-track (FT) dating. These techniques are based on thermally controlled retention of nuclear decay products such as isotopes or radiation damage and are normally integrated over a time scale of 10^5 – 10^7 years (Reiners, 2002).

The $^{40}Ar/^{39}Ar$ ages are determined by gas source mass spectrometry, and are based on the decay of ^{40}K to radiogenic ^{40}Ar (McDougall and Harrison, 1988). (U-Th)/He dating is based on the accumulation of ^{4}He by the α decay of Uranium and Thorium (Reiners, 2002). Apatite, titanite and zircon are common minerals used in the (U-Th)/He dating technique. Fission-tracks occur as the spontaneous fission of ^{238}U atoms cause highly charged nuclei to create zones of damage in a crystal (Reiners, 2002). The age of a mineral or the time the mineral crossed the closure isotherm at some depth below Earth's surface can be determined by the quantity of uranium it contains and the number of tracks created because of the predictable increase in the number of tracks in a mineral over time (Naeser, 2005).

3.3 Sediment Yields

Measurement of sediment yields is a technique that can be used to estimate the erosion of the landscape over modern time-scales by using geomorphic tools such as sediment traps and stream flow monitoring measuring stations (Gellis et al., 2004). These direct measures of sediment flux are only usually applicable or available over years to decades timescale (Kirchner et al., 2001). Conversion of these yields to erosion rates assumes steady state behavior, the assumption that the mass load transported by streams matches what erodes from slopes and also dissolves in the long term (Trimble, 1977; Kirchner et al., 2001).

4.0 The use of ^{10}Be to monitor erosion rates

^{10}Be has been used as a method for studying erosion rates over the $10^3 – 10^6$ timescale (Ahnert, 1970; Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Both Matmon et al. (2003b) and Reuter et al. (2004) used ^{10}Be erosion rates to understand the evolution of the Appalachian Mountains. In the Great Smoky Mountains, Matmon found that erosion rates (25-30 m/My) were controlled by diffusive slope processes and subsurface bedrock erosion. Matmon's results support Hack's *dynamic equilibrium* model in two ways: 1. Erosion rates were similar across different lithologies, and 2. Over varying timescales erosion rates were similar, perhaps due to the equilibrium between isostatic uplift and erosion. Reuter (2005) completed similar work in the Susquehanna River Basin, where erosion rates varied from 4 to 54 m/My. The results of this work infer a dynamic Appalachian Mountains where steep slopes are eroding faster than gentle ones and valleys are lowering faster than ridges (Reuter, 2005). Reuter's work does not strictly support Hack's view of dynamic equilibrium.

5.0 Grain Size

Grain size analysis of different sediment grain sizes is important because erosion rates are directly calculated from the concentration of ^{10}Be in sediment. If nuclide concentration consistently differs between grain sizes, then we need to examine the active geomorphic processes that determine how the sediments are dosed by cosmic rays as they are being transported downslope and downstream. Matmon et al.'s (2003b) grain size analysis indicates that cosmogenic nuclide concentrations vary systematically with grain size: smaller grains have higher ^{10}Be concentrations than larger ones. He inferred from these data that different grain sizes have different histories; specifically that any clasts that began their journey from high slope locations disintegrate into constituent sand grains before reaching streams. Larger clasts can only survive short transport distances and thus are from lower slope locations, and therefore larger clasts must have less cosmic ray dosing (the dosing being less at low elevation). Similar research regarding cosmogenic dosing across varying clast sizes can be found in the work of Brown in Puerto Rico and Clapp in arid environments (Brown et al., 1995; Clapp et al., 1997, 1998, 2001, 2002). Clapp found no ^{10}Be concentration dependence on grain size. Brown attributed the grain size relationship he found to deep excavation of large clasts by landslides.

6.0 Significance and Specific Goals for Investigation

Understanding erosion and sediment production and the processes controlling landscape change is fundamental to geomorphology. In pursuit of this quest, the Appalachian Mountains have been intensively studied to understand the geomorphic processes relating to the evolutional history following the cessation of mountain building (Miller and Duddy, 1989; Pazzaglia and Brandon, 1996; Naeser, 2001, 2005; Matmon et al., 2003a, 2003b; Reuter et al., 2003, 2004; Morgan, 2004). It is the advent of new techniques, such as the use of the cosmogenic isotope ^{10}Be, that allow for the quantitative measurement of erosion rates over intermediate timescales and the testing of existing hypotheses that makes further investigation of the erosional history of the Appalachians important and stimulating. Following in the footsteps of Matmon et al. (2003b) and Reuter et al. (2004), this work will investigate the erosional history of a part of the Appalachians that is confined within the boundaries of the Shenandoah National Park. In developing some understanding of the erosional history of this part of the Appalachians, I hope to find consistencies in erosional rates with the work of Matmon and Reuter and provide further understanding of the Appalachian Mountains from the Susquehanna River Basin in the north to the Great Smoky Mountains in the South.

The primary goals of my study are:

- To consider how rapidly basins of different lithologies of Blue Ridge in Shenandoah National Park are eroding.
- To explore the relationships between lithology, slope, and basin area.
- To compare the relationships between ^{10}Be based erosion rates, slope, grain size, and lithology with those reported by Matmon et al. (2003a, 2003b) and Reuter (2005).

7.0 Work Plan

In the fall of 2005, I collected four samples, one from each lithology (basalt, quartzite, siliciclastics and granite), and split each of these samples into four grain sizes (0.25 – 0.85 mm, 0.85 – 2 mm, 2 – 10 mm, and >10 mm). I have begun processing these samples in the lab, as outlined below in the lab work section (7.3). I am awaiting the results from the AMS at Lawrence Livermore Laboratory.

7.1 GIS Analysis of the Shenandoah Park Landscape

I will use ArcGIS to delineate drainage basins within which I will sample. This will entail using GIS layers including: DEM’s (Digital Elevation Models) of the park along with bedrock geology and hillshade that will provide an overall picture of the physiography and principal bedrock formations found within the park. I intend to use GIS to generate a list of basins that details criteria such as basin size, location, lithology, mean slope, and elevation range. Once the basins are delineated, I will be 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.

7.2 Sample Collection

I will collect 30 – 40 samples from active river or stream channels within or near to the boundaries of the park (Figs. 1, 2b). The amount of sediment I will collect is based on the results of samples collected in the field in the fall of 2005. In general, for all the quartz-rich lithologies (Pedlar Formation, Swift Run Formation, Weverton Formation, Hampton (Harpers) Formation and the Erwin (Antietam) Formation), ~ 0.5 - 1 kg of sample should be sufficient to carry out the lab processes to isolate ^{10}Be. The quartz yields for basalt based on last fall’s samples indicate that I will need to collect perhaps four times more sample (to capture enough quartz from the thin detrital beds, quartz veins, and clasts within the basalt unit). All samples will be wet sieved in the field to the 0.25 – 0.85 mm size fraction, which is a suitable size for processing in the lab. I will also collect approximately 10 bedrock samples of less than 1 kg. The location of the bedrock samples will be determined from topographic maps of the park and will encompass the same lithologies as those sampled in the drainage basins.

7.3 Lab Work

Quartz will be 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.

7.4 Data Analysis and Testing Theory

Statistical Analysis

Once I get results from Livermore Laboratory, the concentration of ^{10}Be will be modelled into an erosion rate using the interpretive equation of Lal (1991). I will perform statistical analysis on the data. Erosion rates will be analysed with respect to lithology, slope, and grain size. I will complete a one-way ANOVA analysis for the four lithologies in order to test for significant differences in erosion rates between lithologies. I will then contrast the four erosion rates of the lithologies to see if there is any correlation between them (Fig. 3a), which will enable me to test Hack's theory of *dynamic equilibrium* as outlined above. If Hack's theory is correct, erosion rate will be independent of lithology. I will also perform a one-way ANOVA test on the concentration of ^{10}Be across four grain-sizes: 0.25 – 0.85mm, 0.85 – 2mm, 2 – 10mm, >10mm, and between the four lithologies to see if there is any correlation between grain size and ^{10}Be concentrations (Fig. 3b). This will enable me to examine the relationship between grain size and ^{10}Be concentration as per Matmon et al. (2003b). I will also 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.

Testing Theory

As both Matmon et al. (2003b) and Reuter (2004) have done, I intend to test Hack's model (1960) of *dynamic equilibrium* by investigating the correlation between erosion rates, slope and lithology. In Hack's model, the landscape can be envisioned as an open system where energy enters and leaves the system, balancing and maintaining equilibrium on a time independent basis. I can test this hypothesis by considering whether erosion rates are dependent on lithology. Hack's *dynamic equilibrium* suggests that erosion rates should be independent of lithology: less resistant lithologies will have shallow slopes and more resistant lithologies will have steeper slopes. According to Hack, forms and processes exhibit a steady state of balance or behavior within a landscape. For example, steady state behavior would be achieved in the Blue Ridge Mountains within the Park if the sediments in rivers were removed from the system at the same rate that the mountain slopes were eroding and replenishing the river sediments. This hypothesis is testable by comparing erosion rates over differing timescales: sediment yields vs. ^{10}Be vs. thermochronology, as Matmon (2003b) did in his study of the Great Smoky Mountains.

8.0 The Significance of the Results

I will analyze my data in the context of erosion rates measured by other researchers in the Appalachians including Matmon et al. (2003b) and Reuter et al. (2004) who utilize ^{10}Be, the fission-track research of Naeser et al. (2005), and the U/He technique employed by Spotila et al. (2004). Utilizing the results of other research will provide me with a framework within which I can interpret my own results. Previous work will also give the framework within which to explore Hack's model of *dynamic equilibrium* and steady state behavior and to determine an erosional history of the central part of the Appalachian Mountains found within the Park boundaries. Correlation of my results with those of other studies outlined will add to a body of knowledge that is unveiling the evolutional history of the Appalachians since the cessation of orogenic events from the Susquehanna in the north to the Great Smoky Mountains in the south. This study will also provide information to the Park that will facilitate their management of the Park's natural resources and provide educational information for the Park's visitors.

6.8 Time Line

Fall 2005	Initial sample collection in the vicinity of the Shenandoah National Park Initial quartz processing
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 – August) 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
Summer 2007	Start writing thesis
Fall 2007	Complete thesis Prepare papers for journal submissions (including invited GSA special paper) Present final work at GSA annual meeting Defend Thesis

Figure 2a. The Blue Ridge Mountains viewed from Shanandoah National Park

Figure 2b. Sampling location in the Park

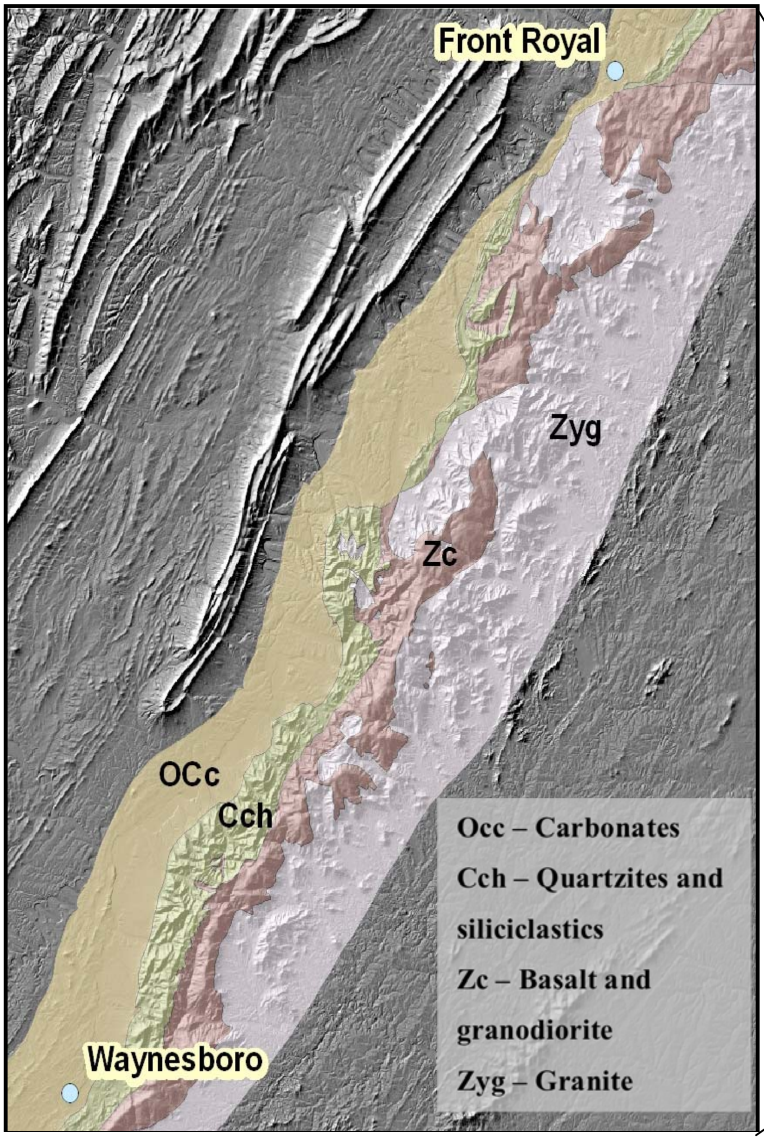

Figure 1. Location of the Shenandoah National Park in Virginia

Lithology

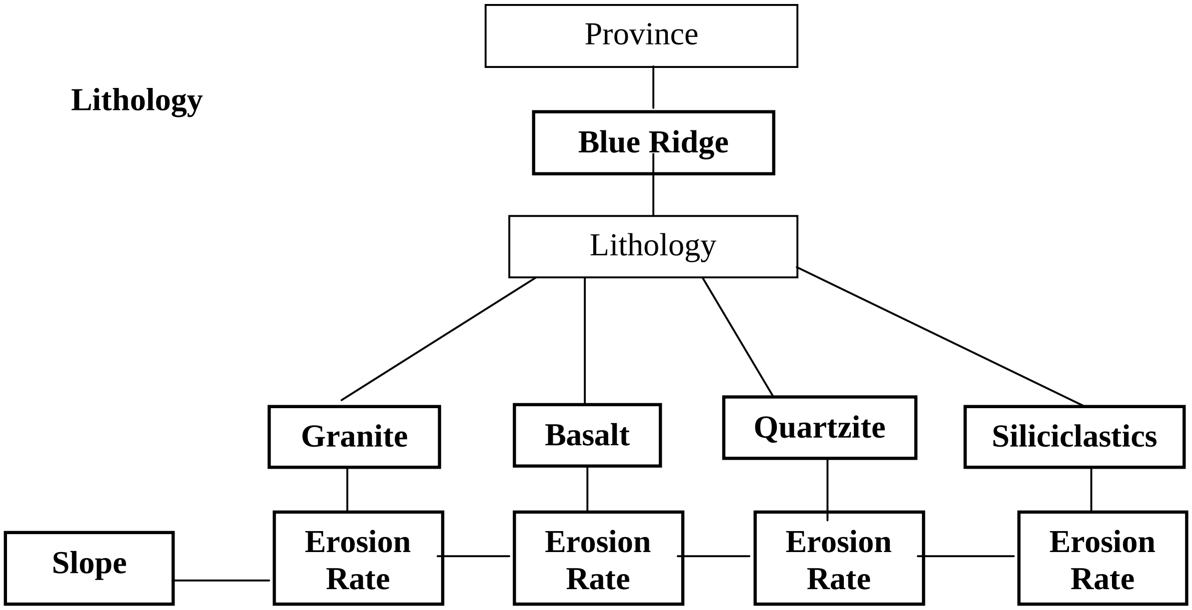

Figure 3a. Data analysis of the samples will take the form of a one-way ANOVA test, which will compare erosion rates across lithologies and slopes, and test for any correlations.

Grain-size Analysis – ^{10}Be Concentrations

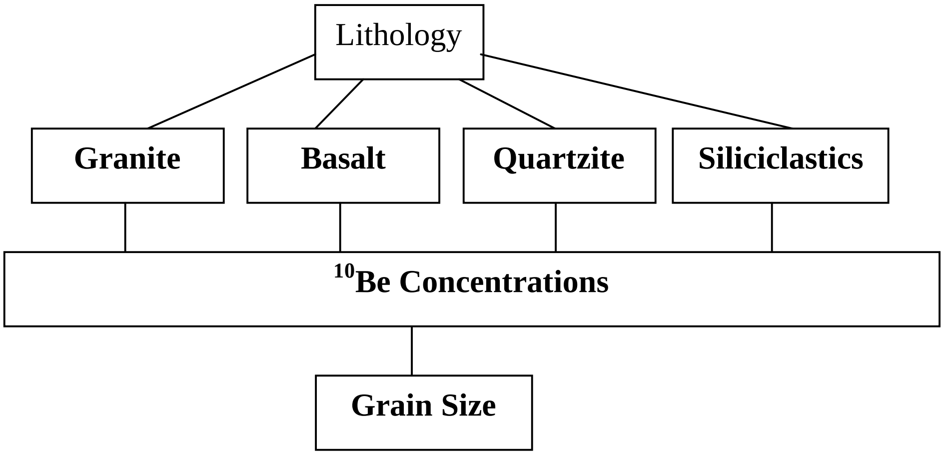

Figure 3b. A one-way ANOVA test will be completed on the concentration of ^{10}Be across four grain-sizes: 0.25 – 0.85mm, 0.85 – 2mm, 2 – 10mm, >10mm, and across the four lithologies, to see if there is any correlation between grain size and ^{10}Be concentrations within the same grain-size fraction.

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