USING ^{10}BE TO INVESTIGATE THE LONG-TERM BEHAVIOR OF THE BLUE RIDGE ESCARPMENT

A Thesis Proposal Presented

by

Colleen L. Sullivan

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

The following members of the Thesis Committee have read and approved this document before it was circulated to the faculty:

___________________________________ Advisor
Paul Bierman, PhD.

___________________________________ Chair
Donna Rizzo, PhD.

____
Keith Klepeis, PhD.

____
Milan Pavich, PhD.

Date Accepted:_________________________________

ABSTRACT

In this study, I will investigate the erosional history of the rugged Blue Ridge escarpment in the southern Appalachian Mountains on a time scale of 10^3 to 10^5 years. By measuring the quantity of ^{10}Be in sediment and exposed bedrock within stream basins draining the escarpment and its adjacent provinces, I will be able to infer erosion rates. Using these data, I will evaluate the spatial variability of escarpment erosion and thus may be able to test Hack's (1960) model of *Dynamic Equilibrium* and Davis' (1889) model of the *Geographic Cycle*. I will test whether ^{10}Be concentration in sediment is a function of grain size in order to investigate sediment generation processes within stream basins. This research will build upon previous investigations that have attempted to explain the persistence of the Blue Ridge escarpment, and more generally, the southern Appalachians as an ancient mountain belt. My results will be evaluated in the context of great escarpments throughout the world in an effort to better understand the tempo of great escarpment erosion and possible migration over time.

1.0 INTRODUCTION

Great escarpments, with their dramatic rise in elevation over short distances, adorn many of the world's passive margins (Cockburn et al., 2000; Gilchrist and Summerfield, 1990; Matmon et al., 2002; Ollier, 1984; Tucker and Slingerland, 1994). The Blue Ridge escarpment, the great escarpment of North America's eastern passive margin, is a unique feature characterized by very rugged, steep slopes; it forms a distinct boundary between the less rugged surfaces of the low-elevation Piedmont and higher-elevation Blue Ridge physiographic provinces (Figure 1) (Dietrich, 1959). The escarpment is located within the southern Appalachian Mountains of Virginia and North Carolina, and forms the drainage divide between the Gulf of Mexico and the Atlantic Ocean (Dietrich, 1959; Spotila et al., 2004). This unique feature is located within a single lithology of schist and mica-rich gneiss and thus cannot be attributed to differences in bedrock erodability (Spotila et al., 2004). Although the escarpment has been the subject of past studies (Dietrich, 1957; Hack, 1982; Ollier, 1984; Pazzaglia and Gardner, 1994; Spotila et al., 2004), there is no general agreement concerning its origin and its erosional history, development, and persistence remain poorly understood (Dietrich, 1957; Spotila et al., 2004).

1.1 ESCARPMENT EVOLUTION

Most researchers agree that passive margin escarpments are the result of rifting. Some favor the evolution of great escarpments from slow, irregular inland erosional retreat of the primary rift shoulder and drainage divide (Ollier, 1984; Spotila et al., 2004), with morphology maintained by erosion and consequent isostatic adjustment (Spotila et al., 2004). Others favor a model of rapid and significant erosion immediately following rifting, and subsequent stability of the resulting passive margin (Matmon et al., 2002). Previous investigators have sought to understand the evolution of the Blue Ridge escarpment over time in the context of other great escarpments (Bank, 2002; Dietrich, 1957, 1959; Hack, 1982; Ollier, 1984; Pazzaglia and Gardner, 1994; Spotila et al., 2004). Most recently, Spotila et al. (2004) used Apatite/He and fission-track analyses along transects across the Blue Ridge escarpment to infer 10 to 100 My patterns of exhumation. Their results revealed a noisy younging trend towards the coast and suggest that erosion has remained active on the passive margin of North America for some time (Spotila et al., 2004).

1.2 Dating Methods

Thermochronologic dating methods such as those applied by Spotila et al. (2004) generally address exhumation rates on a large time scale (10^6-10^8 years) (Naeser et al., 2005; Spotila et al., 2004). In this study, cosmogenic ^{10}Be dating techniques will be applied to samples of river and stream sediment as well as bedrock to evaluate the exposure history of the Blue Ridge escarpment on a shorter time scale (10^3-10^5 years) (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). Both methods reveal exhumation rates recorded within the target rocks. Cosmogenic isotopes, such as ^{10}Be, are produced as high-energy cosmic rays interact with and split nuclei in near surface rock and soil (Bierman, 1994). Both ^{10}Be and ^{26}Al are useful cosmogenic isotopes for evaluating basin-scale parameters as they are produced at measurable rates in quartz, which is geologically abundant (Nishiizumi et al., 1986); both nuclides have relatively long-lived half lives (1.6×10^6 years for ^{10}Be and 710,000 years for ^{26}Al) (Lal, 1988). ^{10}Be and ^{26}Al have been simultaneously analyzed in many similar cosmogenic dating studies, all of which have determined a nearly constant $^{26}Al/^{10}Be$ ratio (Clapp et al., 2002; Clapp et al., 2001; Matmon et al., 2003). Given the consistent behavior of the two isotopes, and because ^{10}Be is generally more easily and reliably measured than ^{26}Al, it will be the only nuclide considered in this study in an effort to avoid collecting redundant data.

1.3 Using Cosmogenic isotopes to infer basin erosion

In an eroding landscape, cosmogenic nuclides accumulate within rock that becomes sediment as it approaches the surface (Lal, 1991). Since rivers transport sediments from basins, the concentration of nuclides in stream sediment samples indicates the overall balance between nuclide (^{10}Be) and sediment production rates in the basin, and can thus be interpreted as a rate of erosion. For example, slowly eroding basins have relatively high ^{10}Be activities compared with rapidly eroding basins, because quartz grains in slowly eroding basins on average spend a longer period of time near the surface, subjected to cosmic-ray dosing. This interpretation assumes that the nuclide concentration in each sample is representative of the concentration in all mass leaving the basin, that sediment transport and production occur at a nearly constant rate, and that measured sediment has no ^{10}Be inherited from a prior period of near-surface irradiation. Similarly, ^{10}Be concentrations within exposed bedrock are a function of the duration of cosmic-ray dosing and can provide bedrock-lowering rates. Sample altitude and latitude are taken into account, as such factors can influence the cosmic-ray dosing at a particular location (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996; Lal, 1991).

2.0 Study Objectives

This study will use erosion rates determined from ^{10}Be analysis of approximately 40 samples of stream sediment and outcropping bedrock collected from transects across the Blue Ridge escarpment in order to evaluate the stability of the rugged landform over time and space. By collecting quartz-bearing sediment and outcropping bedrock samples from a variety of streams draining areas on and near the Blue Ridge escarpment, I will determine ^{10}Be concentrations and infer erosion rates of the landscape. These data will answer the fundamental question of how quickly this part of the southern Appalachian landscape is changing over time and may validate one of the competing theories of rapid vs. slow escarpment retreat.

I will use the isotopic data to test the following hypotheses:

- Erosion rates vary among three distinct physiographic provinces: the steep escarpment, the Blue Ridge province (upland) and the Piedmont province (lowland).
- Erosion rates vary between exposed bedrock and sediment generated within stream basins.
- Slope controls erosion rates at the basin scale and at the escarpment scale.

Another objective of this study will be to determine if grain size influences ^{10}Be production rates in the southern Appalachians (e.g., Matmon et al., 2003). If grain size and isotopic concentration are related as expected, these data will be used to investigate the geomorphic processes that contribute to grain size dependency.

The results of this study will be compared with conclusions drawn from previous investigations of the evolution of the Blue Ridge escarpment (Davis, 1889; Hack, 1960; Spotila et al., 2004). I will also compare my results with cosmogenic studies that have taken place in nearby regions of the Appalachian Mountains (Matmon et al., 2003; Reuter, 2005) in order to determine how the Blue Ridge escarpment fits within the broader context of the modern-day behavior of the southern Appalachians. Finally, I will compare my results with findings from similar studies that have focused on other great escarpments of the world in order to quantify the processes that sustain such dramatic geomorphic features (Matmon et al., 2002; Ollier, 1984; Seidl et al., 1996; Summerfield et al., 1997).

3.0 Study Site

3.1 Geological Setting

The Appalachian Mountains formed during a series of Paleozoic tectonic events beginning with the Permian Alleghenian orogeny that created a mountain range of great relief and ruggedness that may have been similar to the modern Andes (Pazzaglia and Gardner, 1994; Slingerland and Furlong, 1989). Erosion during the Permian and Early Triassic likely eradicated most of the sharp topography, followed by continental rifting in the Mesozoic associated with the opening of the Atlantic Ocean, since which time denudation has prevailed (Pazzaglia and Brandon, 1996).

Amazingly, nearly 300 My after the mountain building events ceased, the Appalachian mountains still exhibit remarkable ruggedness, leading to questions about the rate and distribution of erosional processes acting on them. Hack (1960) proposed a model of *Dynamic Equilibrium* suggesting that most of the present landscape of the Appalachian region is dynamic and that most features are the result of a balance of forces involving uplift, erosion, and rock resistance (Brown et al., 1995; Hack, 1960, 1979, 1982; Matmon et al., 2003). Conversely, Davis (1889) suggested the *Geographic Cycle* as the process that has shaped the region, in which landscape relief evolves solely based on the sum of weathering and transport processes (Davis, 1889). These two classic and different qualitative models of Appalachian morphology will be tested to determine whether escarpment erosion is uniform or spatially varied.

The Blue Ridge escarpment in Virginia and North Carolina is a particularly rugged section of the southern Appalachians, extending southward from the Roanoke River (VA) and ending near Rosman, NC (Hack, 1982). In this area, the Blue Ridge highlands exhibit low relief such that the escarpment is a striking boundary between the highlands and the equally low-relief Piedmont (Figure 1) (Spotila et al., 2004). Unlike most other major topographical features in the Appalachians, the Blue Ridge escarpment and its surroundings are located entirely within the Alligator Back Formation, consisting of micaceous schist and gneiss, and therefore the escarpment morphology cannot be attributed to bedrock erodability (Hack, 1979).

The escarpment is over 450 km long and can be over 500 m high with hillslope angles that locally reach 20-30° (Spotila et al., 2004). The width and height of the escarpment vary to some degree according to regional geology and drainage system configuration (Hack, 1982). The escarpment forms the drainage divide between the Gulf of Mexico and the Atlantic Ocean. The Blue Ridge province exhibits relatively flat topography with most of its streams flowing to the west of the divide, although there are two notable exceptions; the Dan River and the Linville River, that originate on the upland but drain to the east via deeply incised channels cut through the escarpment (Hack, 1982). These two rivers exemplify stream capture processes occurring on the Piedmont, suggesting a westward migration of the escarpment (Hack, 1982). The streams of the similarly low-relief Piedmont province flow to the east toward the Atlantic Ocean, traveling approximately one fifth of the distance of the Gulf of Mexico-draining streams (Figure 2) (Dietrich, 1957).

3.2 Regional Climate

The capacity for erosion and sediment transport of a fluvial system is affected by numerous external factors that are likely driven by climate and climate variability (Ward et al., 2005). Thus, the regional climate largely influences local erosional processes and has likely been an important factor in shaping the present-day landscape of the Blue Ridge escarpment. The region has a humid temperate climate and a major portion of its abundant precipitation (1,020-2,000 mm/yr) takes place during the warmest periods, occurring during a few rather severe storm events (Dietrich, 1959; McNab and Avers, 1996). Numerous alternating frosts and thaws occur each year making frost action an important erosional agent, although most erosion is likely caused by mass wasting and the action of running water (Dietrich, 1959). The study area has not been glaciated (Barron, 1989). The escarpment is well drained by numerous streams and rivers and the quartz-rich gneissic bedrock underlying the Blue Ridge escarpment makes it an ideal setting for ^{10}Be analysis.

4.0 Previous Work

4.1 Blue Ridge Escarpment Studies

While the origin of the Blue Ridge escarpment remains poorly understood, many other continental margins exhibit similar features, although none are quite as old as the Blue Ridge escarpment. Such features exist on nearly all continents, along active and recently rifted margins as well as along older margins (Matmon et al., 2002; Spotila et al., 2004). It is generally agreed that all escarpments are erosionally formed, although there are many hypotheses about how they evolve (Spotila et al., 2004). Accordingly, several theories have been proposed for the origin of the Blue Ridge escarpment.

Hayes and Campbell (1894) suggested monoclinal flexure as a driving factor for the formation of the Blue Ridge escarpment. They suggested that as asymmetrical uplift took place on the upland, stream erosion on the Piedmont accelerated and moved headward creating the scarp (Dietrich, 1959; Hack, 1982).

Davis (1903) suggested that the escarpment developed as a result of the position of the regional drainage divide (Hack, 1982; Spotila et al., 2004). He argued that streams flowing to the Atlantic had an advantage over streams flowing to the Gulf of Mexico because they had a shorter distance to travel (Hack, 1982). This hypothesis has been disputed. Spotila et al. (2003) and Hack (1982) note that western rivers descend to the low continental interior over a similar distance before flowing to the Gulf of Mexico. Building on Davis' model, Dietrich (1957) proposed that the escarpment was formed by erosion accompanying westward migration of the asymmetric drainage divide (Bank, 2002; Dietrich, 1957). Hack (1973) additionally proposed that the persistence of the asymmetric divide is due to resistant sandstones and quartzites on the western margin of the Appalachian plateau (Bank, 2002; Spotila et al., 2004).

White (1950) introduced the hypothesis that the scarp was produced by local, normal-sense reactivation of a fault within the Brevard zone in the Mesozoic (Dietrich, 1957; Hack, 1982; Spotila et al., 2004). His theory was based on diffuse shear planes and aligned bedrock schistosity (Spotila et al., 2004), but evidence for this tectonic rejuvenation has been criticized (Dietrich, 1957). The Brevard zone is a narrow strike-slip fault zone, emerging northeast of Montgomery, AL, continuing on a remarkably straight course northeastward, ending near Mount Airy, NC (Reed and Bryant, 1964). The Brevard zone, however, only coincides with the escarpment for 50 to 60 km, deviating from the escarpment both to the northeast, where it is farther east in the Piedmont, and to the southwest, where it is within the Blue Ridge Mountains (Figure 3) (Hack, 1982; Roper and Justus, 1973).

Rift-flank uplift is a concept commonly applied to great escarpments, suggesting that when uplift occurs next to a rift axis creating an escarpment and asymmetric drainage divide, topography is maintained as the divide migrates away from the rift margin (Ollier, 1984; Spotila et al., 2004).

However this hypothesis has only been briefly considered for the Blue Ridge escarpment (Ollier, 1984).

Pazzaglia and Gardner (1994) proposed flexural isostacy was responsible for creating the Blue Ridge escarpment. They suggested that as the Appalachian Mountains eroded, sediment was carried to the coast and deposited offshore, causing local subsidence of the middle Atlantic margin and flexural rebound inland of the area of subsidence. They have suggested a positive feedback situation in which erosion drives isostatic uplift which in turn causes more erosion, and thus supports the theory of westward migration of the escarpment (Bank, 2002; Pazzaglia and Gardner, 1994; Spotila et al., 2004).

4.2 ^{10}Be Erosion Rate Studies in the Appalachians

Cosmogenic nuclide concentrations in sediments reflect basin-wide average cosmic-ray exposure history (Bierman et al., 2001; Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). Matmon et al. (2003) calculated spatially homogeneous erosion rates of 25-30 m My^{-1} throughout the Great Smoky Mountains in the Southern Appalachians using measured concentrations of cosmogenic ^{10}Be and ^{26}Al in quartz separated from alluvial sediment (Matmon et al., 2003). Reuter et al. (2005) measured ^{10}Be in fluvial sediment samples from the Susquehanna River of the Appalachian Highlands to evaluate the effects of glaciation as well as land use impacts on erosion rates. Erosion rates of 4-54 m My^{-1} were inferred from non-glaciated basins while it was determined that formerly glaciated basins could not be interpreted as they did not conform to the assumptions of steady erosion and constant exposure (Reuter, 2005). The proximity of these study areas to the Blue Ridge escarpment provides an ideal setting for comparing erosion rates within the broader context of the non-glaciated Appalachians.

5.0 Work Completed to Date & Methods

5.1 Sampling

I traveled to the Blue Ridge escarpment along the Virginia-North Carolina border in December 2005 to see the field site, assess basin accessibility in each physiographic province, and collect preliminary samples. I collected river and stream sediment samples (mixed grain sizes) from eight basins, oriented approximately along a transect normal to the escarpment (Figure 3). A variety of basins were sampled in order to gain a preliminary understanding of the variability of ^{10}Be concentration as a function of basin size, slope, and landscape position (Table 1). This particular location of the escarpment was chosen because of its generally centralized position along the length of the landform, the relatively flat lying topography of the upland and the Piedmont provinces, and the escarpment's location distinctly west of the Brevard fault zone.

5.2 Grain Size Investigation

The effects of grain size on ^{10}Be production rates will be investigated in response to recent debate (Belmont et al., 2005; Brown et al., 1995; Matmon et al., 2003) and based on the findings of Matmon et al. (2003), where smaller grain sizes were found to exhibit higher nuclide concentrations than larger ones. In order to investigate these grain-size effects, six of the eight initial samples have been sieved into four size fractions (sand to cobbles), larger grains have been ground to a standard processing size (250-850μm), and each size fraction has been processed separately.

5.3 Sample Processing

All samples that have been collected have undergone preliminary processing at the University of Vermont using standard techniques (Bierman and Caffee, 2002). Samples have been washed and etched multiple times in HCl and HF/HNO_3 solutions in order to remove ^{10}Be produced in the atmosphere that may adhere to grain surfaces. Heavy minerals have been removed to produce nearly pure quartz samples, and all are awaiting final processing in the cosmogenic lab. All of my samples will be analyzed for ^{10}Be by accelerator mass spectrometry at the Lawrence Livermore National Laboratory.

6.0 Work Plan

6.1 Sampling Strategy

I hope to gain further insight into the erosional behavior of the Blue Ridge escarpment by collecting sediment and some bedrock samples from streams that drain the escarpment and its adjacent provinces, measuring ^{10}Be content, and establishing model erosion rates for each sample. In order to maximize the efficiency of my field time, ensure a diverse sampling group, and manage my sampling locations, I have begun to create a GIS database that will allow me to select stream basins from which to collect sediment samples based on stream basin parameters. Using a GIS-based sampling strategy has been shown to provide a more diverse sample set and thus a wider range of erosion rates than similar studies in which sampling strategies were developed by different means (Reuter, 2005). Basins of varying size, slope and physiographic province will be selected from the database prior to sampling and a detailed sampling route will be established. Because it is likely that some proposed sampling locations will prove to be inaccessible while in the field, alternative basins meeting similar criteria will be identified as well. Once samples have been collected and analyzed, the GIS database will also allow me to analyze spatially my data and evaluate visually the erosional behavior of the escarpment.

I plan to evaluate ^{10}Be data oriented along four transects normal to the escarpment, involving all physiographic provinces, and along three transects running parallel to the escarpment, confined within each province (Figure 3). Such spatial orientations will be considered in the GIS-derived sampling plan. One escarpment-normal transect is planned south of the previously sampled transect, where the escarpment deviates east of the Brevard zone near Rosman, NC (Davis, 1993; Hatcher, 1993), and another is planned for the region where the escarpment and the Brevard zone coincide. I also intend to collect samples farther to the north in Virginia, in the region investigated by Spotila et al. (2003). By investigating the escarpment in this manner I hope to address theories tectonically linking the Brevard zone and the Blue Ridge escarpment, and to investigate the previously discussed hypotheses of slow and rapid westward migration of the escarpment. I will also consider the models of Davis and Hack with respect to the Blue Ridge escarpment and the overall morphology of the southern Appalachians.

Ultimately I plan on sampling an additional 20 to 40 stream basins that represent a diverse combination of basin sizes, slopes, and landscape positions. The number of basins to be sampled will depend on the results of the preliminary grain size analyses. If it is found that grain size has no effect on nuclide production rates, a greater variety of basins can be sampled with available funds. However if differences in ^{10}Be result from the test samples, grain size analyses may need to be performed on some future samples, requiring the processing of four samples per basin, and thus fewer basins can be investigated. I also plan to consider erosional discrepancies between exposed bedrock and sediment in each of the physiographic provinces. This approach will be applied to a limited number of samples (approximately 6) spanning all provinces within two transects. Bedrock and sediment samples will be collected from the same area in each of the provinces and ^{10}Be results will be compared. Such results may have implications for migration patterns of the escarpment based on local sediment coverage.

6.2 DATA ANALYSIS

Erosion rates for each sample will be estimated by applying the methods of Lal (1991) and Bierman and Steig (1996). In Lal's model, the measured concentration of ^{10}Be is a function of the site-specific neutron production rate, the erosion rate, the density of sampled material, the nuclide decay constant, and the attenuation depth of neutrons. This model is based on the observed exponential decrease of nuclide production with depth, and thus allows for an interpretation of mass loss rates when considering surface samples. The method described by Bierman and Steig interprets basin-integrated nuclide production rates as a function of basin-specific nuclide and sediment production rates (Bierman and Steig, 1996; Brown, 1991; Granger et al., 1996). The assumptions underlying this model includes sampling of well-mixed sediment, steady state erosion, and no inherited cosmic-ray dosing (Bierman and Steig, 1996). For both models, standard corrections will be applied to account for basin latitude and altitude (Brown et al., 1995; Lal, 1991).

Results will be analyzed as two distinct populations: (1) erosion rates confined within individual escarpment-normal transects, and (2) erosion rates extrapolated to the escarpment scale, based on the escarpment-parallel transects. Sampling site distance from the escarpment will be evaluated, especially with regard to the relative position of the Brevard fault zone. I will use Arc-

GIS-based analyses to test the significance of erosion rates within both populations as a function of basin size, slope, and sample media (sediment or bedrock). Additionally I will test for correlations between grain size fractions and ^{10}Be concentration within both populations. Any conclusions drawn from ^{10}Be results and inferred erosion rates will then be analyzed in the context of: (1) other erosional studies of the Blue Ridge escarpment, (2) other such studies in the southern Appalachians, and tested against the models of Hack (1960) and Davis (1889), and (3) erosional models that have been applied to other great escarpments. Findings from these data could contribute greatly to the understanding of the long-term landscape evolution of passive margins given the antiquity of the Blue Ridge escarpment when compared with other such landforms.

7.0 TIMELINE

Work Completed To Date:
December 2005: Visit field area and sample 8 initial basins (26 samples with grain size splits)
January 2006: Sample etching and mineral separation of initial 26 samples.
Wrote MS thesis proposal
Began creating GIS database

Spring 2006:
Proposal Oral Defense
Complete GIS database and prepare sampling plan for remaining samples
Visit field area over spring break to sample additional basins near transect A (Figure 3)
Get ^{10}Be data from Livermore for initial samples

Summer 2006:
Complete sample collection and begin making quartz from all samples
Analyze initial data
Write GSA national abstract based on initial data

Fall 2007:
Complete all quartz making & prep samples for ^{10}Be analysis
Write and present Progress Report
Present poster at GSA annual meeting
Begin writing thesis

Spring 2007:
^{10}Be data collection at Livermore National Laboratory
Analyze all ^{10}Be data
Continue writing thesis

Summer and Fall 2007:
Complete thesis, defend and complete edits
Submit paper(s) for publication
Present at GSA annual meeting

8.0 FIGURES & TABLES

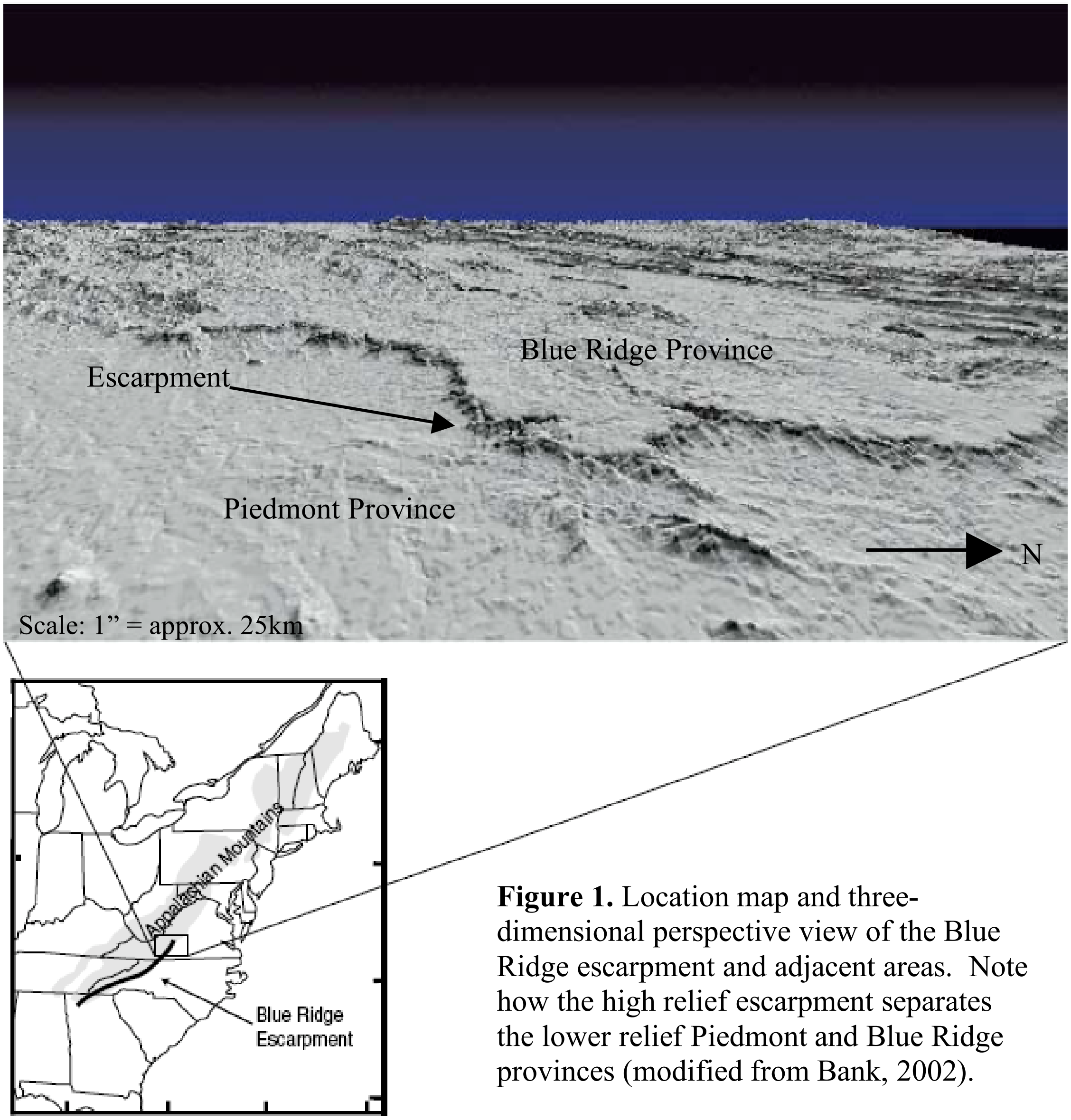

Figure 1. Location map and three-dimensional perspective view of the Blue Ridge escarpment and adjacent areas. Note how the high relief escarpment separates the lower relief Piedmont and Blue Ridge provinces (modified from Bank, 2002).

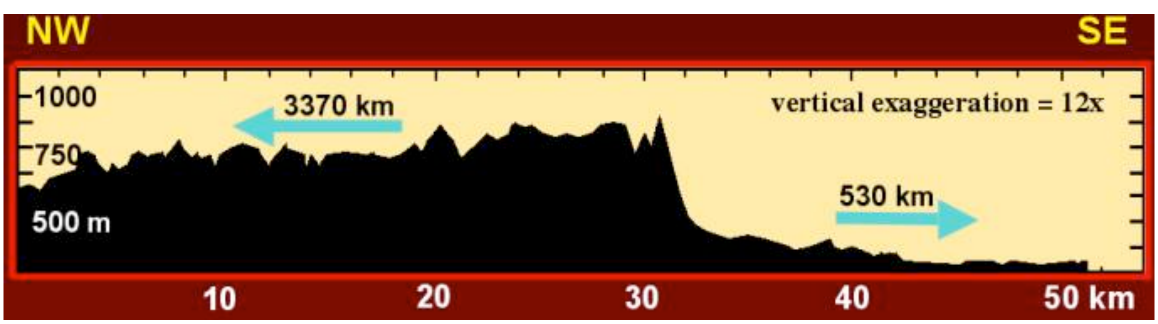

Figure 2. Elevation profile across the Blue Ridge escarpment, illustrating the distance in km rivers must travel to sea level in either direction. (Profile located in the vicinity of transect D in Figure 3) (Spotila, 2005).

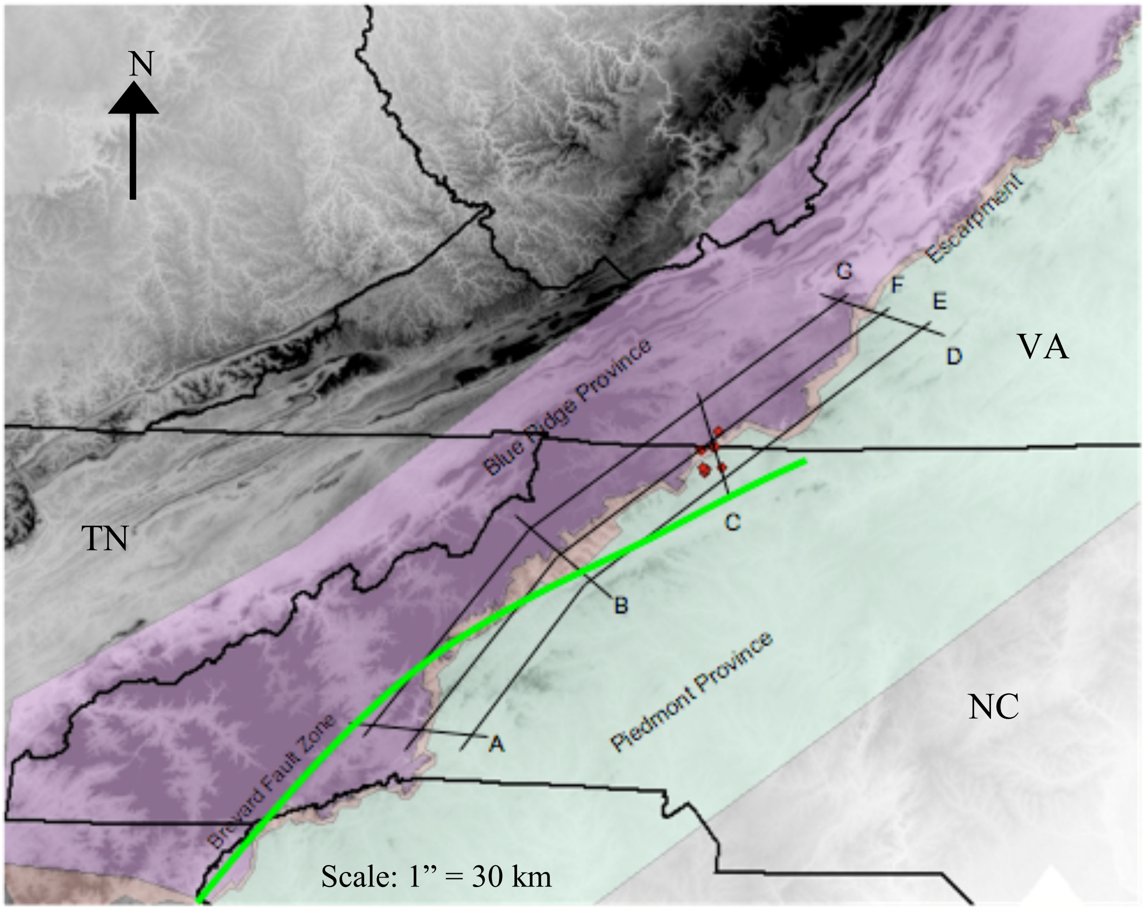

Figure 3. Proposed transects oriented normal to (A,B,C,D) and parallel to (E,F,G) the escarpment. Sample collection sites along transect C are identified as red dots. Physiographic provinces are also shown, designated by the following colors: Blue Ridge: Purple, Escarpment: Pink, Piedmont: Light Blue. Approximate location of Brevard Fault zone shown in green.

Table 1. Description of sediment samples collected in December, 2005.

Sample ID	Province	Approximate Basin Area (km^2)	Approximate Basin Profile Slope	Grain Size Analysis
CS-01	Blue Ridge	2	2.5°	Yes
CS-02	Piedmont	3	2°	Yes
CS-03	Piedmont	>30	2°	Yes
CS-04	Piedmont	1	6°	Yes
CS-05	Piedmont	5	2°	No
CS-06	Escarpment	1	9°	Yes
CS-07	Escarpment	2	12°	Yes
CS-08	Blue Ridge	3	1.5°	No

9.0 REFERENCES

Bank, G.C., 2002, Testing the origins of the Blue Ridge escarpment [Masters thesis]: Blacksburg, Virginia Tech.

Barron, E.J., 1989, Climate Variations and the Appalachians from the Late Paleozoic to the Present: Results from Model Simulations: Geomorphology, v. 2, p. 99-118.

Belmont, P., Pazzaglia, F., and Gosse, J.C., 2005, In situ terrestrial cosmogenic nuclides in alluvial sediment: Grain size matters, GSA Abstract.

Bierman, P.R., 1994, Using in situ produced cosmogenic isotopes to estimate rates of landscape evolution; a review from the geomorphic perspective: Journal of Geophysical Research, B, Solid Earth and Planets, v. 99, p. 13885-13896.

Bierman, P.R., and Caffee, M., 2002, Cosmogenic exposure and erosion history of ancient Australian bedrock landforms: Geological Society of America Bulletin, v. 114, p. 787-803.

Bierman, P.R., Clapp, E.M., Nichols, K.K., Gillespie, A.R., and Caffee, M., 2001, Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport, *in* Harmon, R.S., and Doe, W.M., eds., Landscape Erosion and Evolution Modeling: New York, Kluwer, p. 89-116.

Bierman, P.R., and Steig, E., 1996, Estimating rates of denudation and sediment transport using cosmogenic isotope abundances in sediment: Earth Surface Processes and Landforms, v. 21, p. 125-139.

Brown, E.T., Stallard, R.F., Larsen, M.C., Raisbeck, G.M., and Yiou, F., 1995, Denudation rates determined from the accumulation of in situ-produced ^{10}Be in the Luquillo Experimental Forest, Puerto Rico: Earth and Planetary Science Letters, v. 129, p. 193-202.

Brown, R.W., 1991, Backstacking apatite fission-track "stratigraphy"; a method for resolving the erosional and isostatic rebound components of tectonic uplift histories: Geology (Boulder), v. 19, p. 74-77.

Clapp, E., Bierman, P.R., and Caffee, M., 2002, Using ^{10}Be and ^{26}Al to determine sediment generation rates and identify sediment source areas in an arid region drainage basin: Geomorphology, v. 45, p. 89-104.

Clapp, E.M., Bierman, P.R., Nichols, K.K., Pavich, M., and Caffee, M., 2001, Rates of sediment supply to arroyos from upland erosion determined using in situ produced cosmogenic ^{10}Be and ^{26}Al: Quaternary Research (New York), v. 55, p. 235-245.

Cockburn, H.A.P., Brown, R.W., Summerfield, M.A., and Seidl, M.A., 2000, Quantifying passive margin denudation and landscape development using a combined fission-track thermochronology and cosmogenic isotope analysis approach: Earth and Planetary Science Letters, v. 179, p. 429-435.

Davis, T.L., 1993, Geology of the Columbus Promontory, North Carolina: Hatcher, R.D. Jr. and Davis T.L., editors, Studies of Inner Piedmont Geology with a focus on the Columbus Promontory: Carolina Geological Society Guidebook, p. 17-44.

Davis, W.M., 1889, The Rivers and Valleys of Pennsylvania: National Geographic Magazine, v. 1, p. 183-253.

Dietrich, R.V., 1957, Origin of the Blue Ridge Escarpment directly southwest of Roanoke, Virginia: Virginia Journal of Science, v. 9, p. 233-246.

—, 1959, Geology and mineral resources of Floyd County of the Blue Ridge Upland, southwestern Virginia: Bulletin of the Virginia Polytechnic Institute, v. 12.

Gilchrist, A.R., and Summerfield, M.A., 1990, Tectonic models of passive margin evolution and their implications for theories of long-term landscape development, *in* Kirkby, M.J., ed., Process Models and Theoretical Geomorphology: Wiley, Chichester, p. 55-84.

Granger, D.E., Kirchner, J.W., and Finkel, R., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments: Journal of Geology, v. 104, p. 249-257.
Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions: American Journal of Science, v. 258A, p. 80-97.
—, 1979, Rock control and tectonism, their importance in shaping the Appalachian highlands: U.S. Geological Survey professional paper, v. 1126-B, p. 17.
—, 1982, Physiographic divisions and differential uplift in the Piedmont and Blue-Ridge: U.S.Geological Survey professional paper, v. 1265, p. 49pp.
Hatcher, R.D.J., 1993, Perspective on the tectonics of the Inner Piedmont, Southern Appalachians: Hatcher, R.D. Jr. and Davis T.L., editors, Studies of Inner Piedmont Geology with a focus on the Columbus Promontory: Carolina Geological Society Guidebook, p. 1-16.
Lal, D., 1988, In situ-produced cosmogenic isotopes in terrestrial rocks: Annual Reviews of Earth and Planetary Science, v. 16, p. 355-388.
—, 1991, Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424-439.
Matmon, A., Bierman, P., and Enzel, Y., 2002, Pattern and tempo of great escarpment erosion: Geology, v. 30, p. 1135-1138.
Matmon, A.S., Bierman, P., Larsen, J., Southworth, S., Pavich, M., Finkel, R., and Caffee, M., 2003, Erosion of an ancient mountain range, the Great Smoky Mountains, North Carolina and Tennessee: American Journal of Science, v. 303, p. 817-855.
Naeser, C.W., Naeser, N.D., and Southworth, S., 2005, Tracking across the southern Appalachians: in Hatcher, R.D, Jr. and Merschat, A.J., eds., Blue Ridge Geology Geotraverse East of the Great Smoky Mountains National Park, Western North Carolina: North Carolina Geological Survey, Carolina Geological Society Annual Field Trip Guidebook, p. 67-72.
Nishiizumi, K., Lal, D., Klein, J., Middleton, R., and Arnold, J.R., 1986, Production of ^{10}Be and ^{26}Al by cosmic rays in terrestrial quartz in situ and implications for erosion rates: Nature, v. 319, p. 134-136.
Ollier, C.D., 1984, Morphotectonics of continental margins with great escarpments, *in* Morisawa, M., and Hack, J.T., ed., Tectonic Geomorphology, Volume International Series 15: Binghamton Symposia in Geomorphology: Boston, Unwin Hayman, p. 3-25.
Pazzaglia, F.J., and Brandon, M.T., 1996, Macrogeomorphic evolution of the post-Triassic Appalachian mountains determined by deconvolution of the offshore basin sedimentary record: Basin Research, v. 8.
Pazzaglia, F.J., and Gardner, T.W., 1994, Late Cenozoic flexural deformation of the middle U. S. Atlantic passive margin: Journal of Geophysical Research, B, Solid Earth and Planets, v. 99, p. 12,143-12,157.
Reed, J.C., and Bryant, B., 1964, Evidence for strike slip faulting along the Brevard zone in North Carolina: GSA Bulletin, v. 75, p. 1177-1195.
Reuter, J., 2005, Erosion rates and patterns inferred from cosmogenic 10Be in the Susquehanna River basin [Masters thesis]: Burlington, University of Vermont.
Roper, P.J., and Justus, P.S., 1973, Polytectonic evolution of the Brevard zone: American Journal of Science, v. 273A, p. 105-132.
Seidl, M.A., Weissel, J.K., and Pratson, L.F., 1996, The kinematics and pattern of escarpment retreat across the rifted continental margin of SE Australia: Basin Research, v. 8, p. 301-316.
Slingerland, R., and Furlong, K.P., 1989, Geodynamic and Geomorphic Evolution of the Permo-Triassic Appalachian Mountains: Geomorphology, v. 2, p. 23-27.

Spotila, J.A., Bank, G.C., Reiners, P.W., Naeser, C.W., Naeser, N.D., and Henika, B.S., 2004, Origin of the Blue Ridge escarpment along the passive margin of Eastern North America: Basin Research, v. 16, p. 41-63.

Summerfield, M.A., Brown, R.W., Van Der Beek, P., and Braun, J., 1997, Drainage divides, denudation, and the morphotectonic evolution of high-elevation passive margins: Geological Society of America Abstracts with Programs, v. 29, p. 476.

Tucker, G.E., and Slingerland, R.L., 1994, Erosional dynamics, flexural isostasy, and long-lived escarpments: A numerical modeling study: Journal of Geophysical Research, v. 99, p. 12,229-12,243.

Ward, D.J., Spotila, J.A., Hancock, G., and Galbraith, J.M., 2005, New constraints on the late Cenozoic incision history of the New River, Virginia: Geomorphology, v. 72, p. 54-72.

ELECTRONIC REFERENCES

McNab, W.H. and Avers, P.E., 1996, Ecological Subregions of the United States, United States Forest Service, Chapter 18. http://www.fs.fed.us/land/pubs/ecoregions/ch18.html. Accessed March, 2006.

Spotila, J.A., 2005, Origin of the Blue Ridge Escarpment, southern Appalachians. http://www.geol.vt.edu/profs/js/js-bre.html. Accessed March, 2006.