^{10}BE EROSION RATES AND LANDSCAPE EVOLUTION OF THE BLUE RIDGE ESCARPMENT, SOUTHERN APPALACHIAN MOUNTAINS

A Thesis Presented

by

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Abstract

The Blue Ridge escarpment, located within the southern Appalachian Mountains of Virginia and North Carolina, forms a distinct, steep boundary between the less rugged lower-elevation Piedmont and higher-elevation Blue Ridge physiographic provinces. The rugged topography of the Blue Ridge escarpment and the antiquity of the passive margin of eastern North America have lead to questions about the rates and patterns of erosion that have acted on the escarpment over time.

It is generally agreed that great escarpments, like the Blue Ridge escarpment, are the result of rifting. There are two primarily accepted models explaining the evolution of passive margin escarpments: evolution from slow and irregular inland erosional retreat of the primary rift shoulder and drainage divide, and evolution from rapid and significant erosion immediately following rifting with subsequent stability of the resulting passive margin. The passive margin of eastern North America is old; rifting terminated ~200 Ma. Thus, a clear understanding of the processes controlling the erosion and evolution of the Blue Ridge escarpment may provide insight about the geomorphic evolution of similar escarpments on younger passive margins.

To understand better the geomorphic evolution of the Blue Ridge escarpment and to investigate how quickly this landform and its adjacent physiographic provinces are changing, I measured cosmogenic ^{10}Be in sediment (n=47) from stream basins (n=29) and in exposed bedrock (n=3) along four transects normal to the escarpment. I used a GIS database to select basins with a wide variety of parameters that may influence erosion rates, such as basin size, average basin slope, landscape position and relative position of the Brevard fault zone.

These ^{10}Be measurements allowed me to model erosion rates on the scale of 10^4-10^5 years. Basin averaged cosmogenic erosion rates measured on and near the Blue Ridge escarpment are slow (6.5-38 m My^{-1}). These erosion rates are generally consistent with those measured elsewhere in the southern Appalachians and show a positive relationship between erosion rate and average basin slope. Thermochronologically estimated rates of erosion are similarly slow (8-29 m My^{-1}). Analysis of these basin averaged erosion rates in conjunction with the existing thermochronologic data for the escarpment, indicates that the majority of erosion that shaped the Blue Ridge escarpment occurred immediately following rifting in the Mesozoic, and since then, the escarpment's position has generally remained stable.

The cosmogenic data, when considered along with the distribution of basin slopes in each physiographic province, suggest that the escarpment is eroding more rapidly than the Blue Ridge, which is eroding more rapidly than the Piedmont. If this relationship has been maintained over time, the escarpment has been retreating and lowering but at extremely slow rates.

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Chapter 1: Introduction

This study investigates the rates of geomorphic change acting on passive margin great escarpments. Great escarpments, characterized by their linear trends, very steep slopes and dramatic elevation differences over short distances, adorn many passive margins worldwide (Bierman and Caffee, 2001; Brown et al., 2000; Fleming et al., 1999; Heimsath et al., 2006; Ollier, 1984; Persano et al., 2002; Spotila et al., 2004; Summerfield et al., 1997; Vanacker et al., 2007). These mega geomorphic features have been extensively studied in terms of the climatic, tectonic and geomorphic processes that shape them in order to better understand their evolution (Cockburn et al., 2000; Gilchrist and Summerfield, 1990; Heimsath et al., 2006; Matmon et al., 2002; Ollier, 1984; Persano et al., 2002; Seidl et al., 1996; Spotila et al., 2004; Summerfield et al., 1997; Tucker and Slingerland, 1994). The study area for this research, the Blue Ridge escarpment, is located within the ancient southern Appalachian Mountains. It is unique in its age because rifting of the eastern passive margin of North America terminated over 200 Ma (Schlische, 1993), well before the rift events that created most other similar escarpments (Bierman and Caffee, 2001; Brown et al., 2000; Fleming et al., 1999; Heimsath et al., 2006; Ollier, 1984; Persano et al., 2002; Spotila et al., 2004; Summerfield et al., 1997; Vanacker et al., 2007).

The research presented in this thesis includes 50 new cosmogenic ^{10}Be measurements made in fluvial sediment and bedrock. These ^{10}Be concentrations have been modeled as erosion rates, integrated on a 10^4-10^5 year time scale, and have been used to provide insight about the geomorphic evolution of the Blue Ridge escarpment. I evaluated the spatial distribution of erosion rates along the Blue Ridge escarpment in the context of other escarpments worldwide in an attempt to quantify better the post-rift geomorphic history of passive margin great escarpments in general.

Background

Passive margin escarpments are the result of rifting, and following the cessation of active rifting, they are shaped by erosional processes (Matmon et al., 2002; Ollier, 1984). Some favor the evolution of great escarpments from slow and irregular inland erosional retreat of the primary rift shoulder and drainage divide, with morphology maintained by erosion and consequent isostatic adjustment (Ollier, 1984; 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).

In an eroding landscape, cosmogenic nuclides such as ^{10}Be accumulate within rock that becomes sediment as it approaches the surface (Lal, 1991). Since rivers transport sediments from basins, the concentration of ^{10}Be in fluvial sediment indicates the overall balance between ^{10}Be and sediment production rates in the basin, and can therefore be interpreted as a rate of erosion. For example, slowly eroding basins have relatively high ^{10}Be concentrations when 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 (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). 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).

Cosmogenic erosion rates can be useful for addressing geologically recent rates of landscape change because of the temporal resolution they provide. Such erosion rates indicate the geomorphic behavior of a landform over the past 10^4-10^5 years and can allow for an interpretation of geologically recent passive margin escarpment development. High rates of cosmogenic erosion indicate active downwearing of an escarpment, and differential erosion rates between the upland and lowland can indicate escarpment retreat, whereas slow erosion rates imply relative escarpment stability.

Motivation and Objectives

This thesis presents measurements of ^{10}Be in fluvial sediment from 29 stream basins draining the Blue Ridge escarpment and the adjacent Blue Ridge and Piedmont provinces in western North Carolina and Virginia. A clear understanding of the rate at which the escarpment is eroding can provide insight about the post-rift development of the Blue Ridge escarpment and the passive margin of eastern North America. The specific objectives of my research are:

- to quantify basin-scale ^{10}Be erosion rates for the Blue Ridge escarpment and the surrounding Blue Ridge and Piedmont physiographic provinces;
- to test for relationships between ^{10}Be erosion rates and specific landscape characteristics including basin size, basin slope and landscape position;

- to determine whether the Blue Ridge escarpment has evolved according to a model of ongoing, significant, and parallel retreat, or whether it evolved by rapid and significant erosion immediately following rifting followed by subsequent landscape stability; and
- to determine whether grain size influences ^{10}Be concentration in fluvial sediment on and near the Blue Ridge escarpment.

Structure of this thesis

This journal-style thesis consists of one paper that has been submitted for publication with additional chapters providing supporting information. Chapter 1 is an introduction and presents an overview of how ^{10}Be erosion rates are used to study landscape change and their significance in understanding the development of passive margin escarpments. The specific goals of my research are laid out as well. Chapter 2 contains a detailed summary of the methods used to conduct this research and prepare the publication presented in Chapter 3. Chapter 3 is a journal article that has been submitted to a special issue of *Earth Surface Processes and Landforms* focused on passive margins. It presents detailed results and analyses of the erosion rates that have acted on the Blue Ridge escarpment, and presents a large-scale geomorphic model for its evolution. This paper includes a significant review of relevant literature. Chapter 4 contains my conclusions and recommendations for future work.

Chapter 2: Methods

This chapter provides a summary of the methods used for the data collection and analysis of erosion rates on and near the Blue Ridge escarpment. The selection of sample locations, field methods, laboratory techniques, and analytical techniques are described in detail.

Transect Locations

After a thorough review of available literature about the geology and geomorphology of the Blue Ridge escarpment and its surroundings, I devised a sampling strategy that allowed me to investigate patterns of erosion along the length of the Blue Ridge escarpment. Sampled basins are oriented along transects that cross cut the escarpment at four different locations. The southern transect, Transect A, is situated where the escarpment deviates east of the Brevard fault zone near Hendersonville, NC. Transect B is located to the north of Transect A in the area where the Brevard fault zone coincides with the Blue Ridge escarpment near Black Mountain, NC. Well north of Transect B, Transect C lies along the escarpment near the border of North Carolina and Virginia, where the escarpment is distinctly west of the Brevard fault zone. The northern transect, Transect D, also situated to the west of the Brevard zone, is in the same general vicinity as thermochronologically estimated rates of erosion reported by Spotila et al. (2003).

Basin Selection

The 32 stream basins that I sampled were selected as a function of basin size, slope, and physiographic province in an effort to establish a diverse set of samples and thus consider a wide range of factors that may influence erosion rates. For Transects C and A, collected in December 2005 and March 2006, respectively, basins were selected using 1:24000 USGS topographic maps to manually delineate drainage basins and calculate average basin slopes. Then, based on relative landscape position and sample location accessibility, I selected a varied suite of basins for each transect. In the spring of 2006, I created a GIS database that I used to select suitable stream basins for Transects B and D based on stream-basin parameters derived from 30 m USGS digital elevation models. 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 were selected from the database prior to sampling and I ultimately used 1:24000 USGS topographic maps to confirm the accessibility and appropriateness of each GIS-selected basin. I then established a detailed sampling route along with a series of alternative sampling locations that were sampled in cases where the originally selected basins proved to be inaccessible or appeared to have been altered by means other than natural fluvial processes.

Because the 32 basins I sampled are only a small subset of all drainage basins on and near the Blue Ridge escarpment, with the help of Luke Reusser, I evaluated how well the basins I had sampled represented the landscape as a whole. To characterize drainage basin attributes for each of the three physiographic provinces, we subdivided a swath of the landscape that included the four sampled transects, and spanned the Blue Ridge upland, the escarpment face, and the Piedmont lowland, into constituent tributary drainage basins (5.6 ± 4.3 km^2, median=4.6 km^2, n=2135) using a 30 m DEM data obtained from the USGS seamless data server and ArcGIS. During basin delineation, the average size was set to approximate that of the basins that were actually sampled, for which I was able to get data (8.1 $\pm$ 10.3 km^2, median=5.0, n=29). We assigned each sub-basin to the Blue Ridge, escarpment, or Piedmont categories based upon which province the majority of the basin fell within. Using summary statistics for each sub-basin, I constructed probability density functions showing the distribution of mean slopes for all sub-basins within a given province. In this way, I was able to accurately model the average basin slope for each physiographic province and adjust for biases in my sampled basins.

Bedrock Sample Selection

I chose the 3 outcrops that I sampled for bedrock erosion rates along the escarpment based on accessibility and occurrence. Few suitable outcrops were found while sampling during the heavily vegetated month of June of 2006. The sampled outcrops were ~1 m higher than the surrounding soil cover, and samples were collected from the upper flat surface of the outcrops. Sample thicknesses ranged from 2-5 cm. CSB-1 was collected from a ~1m^2 outcrop of moderately weathered bedrock along the steep escarpment. CSB-2 was collected from a less weathered flat planar outcrop, ~150 m^2 just over the crest of the escarpment within the Blue Ridge province. CSB-3 was collected from a moderately weathered ~1m^2 outcrop just over the crest of the escarpment within the Blue Ridge province.

Field Methods

With the help of Corey Coutu and Luke Reusser, I collected fluvial sediment from the bed of streams draining the preselected basins and recorded the location of each sampling site with GPS in addition to marking each location on a topographic map. I also took digital photographs of each sampling site so that they can be easily revisited in the future (available: http://www.uvm.edu/cosmolab/people/colleen.html). For Transects A and C, which were sampled in the winter months, I collected approximately 4 liters of sediment of mixed grain sizes. The samples were stored in labeled plastic bags and were shipped back to the University of Vermont where they were dried in an oven and then sieved using a rotational tapping device. Six samples from Transect C (n=8) were sieved into four grain size fractions: 0.25-0.85 mm, 0.85-2.0 mm, 2.0-9.0 mm, and >9 mm. Grain size fractions larger than 0.85 mm were then ground down to the 0.25-0.85 mm size fraction and each was processed individually. Samples from transect A (n=7) and the remaining two samples from transect C were sieved and only the 0.25-0.85 mm sand size fractions were processed. Transects B (n=8) and D (n=8) were sampled in June and were wet sieved in the field. Approximately 2 liters of the 0.25-0.85 mm grain size fractions were collected. The sieved samples were then stored in labeled plastic bags and were shipped back to the University of Vermont for processing.

Bedrock samples (n=3) were collected from outcrops along the top of the escarpment with a hammer and chisel. They were then returned to the University of Vermont where they were ground and sieved to the 0.25-0.85 mm size fraction for processing.

Lab Methods

All samples were processed according to standard techniques (Bierman and Caffee, 2001). Samples were initially washed, etched in 6N hydrochloric acid (8 hours at minimum), and dried, then etched in 1% hydrofluoric and nitric acid (8, 12, and 24 hours) and dried again. Heavy minerals were then removed using LST (heavy liquid), and the remaining quartz was again etched in 1% hydrofluoric and nitric acid (48 hours).

Jennifer Larsen isolated ^{10}Be according to standard techniques (Bierman and Caffee, 2001). I traveled to Lawrence Livermore National Laboratory in December 2006 to measure ^{10}Be with the Accelerator Mass Spectrometer (AMS). We ran a process blank with every seven samples and average blank $^{10}Be/^{9}Be$ ratios ($21 \pm 4 \times 10^{-15}$) were subtracted from measured ratios of samples. The blank correction typically represented only several percent of the measured isotopic ratio. An additional post accelerator stripping was done using a supplemental foil for 24 of my 50 samples in order to correct for severe B contamination resulting from roofing work on Delehanty Hall at the University of Vermont, the building in which the cosmogenic laboratory is located. Ratios of secondary standards run with every batch of 7 samples were not biased by the use of post stripping foil nor were the blank values affected; therefore my data has not been compromised by the B and the only impact on the samples is an increase in uncertainty by a percent or two due to loss of ^{10}Be counts. Three samples (CS-11, CS-12, and CS-17) were unable to be analyzed by AMS due to low currents and extreme boron contamination. These samples have been reprocessed in the mineral separation laboratory and are awaiting further processing in the cosmogenic laboratory. For this reason, the journal article presented in Chapter 3 only references the 29 basins for which I had data at the time of submission.

Calculation and analysis of erosion rates

I normalized my isotopic results according to standards prepared by K. Nishiizumi. ^{10}Be concentrations were corrected according to the altitude-latitude scaling function of Lal (1991) considering neutrons only. Basin-scale erosion rates were calculated using methods presented in Bierman and Steig (1996) and bedrock erosion rates were calculated according to methods presented in Lal (1988). I generated model erosion rates using a normalized high latitude, sea level ^{10}Be production rate of 5.2 atoms g^{-1} yr^{-1}. I used logistical regression models, multiple regression models, and a series of one-way analysis of variance tests in order to check for relationships between the isotopic data (erosion rates and ^{10}Be concentration) and basin-specific characteristics such as average basin slope, area and landscape position, all to a 95% confidence level.

Using the actual relationship between mean basin slope and erosion rate from the ^{10}Be analysis of my sampled basins, I predicted rates of erosion for each of the potentially sampled 2,135 basins that make up the landscape as a whole. I then calculated model erosion rates for the escarpment, the Blue Ridge, and the Piedmont physiographic provinces based upon the distribution of mean basin slopes for each province that we found from the landscape characterization GIS analysis.

Chapter 3: Paper submitted to special issue of *Earth Surface Processes and Landforms*

Erosion and landscape evolution of the Blue Ridge escarpment, southern Appalachian Mountains

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Abstract

The Blue Ridge escarpment, located within the southern Appalachian Mountains of Virginia and North Carolina, forms a distinct, steep boundary between the less rugged lower-elevation Piedmont and higher-elevation Blue Ridge physiographic provinces. The rugged topography of the Blue Ridge escarpment and the antiquity of the passive margin of eastern North America have lead some to speculate that the escarpment is an inherited feature of rifting that is still actively retreating. To understand better the geomorphic evolution of the Blue Ridge escarpment and to investigate how quickly this landform and its adjacent provinces are changing, we measured cosmogenic ^{10}Be in sediment (n=47) from stream basins (n=29) and in exposed bedrock (n=3) along four transects normal to the escarpment, allowing us to model erosion rates on the scale of 10^4-10^5 years. Analysis of these basin averaged erosion rates (6.5 - 38 m My^{-1}) in conjunction with existing thermochronologic data, are most consistent with rapid and early erosion post rifting followed by slow downwearing and retreat over the last 100 My. During at least the Cenozoic, the escarpment's position has generally remained stable. Cosmogenic erosion rates measured on and near the Blue Ridge escarpment are consistent with those measured elsewhere in the southern Appalachians and show a positive relationship between erosion rate and average basin slope, but show no such relationship with basin size or relative position of the Brevard fault zone, a fundamental feature of the region. The cosmogenic data, when considered along with the distribution of average basin slopes in each physiographic province, suggest that the escarpment is eroding more rapidly than the Blue Ridge, which is eroding more rapidly than the Piedmont. If this

relationship has been maintained over time, the escarpment has been retreating and lowering but at extremely slow rates.

Introduction

Great escarpments of passive margins have been extensively studied in terms of the climatic, tectonic and geomorphic processes that shape them (Cockburn et al., 2000; Gilchrist and Summerfield, 1990; Heimsath et al., 2006; Matmon et al., 2002; Ollier, 1984; Persano et al., 2002; Seidl et al., 1996; Spotila et al., 2004; Summerfield et al., 1997; Tucker and Slingerland, 1994). The Blue Ridge escarpment, located inland of the passive margin of eastern North America (Figure 1), is a unique feature of the southern Appalachian Mountains characterized by its linear trend, its steep slopes (~20°-30°) and a dramatic elevation change over short distances. It is sub-parallel to the Atlantic margin and is a distinct boundary between the less rugged lower-elevation Piedmont and higher-elevation Blue Ridge physiographic provinces. The escarpment forms an asymmetric drainage divide wherein streams flowing to the Gulf of Mexico have to travel five times the distance of those flowing to the Atlantic Ocean (Figure 1; Dietrich, 1959; Spotila et al., 2004). The escarpment is generally composed of micaceous schist and gneiss, although locally it is underlain by granitic rocks and quartz-rich metagraywackes. The escarpment's morphology cannot be attributed to differences in the bedrock's resistance to erosion (Hack, 1982; Spotila et al., 2004).

The Blue Ridge escarpment is a prominent feature of the southern Appalachian Mountains. More than 200 My after orogenic events ceased, the Appalachians in general and the Blue Ridge escarpment in particular, still exhibit considerable relief (Davis, 1899;

Hack, 1960). Although the Blue Ridge escarpment has been studied in the past, its erosional history and development remain poorly understood (Battiau-Queney, 1989; Davis, 1903; Dietrich, 1957, 1959; Hack, 1982; Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 1994; Spotila et al., 2004; Tucker and Slingerland, 1994; White, 1950). The Blue Ridge escarpment is smaller, more discontinuous, and on a much older passive margin than most other rift-generated great escarpments (Heimsath et al., 2006; Seidl et al., 1996).

Passive margin escarpments are the result of rifting. Rift basin boundary faults are generally assumed to generate such escarpments. Following the cessation of active rifting these features are shaped by erosional processes (Cockburn et al., 2000; Gilchrist and Summerfield, 1990; Heimsath et al., 2006; Matmon et al., 2002; Ollier, 1984; Persano et al., 2002; Seidl et al., 1996; Spotila et al., 2004; Summerfield et al., 1997; Tucker and Slingerland, 1994). Great escarpments are found either along continental rifts representing early stages of crustal extension, or inland of passive margins representing later stages (Matmon et al., 2002). Some favor the evolution of passive margin great escarpments from slow and irregular inland erosional retreat of the primary rift shoulder and drainage divide (Figure 2; Ollier, 1984; Spotila et al., 2004). In this case, morphology is 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 (Figure 2; Matmon et al., 2002). The passive margin of North America is old. Rifting from Africa terminated ~200 Ma (Schlische, 1993), approximately 50-70 My before the formation and stabilization of many other margins, such as South Africa, Namibia, and Australia (Matmon et al., 2002).

Today these margins exhibit morphologically similar great escarpments (Bierman and Caffee, 2001; Brown et al., 2000; Fleming et al., 1999; Heimsath et al., 2006; Ollier, 1984; Persano et al., 2002; Spotila et al., 2004; Summerfield et al., 1997).

Erosion rates modeled from measured concentrations of cosmogenic nuclides such as ^{10}Be can quantify the rate of landscape change on a 10^4 to 10^5 year time scale and consequently can also quantify the tempo of contemporary passive margin escarpment retreat (Heimsath et al., 2006). Such data, in conjunction with data from geochronometers integrated over longer time frames (~10^8 years), allow for the testing of theories of long-term landscape evolution. For example, if thermochronologic and cosmogenic data indicate rates of retreat for an inland escarpment that are too slow to accommodate for the distance the escarpment has moved over the time interval since rifting began, then a model of a continuously retreating escarpment is not plausible. The erosion responsible for the inland position of the escarpment in such a case must have occurred rapidly, soon after rifting, such that a period of relative erosional stability coincides with the integration time of the thermochronologic data.

Measurements of cosmogenic ^{10}Be in fluvial sediment test the hypothesis that the Blue Ridge escarpment is actively retreating and can determine whether there are statistically different rates of denudation between the Blue Ridge highlands, the Piedmont lowlands, and the escarpment that could lead to changing relief over time. To understand better the evolution of the Blue Ridge escarpment and the southern Appalachian Mountains, we consider the hypothesis that cosmogenic model erosion rates are correlative with basin slope, basin size, and landscape position, including the relative position of the regionally important Brevard fault zone that coincides with the escarpment for a short distance.   Lastly we consider the Blue Ridge escarpment data in the context of existing cosmogenic and thermochronologic Appalachian data sets. By understanding the behavior of the Blue Ridge escarpment over time and space, we can better understand the evolution of passive margin escarpments in general.

Background

Southern Appalachian Mountains

The Appalachian Mountains formed during a series of Paleozoic collisional tectonic events culminating with the cessation of the Permian Alleghenian Orogeny. These events created a mountain range of great relief and ruggedness (Pazzaglia and Gardner, 1994; Slingerland and Furlong, 1989). Erosion during the Permian and early Triassic was followed by continental rifting and rift margin uplift in the Mesozoic associated with the opening of the Atlantic Ocean ~200 Ma. Numerous rift basins formed via normal faulting on the central Atlantic margin of North America during the initial extensional events that separated North America and Africa (Schlische, 1993). The western-most Mesozoic rift basin, the Dan River-Danville basin, is about ~35 km east of a section of the Blue Ridge escarpment (Spotila et al., 2004), and represents the closest mapped normal, boundary fault to the escarpment. After rift shoulder uplift associated with the onset of continental extension ceased, denudation and isostatic compensation have prevailed throughout the range (Judson, 1975; Pazzaglia and Brandon, 1996; Schlische, 1993; Slingerland and Furlong, 1989).

The southern Appalachian Mountains in the area near the Blue Ridge escarpment have a humid temperate climate. A major portion of the region’s abundant precipitation

(~1,100 – 1,500 mm/yr) takes place during the warmest periods, occurring during a few severe storm events (http://www.sercc.com/climateinfo/historical/historical.html; accessed January 2007; Dietrich, 1959). Numerous alternating freeze and thaw cycles occur each year making frost action a potentially important weathering agent. Most physical erosion and sediment transport are likely caused by soil creep, mass wasting, and the action of running water (Dietrich, 1959). Debris flows may affect the steepest terrain, primarily on the escarpment (Witt et al., 2007). The study area has not been glaciated (Barron, 1989; Richmond and Fullerton, 1986) although the climate may have been quite cold and periglacial processes operated during Pleistocene glacial maxima (Delcourt and Delcourt, 1984). The topography of the Appalachian Mountains is less rugged than that of active mountain belts, however the orogenic crustal root beneath the mountain chain is relatively thick (40-50 km) and more typical of much higher mountain ranges (Baldwin et al., 2003; Matmon et al., 2003). The lack of active mountain-scale relief in the Appalachians may be due to local climatic and tectonic conditions that do not support accelerated fluvial and glacial erosion that could lead to relief production caused by valley erosion rates increasing relative to summit lowering rates (Hancock and Kirwan, 2007).

The Brevard fault zone is a major regional structure. It is oriented southwest-northeast and extends for ~600 km from Alabama to Virginia (Figure 1; Roper and Justus, 1973). The Brevard zone was activated during the Taconic and Acadian orogenies, well before the rifting events that formed the Blue Ridge escarpment. In some places it is coincident with the boundary between the Blue Ridge and Piedmont provinces. In the vicinity of the Blue Ridge escarpment, the Brevard fault zone only coincides with the escarpment for 50 to 60 km. It deviates 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 (Hack, 1982; Roper and Justus, 1973).

Great escarpments

Great escarpments associated with extensional tectonics exist on nearly all continents, and are located along active and recently rifted margins as well as along older margins (Matmon et al., 2002; Spotila et al., 2004). Although it is generally agreed that all rift escarpments are formed tectonically by normal faulting and maintained by erosion, there are two alternative hypotheses about how they evolve (Spotila et al., 2004). There is the established paradigm of ongoing, significant, and parallel escarpment retreat (Ollier, 1984; Spotila et al., 2004). In contrast, there is a more recent model of rapid and significant erosion only during the earliest stages of extension followed by the development of a stable passive margin escarpment (Bierman and Caffee, 2001; Heimsath et al., 2006; Matmon et al., 2002; Seidl et al., 1996; Tucker and Slingerland, 1994; Vanacker et al., 2007). Rift escarpments evolve in one of two ways: either laterally by rift-parallel retreat where erosion is concentrated in the narrow escarpment zone or vertically by downwearing where the lowland is strongly incised by seaward flowing rivers (Vanacker et al., 2007).

The pattern and tempo of escarpment erosion is a function of the processes and energy available for the transport of material (Matmon et al., 2002). Escarpments erode more rapidly in embayments, where ground and surface water flow are concentrated, than on interfluves (Heimsath et al., 2000; Seidl et al., 1996). Thus, the form or sinuosity of the escarpment directly depends on the number and configuration of large drainage systems originating on and crossing the escarpment. Some suggest that the frequency and size of escarpment-crossing drainages are related to the structure and drainage system of the margin prior to rifting (Matmon et al., 2002).

Blue Ridge escarpment evolution

Many hypotheses have been advanced in an attempt to explain the evolution of the Blue Ridge escarpment (Davis, 1903; Dietrich, 1957; Hack, 1982; Hayes and Campbell, 1894; Ollier, 1984; Pazzaglia and Gardner, 1994; Spotila et al., 2004; White, 1950). Cosmogenic erosion rate data, in conjunction with existing thermochronologic information, can be used to test these hypotheses. Hayes and Campbell (1894) suggested that monoclinal flexure formed the Blue Ridge escarpment. 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 (Davis, 1903; Hack, 1982; Spotila et al., 2004). Davis 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. This hypothesis has been disputed by Hack (1982), who noted 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 (1975) additionally proposed that the highlands west of the escarpment have persisted due to resistant sandstones and quartzites, which set the base level for westward draining streams (Bank, 2002; Hack, 1975; 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 during 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; White, 1950). Evidence for tectonic rejuvenation has been criticized (Dietrich, 1957), as the Brevard fault zone only coincides with the escarpment for 50 to 60 km (Hack, 1982; Roper and Justus, 1973).

Rift-flank uplift followed by parallel slope retreat is a concept commonly applied to great escarpments. Uplift occurs along a rift axis, creating an escarpment and asymmetric drainage divide, and topography is maintained as the divide migrates away from the rift margin (Ollier, 1984; Spotila et al., 2004). This hypothesis has only been briefly considered for the Blue Ridge escarpment (Ollier, 1984). Pazzaglia and Gardner (1994) proposed that flexural isostasy 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 suggest a positive feedback situation in which erosion drives isostatic uplift which in turn causes more erosion, with continued westward migration of the escarpment over time (Bank, 2002; Pazzaglia and Gardner, 1994; Spotila et al., 2004).

Cosmogenic nuclides in erosion studies

In situ-produced cosmogenic nuclides such as ^{10}Be have been used to quantify bedrock erosion (Hancock and Kirwan, 2007; Lal, 1988; Nishiizumi et al., 1986), soil production (Heimsath et al., 1997) and basin-wide average rates of erosion (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). These nuclides are produced in materials at or near Earth's surface as cosmic rays interact with minerals such as quartz in rock and sediment (Lal, 1991). Similarly, ^{10}Be concentrations within exposed bedrock are a function of cosmic-ray dosing as the rock is exposed to the earth's surface and thus can be used to model bedrock-lowering rates (Bierman and Caffee, 2002).

Cosmogenic nuclides have provided erosion rate data for several passive margin escarpments worldwide (Bierman and Caffee, 2001; Cockburn et al., 1999; Fleming et al., 1999; Heimsath et al., 2006; Seidl et al., 1996; Vanacker et al., 2007). This technique has also commonly been used elsewhere in the Appalachian Mountains to evaluate erosion rates (Hancock and Kirwan, 2007; Matmon et al., 2003; Reuter et al., accepted). Cosmogenic nuclide analysis has proven to be a useful tool for understanding geologic rates of surface change and bedrock erosion because the penetration depth of cosmic rays buffers the impact of both human-induced and naturally-forced episodic erosion (Bierman and Steig, 1996; Kirchner et al., 2001; Matmon et al., 2003).

Methods

To test the variety of hypotheses related to the evolution of the escarpment and the southern Appalachians in general, we collected fluvial sediment samples from 29 basins, each located predominantly within one of two physiographic provinces: Blue Ridge and Piedmont, and along the Blue Ridge escarpment (Figure 3). For this study we have considered the escarpment as its own province, and we collected samples only from the inner Piedmont, a zone within 20 km of the escarpment. We selected basins suitable for sampling using a GIS database to determine basin size, average basin slope and landscape position, in addition to 1:24,000 USGS topographic maps. Rather than sampling randomly, we sampled locations that represented a variety of basin sizes and slopes within each physiographic province in an effort to investigate a range of factors that may influence erosion rates. The sediment samples were collected from four transects, each normal to the escarpment, separated by ~320 km in total (Figure 4). Two transects were situated at the southern end of the escarpment, one where the Brevard fault zone is completely within the Blue Ridge province and the other where it coincides with the escarpment. The remaining two transects were located along the northern end of the escarpment where the Brevard zone is completely within the Piedmont province.

We selected 3 bedrock outcrops for sampling based on accessibility and suitability. These outcrops were ~1 m higher than the surrounding soil cover, and samples were collected from the upper flat surface of the outcrops. Sample thicknesses ranged from 2-5 cm.

We collected fluvial sediment from streambeds and recorded the location of each sampling site with GPS (Figure 4, Table 1). We sieved six samples from Transect C into four grain size fractions: 0.25-0.85 mm, 0.85-2.0 mm, 2.0-9.0 mm, and >9.0 mm in order to test whether a relationship exists between sediment grain size and ^{10}Be concentration. Grain size fractions larger than 0.85 mm were ground and sieved to 0.25-0.85 mm and each sample was processed individually. For all other samples (n=23), we processed only the 0.25-0.85 mm sand-size fraction. Bedrock samples (n=3) were ground to sand-size particles for processing. We isolated quartz (13-41 g) using the method of Kohl and Nishiizumi (1992). All samples were then processed at the University of Vermont using techniques outlined in Bierman and Caffee (2001). We ran a process blank with every seven samples and average blank ^{10}Be/^{9}Be ratios ($21 \pm 4 \times 10^{-15}$) were subtracted from measured ratios of samples. The blank correction typically represented only several percent of the measured isotopic ratio.

^{10}Be was measured at the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory and results were normalized to standards prepared by K. Nishiizumi. ^{10}Be concentrations were corrected according to the altitude-latitude scaling function of Lal (1991) considering neutrons only. Basin-scale erosion rates were calculated using methods presented in Bierman and Steig (1996) and bedrock erosion rates were calculated according to methods presented in Lal (1988). We generated model erosion rates using a normalized high latitude, sea level ^{10}Be production rate of 5.2 atoms g^{-1} yr^{-1}. We used logistical regression models, multiple regression models, and a series of one-way analysis of variance tests in order to check for relationships between the isotopic data (erosion rates and ^{10}Be concentration) and basin-specific characteristics such as average basin slope, basin area and landscape position, all to a 95% confidence level.

In sampling a limited number of drainage basins across a region for erosion rate modeling with ^{10}Be, it is prudent to consider how representative the sampled basins are of the surrounding landscape as a whole. To characterize physical differences between the three physiographic provinces, we subdivided a swath of the landscape encompassing the four sampled transects, including the Blue Ridge upland, the escarpment face, and the Piedmont lowland, into constituent tributary drainage basins (5.6 ± 4.3 km^2, median=4.6 km^2, n=2135) using a 30 m DEM, obtained from the USGS seamless data server, and ArcGIS. During basin delineation, the average basin size was set to approximate that of the basins that were actually sampled (8.1 ± 10.3 km^2, median=5.0, n=29). We assigned each resultant sub-basin to the Blue Ridge, escarpment, or Piedmont based upon which province the majority of the sub-basin fell within. Because the escarpment covers only a narrow zone of the landscape, some modeled escarpment basins include headwaters that originate on the lower relief Blue Ridge province. Similarly, for some modeled Piedmont basins small portions of the lower escarpment may contribute sediment to the drainage basin. Using summary statistics for each sub-basin, we constructed probability density functions showing the distribution of mean slopes for all sub-basins within a given province.

Using the actual relationship between mean basin slope and erosion rate from our ^{10}Be analysis, we predicted rates of erosion for each of the potentially sampled 2135 sub-basins. Based upon the distribution of mean slopes across each province, and the relative area of each sub-basin, we calculated model erosion rates for the Blue Ridge, the escarpment, and the Piedmont provinces in their entirety.

Data

Fluvial samples from on and near the Blue Ridge escarpment contain significant amounts of ^{10}Be (1.2-11.1 10^5 atoms g^{-1}) implying low rates of erosion and considerable landscape stability (Table 2). Considering the 0.25-0.85 mm grain size fraction data from all transects, sediment samples from the Blue Ridge province (n=10) yield an average normalized ^{10}Be concentration of 2.94 $\pm$ 0.86 (1σ) 10^5 atoms g^{-1} and an average model erosion rate of 12.2 $\pm$ 6.3 (1σ) m My^{-1}. Those basins draining only the escarpment (n=7) yield an average normalized ^{10}Be concentration of 1.73 $\pm$ 0.65 (1σ) 10^5 atoms g^{-1} and an average model erosion rate of 20.1 $\pm$ 6.6 (1σ) m My^{-1}. Fluvial sediment samples from the Piedmont province (n=12) yield an average normalized ^{10}Be concentration of 2.64 ± 1.17 (1σ) 10^5 atoms g^{-1} and an average model erosion rate of 15.0 ± 9.0 (1σ) m My^{-1}.

Using multiple regression analysis, slope emerged as the only significant landscape parameter related to erosion. In general, basins with steeper slopes have higher erosion rates than basins with gentler slopes (Figure 5). For the entire dataset, there is a positive relationship between average basin slope and erosion rate (erosion rate (m My^{-1}) =slope (degrees) *0.912+0.78, R^2=0.41, P<0.0001). The predictive power of this relationship is weak; however, when average basin slope per province is considered with respect to average erosion rate per province, the relationship becomes much more powerful (R^2=0.99; inset of Figure 5). The slope-erosion rate relationship also holds true for basins sampled in the Blue Ridge province (R^2=0.41) and for basins in the Piedmont (R^2=0.37); however, there is no relationship between slope and erosion rate for escarpment samples, which cover only a narrow range of slopes (R^2=0.08). There is no significant relationship between erosion rate and basin area when the entire dataset is considered (R^2=0.017, P=0.49) (Figure 6). A relationship can be seen between basin elevation (corresponding to physiographic province) and erosion rate (Figure 7); however, no statistical relationship exists between physiographic province and erosion rate. In general, mid-elevation basins, those on the steep escarpment, are eroding most rapidly.

Because average basin slope and erosion rate are correlated, it is critical to know the slope distribution of drainage basins within each physiographic province in order to evaluate whether the samples we collected are representative of the subpopulations within each province. Using GIS analysis, we found the average slope of all small basins ($\sim$5.6 km^2) within the Blue Ridge province is 12.8° (n=968). All small basins within the escarpment province yield an average slope of 17.7° (n=428) and all small basins within the Piedmont province yield an average slope of 9.0° (n=738). These province-averaged slopes are different than the average slopes of the basins we sampled from each province (Blue Ridge, 12.8° vs. 12.0°; escarpment 17.7° vs. 21.7°; Piedmont 9.0° vs. 15.3°). Thus, we conclude that our samples are not representative of the province averaged populations in terms of average basin slope. Therefore, we cannot use our sample sets directly to test for erosion rate differences.

However, the dependence of erosion rate on slope allows us to model erosion rates for each physiographic province by convolving the slope/erosion relationship shown in Figure 5 with the integral of basin average slopes for each province (Figure 8). Doing such a calculation, we find that the integrated model erosion rate for the Piedmont (9.7 m My^{-1}) is lower than for the Blue Ridge (12.5 m My^{-1}). The model suggests that the escarpment as a whole is eroding more rapidly (17.1 m My^{-1}) than either the Piedmont lowland or the Blue Ridge upland.

Nuclide concentration data for the six samples in which multiple grain sizes were analyzed separately (CS-01, CS-02, CS-03, CS-04, CS-06, CS-07) show no consistent pattern of nuclide concentration and grain size (Figure 9). Only 1 of these 6 samples (CS-07) shows a monotonic decrease of ^{10}Be concentration with increasing grain size. In 4 samples (CS-01, CS-02, CS-03, CS-04) the largest grain size yields the highest ^{10}Be concentration, with no systematic pattern between smaller grain sizes. The remaining sample (CS-04) exhibits no systematic relationship among grain sizes. Integrating the results for all grain sizes of all 6 samples, no statistically significant relationship exists between ^{10}Be concentrations and grain size ($F_{3,20}$=0.246, P=0.86).

Bedrock erosion rates for samples collected from outcrops on the escarpment were highly variable and were modeled as 56.8 m My^{-1} (CSB-1, gneiss), 1.7 m My^{-1} (CSB-2, gneiss) and 17.4 m My^{-1} (CSB-3, metagraywacke and mica schist). CSB-1 was collected from a ~1m^2 outcrop of moderately weathered bedrock along the steep escarpment. CSB-2 was collected from a less weathered flat planar outcrop, ~150 m^2 just over the crest of the escarpment within the Blue Ridge province. CSB-3 was collected from a moderately weathered ~1m^2 outcrop just over the crest of the escarpment within the Blue Ridge province.

Discussion

Comparing rates of erosion

Cosmogenically determined erosion rates for basins draining the Blue Ridge escarpment indicate that it and the surrounding landscape are eroding slowly over a 10^4-10^5 year timescale (6.5-38 m My^{-1}). These basin scale rates are fully consistent with those measured cosmogenically elsewhere in the southern and central Appalachian Mountains (~2-54 m $My\text{-}^1$) including other fluvial sediment samples from the Great Smoky Mountains, Shenandoah National Park, the Susquehanna drainage basin, and the New River basin (Duxbury et al., 2006; Granger et al., 1997; Matmon et al., 2003; Reuter et al., accepted). Similar to other Appalachian studies, we find no correlation between basin size and erosion rate suggesting a lack of significant sediment storage (and thus post-hillslope cosmic-ray dosing) in the small basins we sampled (Figure 6).

To place these data from the passive margin ancient Appalachian orogen in the context of active orogen erosion, consider that Wobus et al. (2005) used cosmogenic ^{10}Be in fluvial sediment to calculate erosion rates of 180-770 m My^{-1} in the central Nepalese Himalaya and Duncan et al. (2001) measured rates several times higher in Bhutan at the eastern Himalayan syntaxis, an area of great relief, high elevations, and highly active surface and tectonic processes (Zeitler et al., 2001).

Lowering rates of exposed bedrock on the Blue Ridge escarpment are more variable (1.7-57 m My^{-1}) than drainage basin average rates (as would be expected from the lack of natural amalgamation), but are also generally consistent with those measured elsewhere in the Appalachians (4-11.5 m My^{-1} in the Georgia Piedmont, 2-9.5 m My^{-1} at Dolly Sods, West Virginia, and 5-48 m My^{-1} in the Great Smoky Mountains; Bierman et al., 1995; Hancock and Kirwan, 2007; Matmon et al., 2003).

The cosmogenic data indicating slow rates of denudation integrated over 10^4-10^5 years near the Blue Ridge escarpment are consistent with existing thermochronologic data integrating over longer time frames. Spotila et al. (2004) used apatite (U-Th)/He analysis to calculate long-term (10^8 years) model erosion rates of 8-22 m My^{-1} across the escarpment from the Blue Ridge toward the inner Piedmont. Spotila et al. (2004) also reported erosion rates calculated across the escarpment using fission track analysis of apatite in rock of 22-29 m My^{-1} integrated over a similar 10^8 time scale (Figure 10).

Interpretation of the thermochronologic data as erosion rates is subject to a variety of uncertainties. These include the inability to constrain the geothermal gradient over time and systematic uncertainties in the correction of measured gas concentrations for ejection, implementation, and diffusion (Reiners and Ehlers, 2005). Despite uncertainties in both the cosmogenic and thermochronologic methods, erosion rates modeled both cosmogenically and thermochronologically, fall within the same range. This similarity of slow model erosion rates integrated over very different timeframes is consistent with long-term stability of the landscape on and near the escarpment. Interestingly, if the slope/erosion rate relationship we measured holds farther away from the escarpment, then the lower slopes of the outer Piedmont would suggest low erosion rates there. The preferential erosion of the inner Piedmont hypothesized by Spotila et al. (2004) is consistent with the cosmogenic measurements.

Inferring sediment weathering and delivery processes

The lack of systematic correlation between grain size and ^{10}Be concentration has direct implications for actively occurring weathering and sediment delivery processes. For example, Brown et al. (1995) suggested that lower ^{10}Be concentrations in larger grain sizes could be the result of mass wasting events excavating deeply buried coarse material which had little exposure to cosmic radiation. Landslides rapidly carried these large clasts down slope and into the stream channel. The only basin where we measured a monotonic decline in ^{10}Be with increasing grain size (CS-07) drains only the steep escarpment. Of all 3 provinces, escarpment basins are the most likely ones to be affected by debris flows due to their higher relief, generally steeper and longer slopes, and the orographic forcing of precipitation as air masses, particularly during storm events, are lifted up and over the escarpment face (Witt et al., 2007).

In contrast to the Brown hypothesis, Matmon et al. (2003) suggested that the systematic difference in ^{10}Be concentrations measured in fluvial sediment samples from the Great Smoky Mountains (lower ^{10}Be concentrations in large grains) was caused by weakly cemented sandstone clasts disintegrating into sand grains during transport downslope in the soil mantle. Thus, clasts collected in streams were locally sourced at low elevations where production rates were less than basin-average rates.

Grain size specific ^{10}Be data from the Blue Ridge escarpment study area clearly indicate that clast transport processes and exposure histories are different than in the Great Smoky Mountains. Rather than large grains having less ^{10}Be than smaller grains, in four samples (CS-01, CS-02, CS-03 and CS-06), the largest grains contain the most ^{10}Be suggesting that larger clasts have longer near-surface residence times than sand. The existence of quartz veins in the micaceous schist and gneiss underlying the escarpment (and the long-term survival and presumably accumulated cosmic-ray dosing of quartz pebbles in the subaerial weathering environment) suggest that varying lithologic properties control, at least in part, the relationship between grain size and ^{10}Be concentration.

Inferring large-scale geomorphic process controls

Examining the Blue Ridge escarpment data set in the context of landscape scale descriptors such as slope, allows us to infer geomorphic processes at the basin scale. For example, basin average slope and basin average erosion rate are clearly and positively related in the data set as a whole (Figure 5, R^2=0.41, P<0.0001). A similar slope-erosion rate relationship has been found elsewhere in the southern Appalachians; steep basins throughout the mountain range are eroding more rapidly than gently-sloped basins (Matmon et al., 2003; Reuter et al., accepted). A relationship between slope and erosion is inconsistent with an Appalachian landscape that is currently in dynamic equilibrium as suggested by Hack (1960), who argued that all elements of the topography are mutually adjusted and thus eroding at the same rate. It would appear that the forces that drive erosion and sediment transport on slopes, including soil creep, landsliding, and stream incision, are more efficient on steeper slopes (Heimsath et al., 1997; Montgomery and Brandon, 2002) than gentle slopes, and therefore the topography is not completely adjusted to rock strength as suggested by Hack's dynamic equilibrium theory.

Implications for the development of passive margin escarpments over time

The steep Blue Ridge escarpment is eroding more rapidly than the adjacent but more gently-sloped uplands and lowlands, thus providing a means for retreat over time. Since base level for the escarpment is set by the Piedmont, and since we model overall Piedmont lowering at 9.7 m My^{-1} and escarpment erosion at 17.1 m My^{-1}, the difference between the vertical lowering component, as set by Piedmont erosion, and total escarpment erosion could be taken as the escarpment's lateral retreat rate. If this calculation is valid, the escarpment is retreating about 7 m My^{-1} (Figure 11).

The cosmogenic data are counter to the hypothesis that the escarpment resulted from differential erosion because the Piedmont is eroding more slowly than the Blue Ridge. The difference in modeled rates of lowering for the Piedmont (9.7 m My^{-1}) and Blue Ridge provinces (12.5 m My^{-1}) suggests that over time, relief across the escarpment should very slowly decrease (~3 m My^{-1}) if the slope distributions and the erosion/slope relationship remain similar (Figure 11). Thus, we conclude on the basis of our measurements and modeling that the Blue Ridge escarpment is both retreating and lowering, albeit at extremely slow rates.

If we extrapolate the escarpment retreat rate calculated above (~7 m My^{-1}), total escarpment retreat would be ~1.4 km since the opening of the Atlantic Ocean basin ~200

Ma. Existing geologic maps do not show any normal faults closer than the Dan River-Danville rift boundary fault, ~35 km east of the escarpment base. It remains unclear whether the Dan River-Danville border fault is the actual margin that generated the Blue Ridge escarpment because the fault covers only ~25% of the length of the escarpment (Figure 1). Because it is the closest fault associated with Mesozoic rifting, we assume the original position of the escarpment to be at or near the boundary fault of the Dan River-Danville rift basin. In such a case ~35 km of retreat would be required to move the escarpment to its present location from the boundary fault of the Dan River-Danville rift basin (Schlische, 1993; Spotila et al., 2005). Therefore, the cosmogenic erosion rate data and modeling suggest that the Blue Ridge escarpment is today eroding an order of magnitude more slowly than the mean rate of retreat that would be required to bring the landform steadily inland from the western boundary fault of the western-most Mesozoic rift basin since the opening of the Atlantic Ocean. Because the Dan River-Danville rift basin is too far away for the escarpment to have retreated at a constant rate over 200 Ma, we conclude that this escarpment, like some others (Australia, Namibia, South Africa, Sri Lanka), likely rapidly retreated early in its history and since then, has remained on average, a very stable element of the landscape.

Great escarpments bordering other passive continental margins have been the subjects of studies similar to this one, attempting to quantify the erosional processes and rates acting on such landforms (Bierman and Caffee, 2001; Brown et al., 2000; Cockburn et al., 1999; Fleming et al., 1999; Heimsath et al., 2006; Summerfield et al., 1997). In Namibia, Bierman and Caffee (2001) found ^{10}Be and ^{26}Al erosion rates modeled from sediment collected from a basin on the escarpment were several times faster (16 m My^{-1})

than those calculated for a basin on the highlands (5 m My^{-1}) or a basin on the coastal plain (8 m My^{-1}). They found no evidence of significant, ongoing escarpment retreat and concluded that the escarpment of the western margin of southern Africa is a stable and slowly eroding feature. Brown et al. (2000) suggest a phase of enhanced denudation immediately following rifting of the southern Atlantic African margin based on apatite fission track data. On the opposite margin of southern Africa, Fleming et al. (1999) reported cosmogenic ^{36}Cl erosion rates between 50-95 m My^{-1} for the Drakensberg escarpment in South Africa. These rates, when considered in the context of the apatite fission track data presented by Summerfield et al. (1997) which reveal a trend of significant erosion immediately following continental break up, suggest that the contemporary Drakensberg escarpment is also a stable landscape feature.

In Australia, Heimsath et al. (2006) reported ^{10}Be and ^{26}Al erosion rates of 3-57 m My^{-1} across the escarpment situated on the southeastern passive margin of the continent. These results support low-temperature thermochronologic data for the same region (Persano et al., 2002), which suggest that the escarpment is relatively stable after having retreated rapidly immediately following rifting (Heimsath et al., 2006). Vanacker et al. (2007) used cosmogenic nuclides in river sediments from small catchments across the Sri Lankan escarpment to investigate factors controlling the long-term relief development of passive margins. They found low average denudation rates that did not support a model of a continuously retreating escarpment.

Slow overall erosion rate data from these aged passive margin escarpments, in addition to the Blue Ridge escarpment data we have presented, refutes the paradigm of major and continuous escarpment retreat, which would warrant more rapid cosmogenic erosion rates along passive margins. Additionally, given the modest erosion rates measured so far on many great escarpments, geochronologic data also appear to disprove the hypothesis of steady, on-going escarpment evolution by prolonged and significant erosion. Great escarpments appear to be stable, slowly changing landscape features in passive margin environments.

Conclusions

The Blue Ridge escarpment is a stable feature on an ancient passive margin. It, and the bordering Blue Ridge highlands and Piedmont lowlands are eroding slowly (6.5-38 m My^{-1} for fluvial sediment and 2-57 m My^{-1} for bedrock). The cosmogenic data, when considered in conjunction with existing thermochronologic data, provide no evidence of substantial, ongoing escarpment retreat. Rather, the data suggest very slow retreat and lowering over time. Our findings on the Blue Ridge escarpment mirror those of other workers in South Africa, Namibia, Australia, and Sri Lanka. This suggests that a model of rapid initial rift shoulder retreat, followed by slow erosion, is most consistent with accumulating geochronologic data.

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Figure Captions

Figure 1 – Map of Atlantic margin of the United States showing the Blue Ridge and Piedmont physiographic provinces, location of the Blue Ridge escarpment, location of the Brevard fault zone, and location of the Dan River-Danville basin, the western-most Mesozoic rift basin. Inset cross section indicates the asymmetry of the drainage divide at the top of the Blue Ridge escarpment (cross section modified from Spotila et al., 2004).

Figure 2 – Stepwise diagram of two models of escarpment evolution. A) Demonstrates continual and ongoing escarpment retreat over time. B) Demonstrates significant escarpment retreat following rifting with subsequent erosional stability of the escarpment.

Figure 3 – Landscape photographs of each province and large scale province location map: A) Blue Ridge near sample site CS-27 showing subdued relief. B) View of escarpment near Fancy Gap, VA showing heavy vegetation and steep topography. C) Piedmont view facing east from the escarpment near Chimney Rock, NC showing subdued relief and stream network flowing toward the coast.

Figure 4 – Transect locations crosscutting the Blue Ridge escarpment on shaded relief map from 30m DEM. State boundaries are noted in gray along with the position of the Brevard Fault zone. A) Basin boundaries and sample locations for transect

A. B) Basin boundaries and sample locations for transect B. C) Basin boundaries and sample locations for transect C. D) Basin boundaries and sample locations for transect D. Escarpment location is noted for each transect basin location map.

Figure 5 – Erosion rates are positively correlated to mean basin slope for each province and for the entire sample population. Model equation and line of best fit are also displayed. Inset shows average basin erosion rate and average basin slope for each physiographic province are well and positively correlated indicating the importance of slope in influencing erosion rates where lithology is homogeneous. Uncertainties are plotted as one standard error of the mean. Number of individual basins indicated for each province below the plotted data.

Figure 6 – No relationship exists between basin area and erosion rate.

Figure 7 – Mean basin elevation generally correlates well with erosion rate and physiographic province. Error bars are calculated propagating 10% (1σ) uncertainty in production rates. Mid-elevation basins from the escarpment generally have elevated rates of erosion.

Figure 8 – Cumulative frequency plot of average basin slope for each province with sampled basins noted on curve. Blue Ridge samples are representative of the Blue Ridge population. Both escarpment and Piedmont samples are biased

toward high slope basins. Inset histograms show distribution of slopes within each province: Blue Ridge, escarpment, Piedmont.

Figure 9 – No systematic relationship exists between grain size fraction and measured ^{10}Be concentration. Errors are propagated 1σ uncertainties in analytical measurements. In four samples, the largest grain size fraction (>9.0 mm) has the greatest concentration of ^{10}Be. Only in one sample (CS-07) is there a monotonic relationship of decreasing ^{10}Be concentration with larger grain sizes.

Figure 10 – Erosion rates calculated with ^{10}Be are similar to those calculated by Spotila et al. (2004) using thermochronologic methods (U/Th-He and fission tracks) along the northern reaches of the Blue Ridge escarpment.

Figure 11 – Model of Blue Ridge escarpment retreat and lowering over time. Province averaged model erosion rates are used to calculate average retreat and lowering of escarpment.

Tables

Table 1. Sample locations and basin characteristics

Sample ID	Transect	Province[1]	Average basin slope[2] (degrees)	Basin Area (km^2)	Average Basin Elevation[2] (m)	Northing[3] (m)	Easting[3] (m)
CS-01	C	BR	9	2	860	4052473	519821
CS-02	C	P	12	3	468	4033417	513601
CS-03	C	P	13	21	430	4035645	514864
CS-04	C	P	19	1	487	4036327	512690
CS-05	C	P	13	4	467	4036490	512644
CS-06	C	E	22	0.5	593	4043783	512499
CS-07	C	E	21	1	710	4045630	517960
CS-08	C	BR	8	4	854	4045224	518682
CS-09	A	BR	11	4	678	3910553	373547
CS-10	A	BR	4	0.6	707	3913503	372700
CS-13	A	P	10	3	377	3908231	389009
CS-14	A	P	22	0.7	564	3906162	387824
CS-15	A	P	12.5	18	443	3911375	392577
CS-16	B	BR	18.5	11	867	3934029	374815
CS-18	B	BR	13	3.6	796	3942736	379547
CS-19	B	E	24	7	692	3944248	389654
CS-20	B	P	19	35	663	3942497	393242
CS-21	B	P	15	46	578	3938422	394505
CS-22	B	E	19	10.6	698	3936788	389689
CS-23	B	P	18.5	4.5	662	3931849	394142
CS-24	B	BR	21	5.3	1034	3934672	372643
CS-25	D	BR	10	5	896	4063652	550645
CS-26	D	BR	15	5	911	4069913	547919
CS-27	D	BR	10	9	945	4067355	556071
CS-28	D	E	19	6	606	4071296	562620
CS-29	D	P	21	5	596	4064685	569117
CS-30	D	P	9	4.5	418	4057358	573287
CS-31	D	E	23	5.5	671	4057818	558967
CS-32	D	E	24	10	540	4052376	549082
CSB-1	NA	E	NA	NA	NA	4052492	521645
CSB-2	NA	E	NA	NA	NA	3921775	386359
CSB-3	NA	E	NA	NA	NA	3942519	385776

[1]Provinces are designated as: BR-Blue Ridge, E-Escarpment, P-Piedmont.
[2]Average basin slope and elevation were calculated from 30m DEM for each basin based on sampling location. [3]All GPS locations provided in UTM NAD27 CONUS, zone 17.

Table 2. Cosmogenic nuclide data and erosion rates

Sample ID	Grain Size Fraction (mm)	Erosion rate[1] (m My^{-1})	Normalized ^{10}Be (10^5 atoms g^{-1})	Measured ^{10}Be concentration (10^5 atoms g^{-1})
CS-01	.25-.85	8.8 ± 1.1	3.48 ± 0.09	6.44 ± 0.17
CS-01	.85-2.0	7.9 ± 1.0	3.87 ± 0.11	7.16 ± 0.20
CS-01	2.0-9.0	8.4 ± 1.1	3.65 ± 0.10	6.75 ± 0.19
CS-01	>9.0	5.0 ± 0.7	6.03 ± 0.17	11.14 ± 0.32
CS-02	.25-.85	8.1 ± 1.1	3.79 ± 0.12	5.11 ± 0.16
CS-02	.85-2.0	8.3 ± 1.1	3.71 ± 0.10	5.00 ± 0.13
CS-02	2.0-9.0	9.0 ± 1.2	3.41 ± 0.09	4.60 ± 0.12
CS-02	>9.0	6.6 ± 0.9	4.64 ± 0.14	6.26 ± 0.19
CS-03	.25-.85	10.9 ± 1.4	2.85 ± 0.09	3.73 ± 0.12
CS-03	.85-2.0	11.0 ± 1.4	2.81 ± 0.09	3.68 ± 0.12
CS-03	2.0-9.0	12.6 ± 1.6	2.48 ± 0.08	3.24 ± 0.10
CS-03	>9.0	9.3 ± 1.2	4.36 ± 0.12	4.36 ± 0.12
CS-04	.25-.85	12.9 ± 1.7	2.41 ± 0.08	3.30 ± 0.11
CS-04	.85-2.0	12.3 ± 1.6	2.52 ± 0.08	3.44 ± 0.11
CS-04	2.0-9.0	14.2 ± 1.8	2.20 ± 0.07	3.01 ± 0.09
CS-04	>9.0	13.7 ± 1.8	2.27 ± 0.07	3.10 ± 0.09
CS-05	.25-.85	8.4 ± 1.1	3.67 ± 0.12	4.80 ± 0.15
CS-06	.25-.85	19.6 ± 2.5	1.60 ± 0.04	2.39 ± 0.06
CS-06	.85-2.0	21.3 ± 2.7	1.47 ± 0.05	2.20 ± 0.07
CS-06	2.0-9.0	20.9 ± 2.7	1.50 ± 0.05	2.25 ± 0.07
CS-06	>9.0	17.7 ± 2.3	1.77 ± 0.05	2.66 ± 0.08
CS-07	.25-.85	10.6 ± 1.4	2.92 ± 0.10	4.81 ± 0.16
CS-07	.85-2.0	14.5 ± 1.9	2.15 ± 0.07	3.55 ± 0.12
CS-07	2.0-9.0	18.0 ± 2.3	1.74 ± 0.06	2.87 ± 0.10
CS-07	>9.0	20.9 ± 2.7	1.50 ± 0.04	2.48 ± 0.07
CS-08	.25-.85	8.3 ± 1.1	3.71 ± 0.12	6.81 ± 0.21
CS-09	.25-.85	11.7 ± 1.5	2.65 ± 0.08	4.16 ± 0.12
CS-10	.25-.85	13.2 ± 1.7	2.37 ± 0.07	3.78 ± 0.11
CS-13	.25-.85	11.2 ± 1.5	2.76 ± 0.12	3.39 ± 0.14
CS-14	.25-.85	37.6 ± 4.8	0.84 ± 0.03	1.21 ± 0.04
CS-15	.25-.85	12.5 ± 1.6	2.49 ± 0.07	3.21 ± 0.09
CS-16	.25-.85	13.4 ± 1.7	2.32 ± 0.06	4.22 ± 0.12
CS-18	.25-.85	10.4 ± 1.3	2.97 ± 0.08	5.13 ± 0.14
CS-19	.25-.85	26.5 ± 3.4	1.19 ± 0.04	1.88 ± 0.06
CS-20	.25-.85	23.2 ± 3.0	1.36 ± 0.05	2.11 ± 0.08
CS-21	.25-.85	18.2 ± 2.3	1.72 ± 0.05	2.51 ± 0.07
CS-22	.25-.85	25.5 ± 3.3	1.23 ± 0.04	1.97 ± 0.07
CS-23	.25-.85	22.0 ± 3.0	1.42 ± 0.08	2.21 ± 0.13
CS-24	.25-.85	29.0 ± 3.7	1.09 ± 0.04	2.26 ± 0.07
CS-25	.25-.85	7.6 ± 1.0	4.01 ± 0.17	7.61 ± 0.32
CS-26	.25-.85	9.2 ± 1.2	3.35 ± 0.10	6.43 ± 0.19
CS-27	.25-.85	8.9 ± 1.2	3.47 ± 0.12	6.80 ± 0.24
CS-28	.25-.85	14.3 ± 1.9	2.18 ± 0.07	3.31 ± 0.11
CS-29	.25-.85	6.5 ± 0.9	4.70 ± 0.13	7.04 ± 0.20
CS-30	.25-.85	8.3 ± 1.1	3.69 ± 0.20	4.83 ± 0.26
CS-31	.25-.85	27.6 ± 3.6	1.14 ± 0.04	1.81 ± 0.06
CS-32	.25-.85	16.7 ± 2.1	1.87 ± 0.06	2.69 ± 0.08
CSB-1	NA	56.8 ± 7.8	0.56 ± 0.03	0.69 ± 0.04
CSB-2	NA	1.7 ± 0.2	16.33 ± 0.46	27.10 ± 0.77
CSB-3	NA	17.4 ± 2.3	1.80 ± 0.07	3.34 ± 0.14

[1]Assumed sea-level, high latitude production rate of 5.3 atoms g^{-1}, 1σ uncertainty. [2]Normalized ^{10}Be concentration calculated using neutron only formulation of Lal (1991).

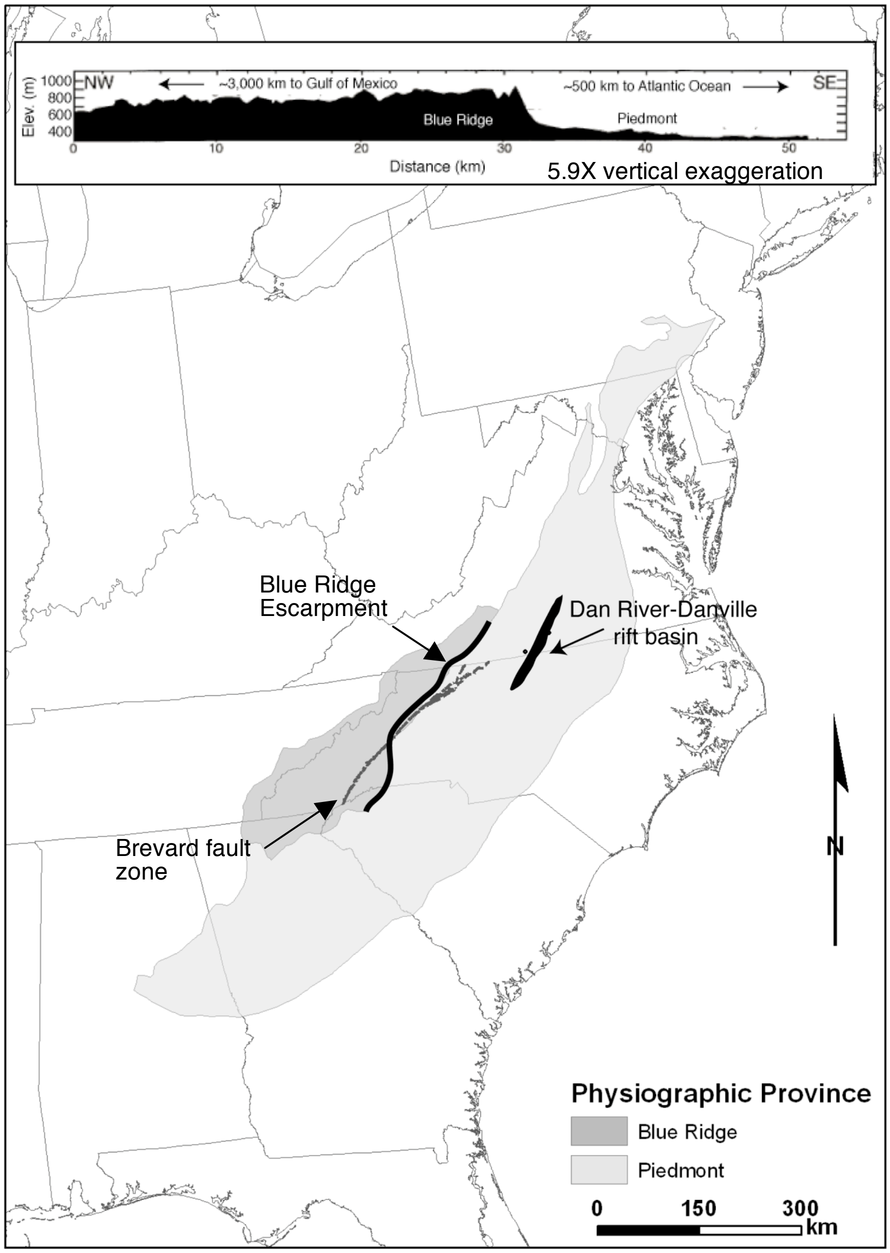
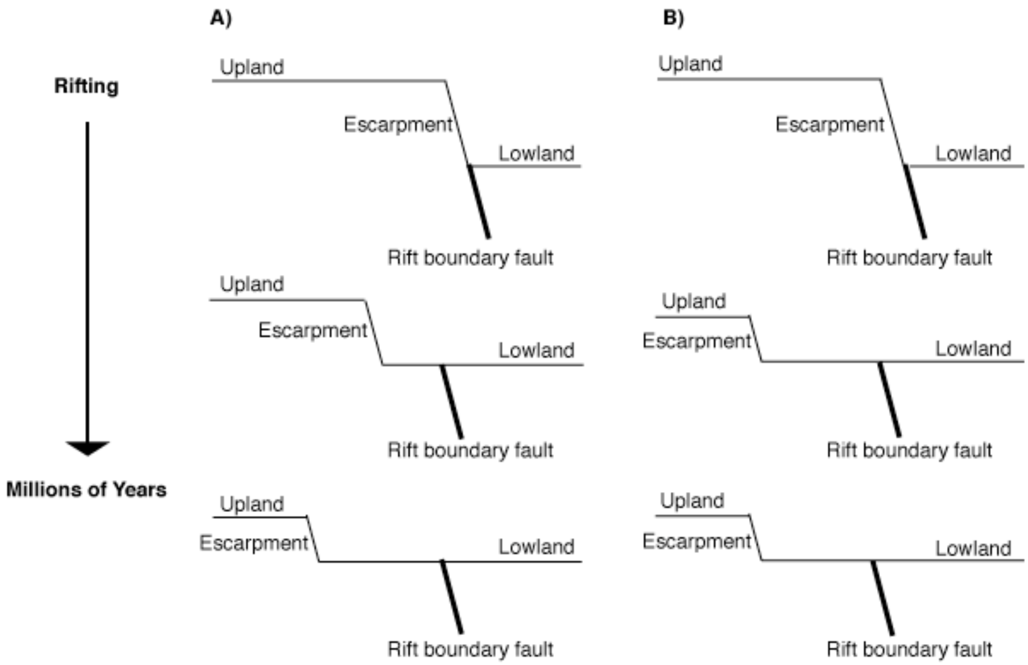

Elev. (m)
1000
800
600
400
NW
~3,000 km to Gulf of Mexico
~500 km to Atlantic Ocean
SE
Blue Ridge
Piedmont
0
10
20
30
40
50
Distance (km)
5.9X vertical exaggeration
Blue Ridge
Escarpment
Dan River-Danville
rift basin
Brevard fault
zone
N
Physiographic Province
Blue Ridge
Piedmont
0
150
300
km

Figure 1



A)
B)
Rifting
Millions of Years
Upland
Escarpment
Lowland
Rift boundary fault
Upland
Escarpment
Lowland
Rift boundary fault
Upland
Escarpment
Lowland
Rift boundary fault
Upland
Escarpment
Lowland
Rift boundary fault
Upland
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Rift boundary fault
Upland
Escarpment
Lowland
Rift boundary fault

Figure 2

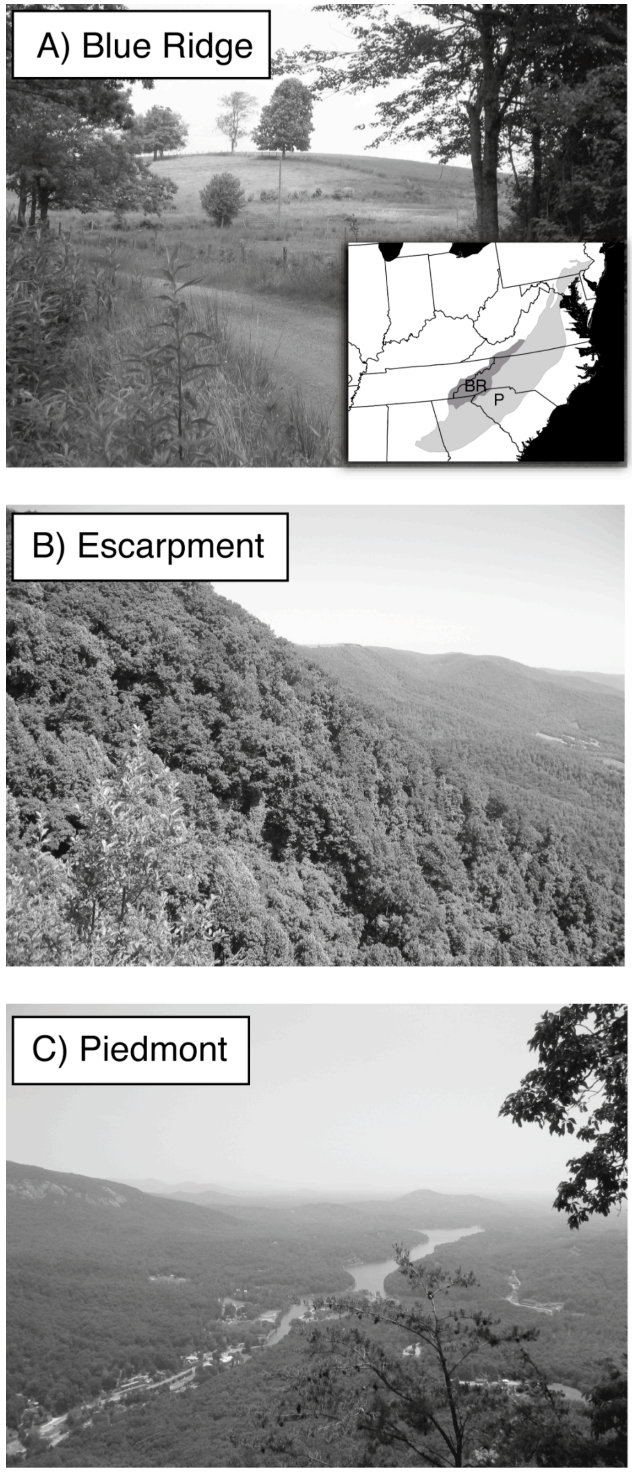
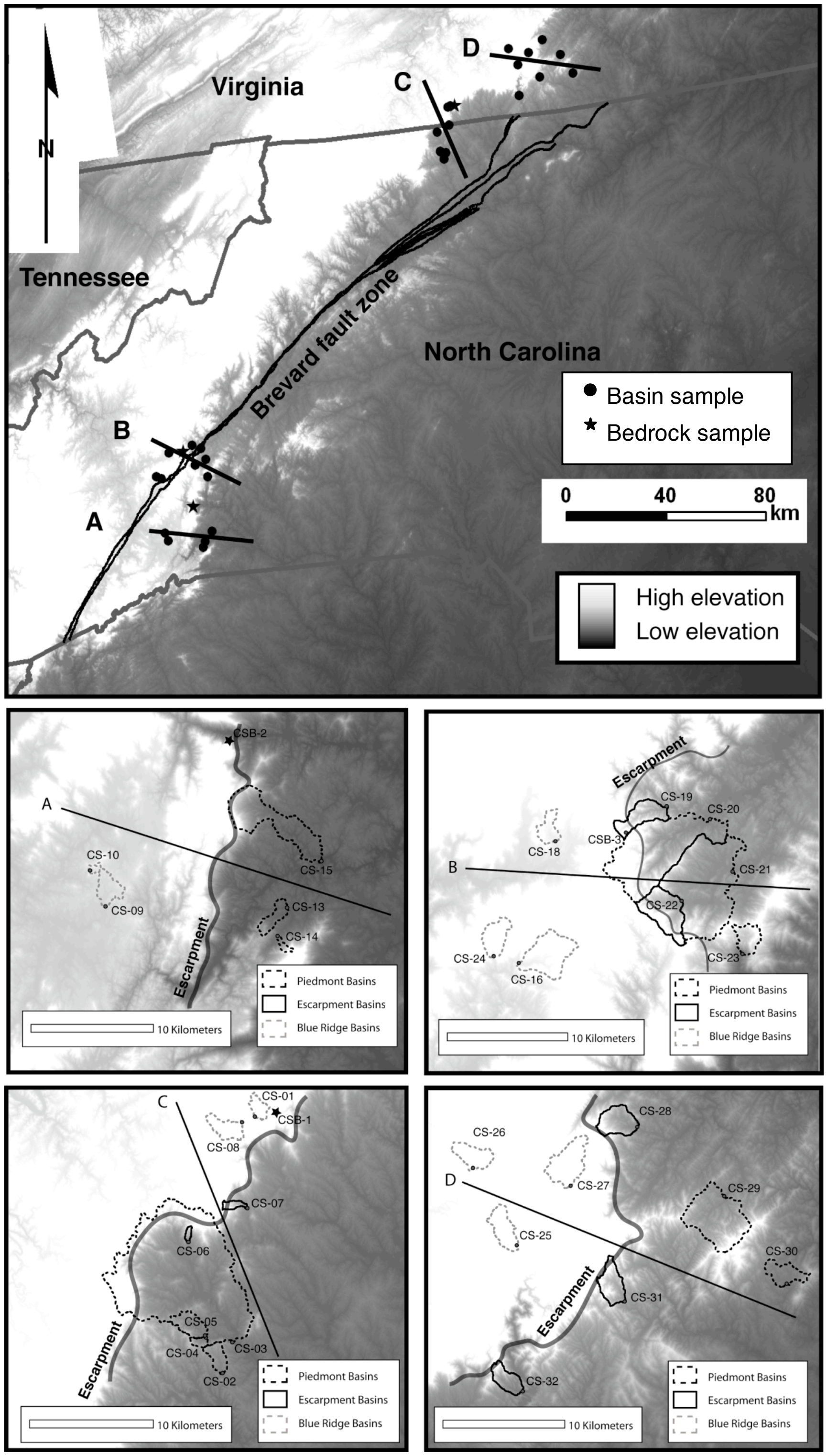


Figure 3



Virginia
Tennessee
North Carolina
Brevard fault zone
N
A
B
C
D
Basin sample
Bedrock sample
0 40 80 km
High elevation
Low elevation
CSB-2
CS-10
CS-09
CS-15
CS-13
CS-14
Escarpment
Piedmont Basins
Escarpment Basins
Blue Ridge Basins
10 Kilometers
CS-18
CSB-3
CS-19
CS-20
CS-21
CS-22
CS-23
CS-24
CS-16
CS-01
CSB-1
CS-08
CS-07
CS-06
CS-05
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CS-31
CS-32

Figure 4

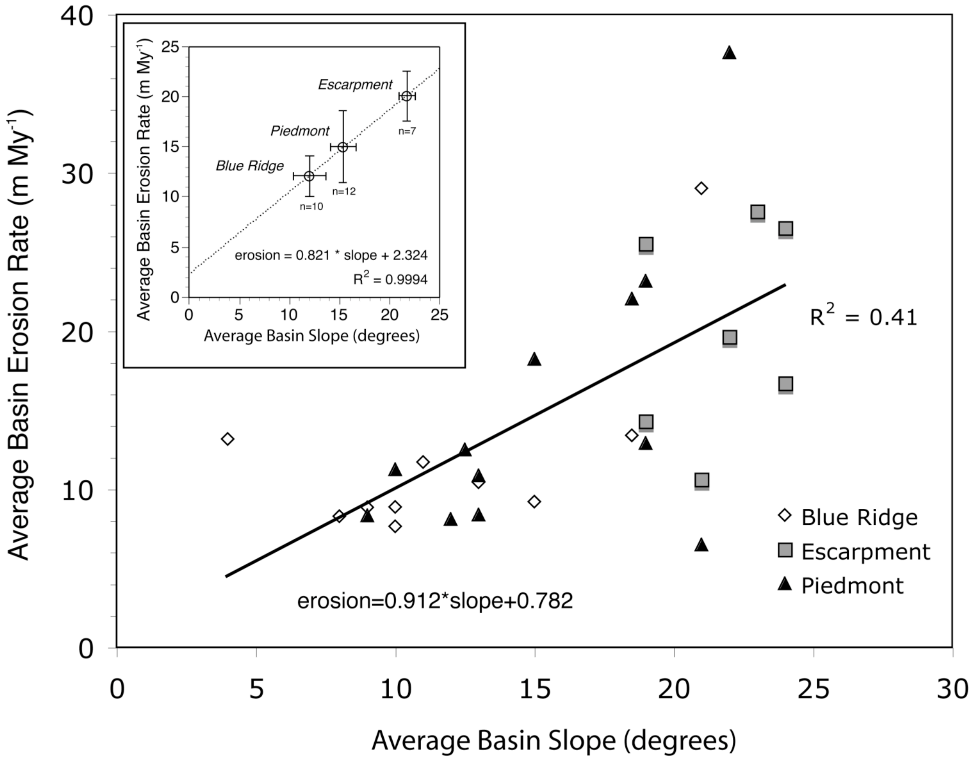

Average Basin Erosion Rate (m My-1)
Average Basin Slope (degrees)
Escarpment
Piedmont
Blue Ridge
n=7
n=12
n=10
erosion = 0.821 * slope + 2.324
R2 = 0.9994
R2 = 0.41
erosion=0.912*slope+0.782
Blue Ridge
Escarpment
Piedmont

Figure 5

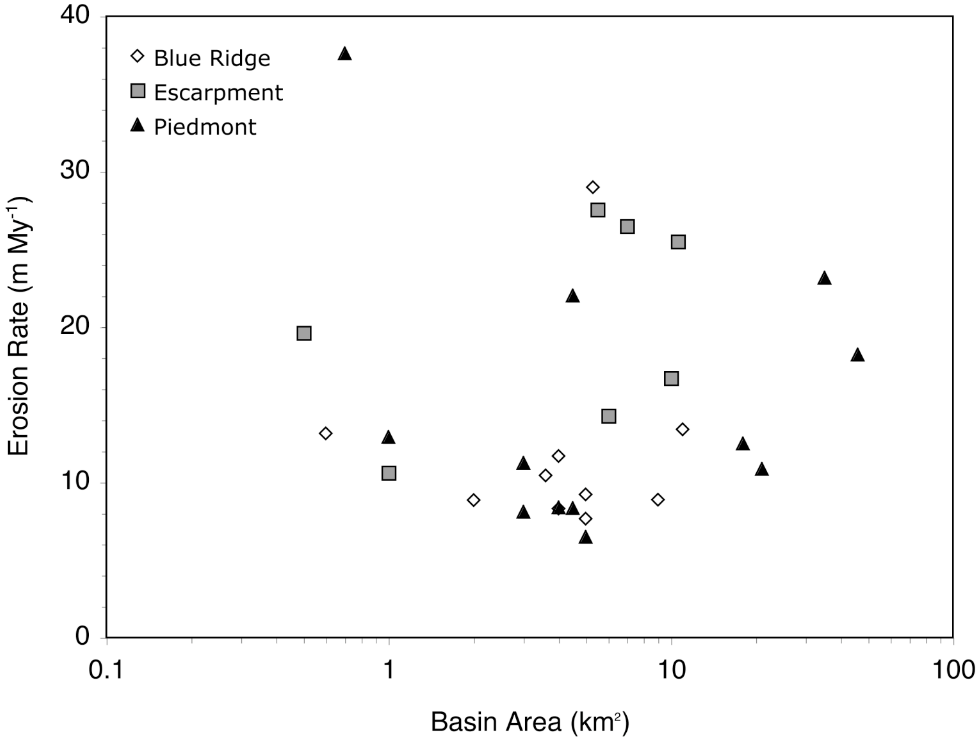

40
30
20
10
0
Blue Ridge
Escarpment
Piedmont
Erosion Rate (m My-1)
0.1
1
10
100
Basin Area (km2)

Figure 6

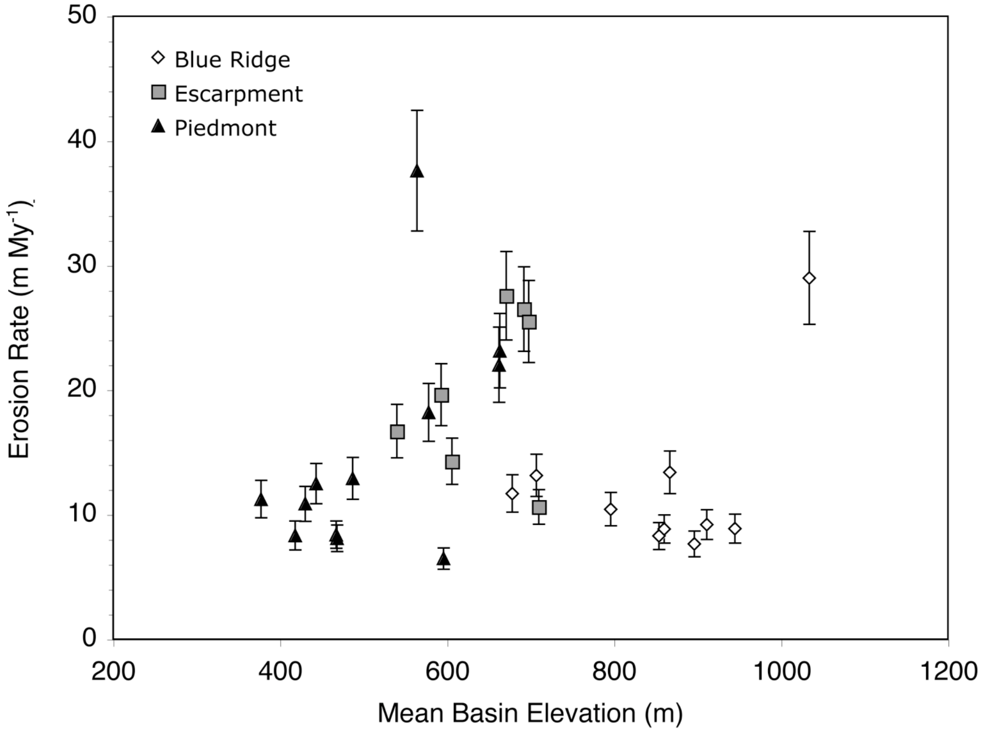

Blue Ridge
Escarpment
Piedmont
Erosion Rate (m My-1)
Mean Basin Elevation (m)
0
10
20
30
40
50
200
400
600
800
1000
1200

Figure 7

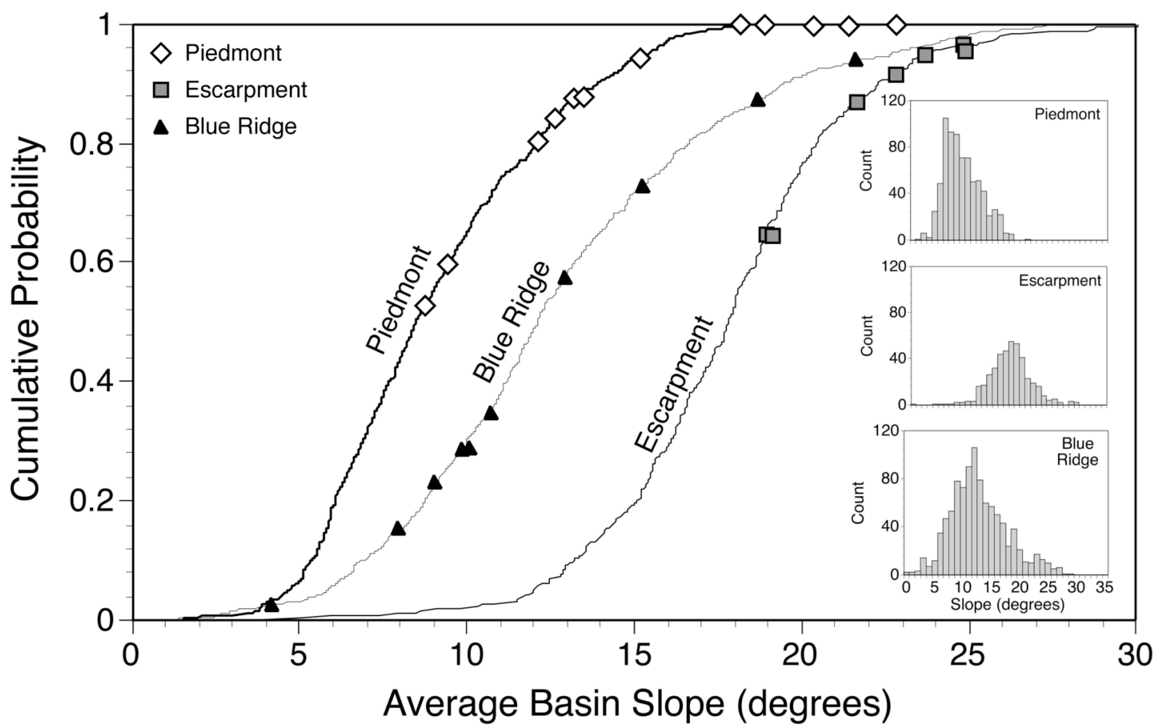
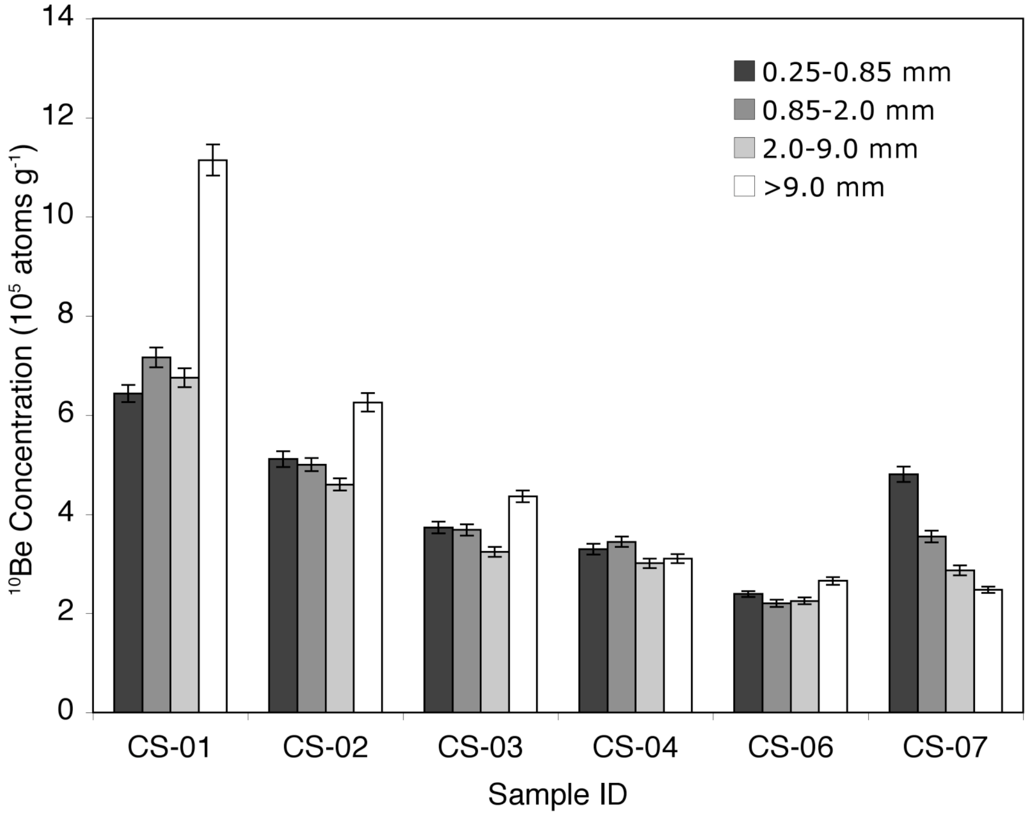

Cumulative Probability
Average Basin Slope (degrees)
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
Piedmont
Escarpment
Blue Ridge
Piedmont
Blue Ridge
Escarpment
Piedmont
Escarpment
Blue Ridge
Count
120
80
40
0
0 5 10 15 20 25 30 35
Slope (degrees)

Figure 8



14
12
10
8
6
4
2
0
^{10}Be Concentration (10^5 atoms g^{-1})
0.25-0.85 mm
0.85-2.0 mm
2.0-9.0 mm
>9.0 mm
CS-01
CS-02
CS-03
CS-04
CS-06
CS-07
Sample ID

Figure 9

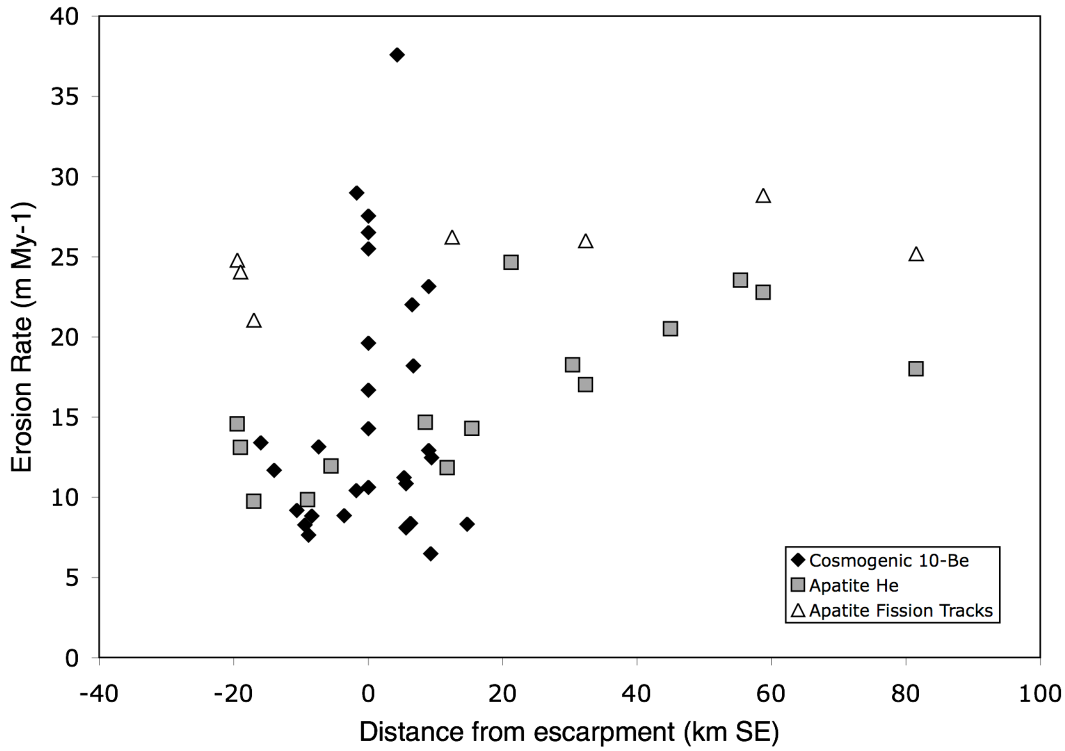
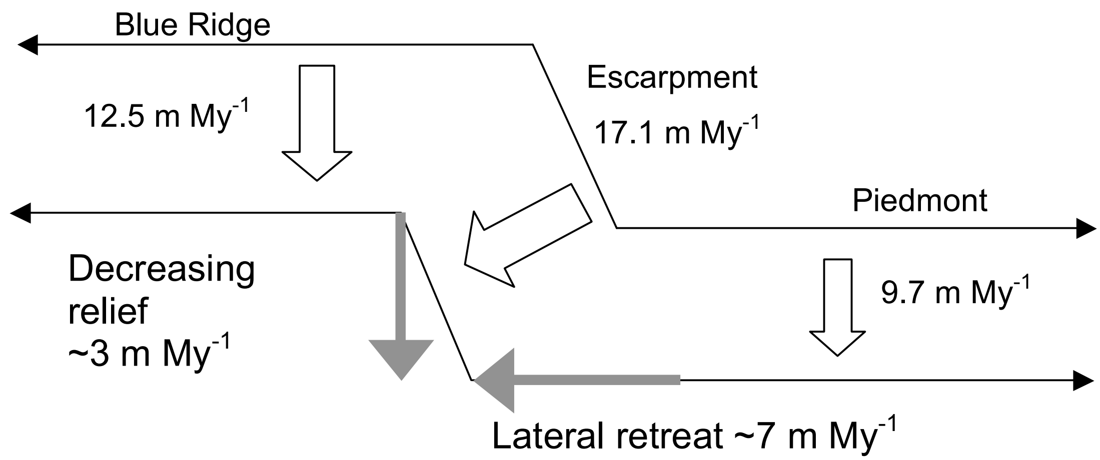

40
35
30
25
20
15
10
5
0
Erosion Rate (m My-1)
-40
-20
0
20
40
60
80
100
Distance from escarpment (km SE)
Cosmogenic 10-Be
Apatite He
Apatite Fission Tracks

Figure 10



Blue Ridge
12.5 m My-1
Escarpment
17.1 m My-1
Piedmont
9.7 m My-1
Decreasing
relief
~3 m My-1
Lateral retreat ~7 m My-1

Figure 11

Chapter 4: Conclusions and Recommendations

Summary of findings

Erosion rates determined from ^{10}Be in fluvial sediment on and near the Blue Ridge escarpment range from 6.5 to 38 m My^{-1} and indicate that the escarpment has not substantially eroded or retreated on the timescale of 10^4-10^5 years. Given the similar rates of erosion calculated for the Blue Ridge escarpment using thermochronologic techniques integrated on a 10^8 years timescale (Spotila et al., 2004), and the distance to the closest probable rift bounding fault that could have generated the escarpment, the Dan River-Danville basin, the majority of erosion forming the Blue Ridge escarpment probably occurred immediately following rifting and that the landform has remained relatively stable since that time.

Cosmogenic erosion rates measured on and near the Blue Ridge escarpment show a positive relationship with basin average slope. These basin scale erosion rates are fully consistent with those measured cosmogenically elsewhere in the southern and central Appalachian Mountains (~2-54 m My-^{1}) including other fluvial sediment samples from the Great Smoky Mountains, Shenandoah National Park, the Susquehanna drainage basin, and the New River basin (Duxbury et al., 2006; Granger et al., 1997; Matmon et al., 2003; Reuter et al., accepted). Lowering rates of exposed rock on the Blue Ridge escarpment (1.7-57 m My^{-1}) are more variable than drainage basin average rates because natural sediment mixing processes occur in streams. No systematic relationship exists between grain size and ^{10}Be concentration in this region of the southern Appalachian Mountains.

Based on the cosmogenic data and modeling presented in this thesis, the Blue Ridge escarpment appears to be both retreating and lowering, but at extremely slow rates. The rate of escarpment retreat I calculated from my data is too slow to sufficiently account for a model of evolution in which the escarpment steadily retreated from the closest potential rift margin (i.e. the nearest rift basin associated with the opening of the Atlantic Ocean basin, the Dan River-Danville basin, is too far away for the escarpment to have retreated at a constant rate over 200 My). Therefore, given the slow rate of escarpment retreat I calculated integrated over 10^4-10^5 years, and given the similarly slow reported thermochronologic rates of erosion integrated over 10^8 years, I conclude that any substantial erosion that could have caused the escarpment to retreat from an original position near the closest rift margin must have occurred soon after rifting. My findings on the Blue Ridge escarpment are similar to those found for other similar escarpments (South Africa, Namibia, Australia, and Sri Lanka), all supporting that a model of rapid initial rift shoulder retreat, followed by slow erosion.

Recommendations for future work

Results from this study provide initial information regarding the rate at which the Blue Ridge escarpment on the eastern passive margin of North America has eroded and evolved to its current status. Here, I provide some suggestions if further investigation is to be done into the evolution of the Blue Ridge escarpment or if a similar approach is to be applied to other passive margin escarpments in the future. The cosmogenic results from this study, when considered along with available thermochronologic data for the escarpment, appear to support a model of rapid and significant initial post-rift erosion and retreat followed by relative stability of the escarpment. However, additional cosmogenic data that includes sample sites farther from the escarpment, both eastward into the outer Piedmont and Coastal Plain and westward into the Valley and Ridge and Appalachian Plateau provinces may provide a deeper understanding of the evolution of the Blue Ridge escarpment. Additionally, in-depth bedrock mapping and seismic data from farther east of the nearby Mesozoic rift basins may indicate more clearly the starting point where the Blue Ridge escarpment was generated. A collaborative review of the cosmogenic, seismic, and mapping data by both southern Appalachian tectonics experts and geomorphologists may provide a more detailed understanding of the pattern and rate of retreat of the Blue Ridge escarpment.

In areas where there is a strong relationship between slope and erosion rate it is essential that sampled basins accurately represent the distribution of average basin slopes in each province, such that sampled basins correctly represent the population. To ensure that representative basins are evaluated, a GIS analysis can be performed prior to sampling that will allow for characterization of the average slope of basins for the entire physiographic region. Once the regional average basin slope is known, GIS can again be used to select potential basins from each distinct region. An arrangement of basins that accurately represent the slope distribution of the landscape should be selected.

Similar studies using cosmogenic isotopes as well as thermochronologic techniques should continue to be conducted on passive margin escarpments. A collaborative review of cosmogenic and thermochronologic data from great escarpments of passive margins of all ages may provide a more comprehensive understanding of the post-rift geomorphic evolution of these features.

Finally, I recommend a comprehensive study of all cosmogenic erosion rate data that exists for the southern Appalachian Mountains. Cosmogenic erosion rate data from many study areas in the southern Appalachians are currently available (Susquehanna River, Great Smoky Mountains, Shenandoah National Park and the Blue Ridge escarpment), and more work is currently underway in the southern Appalachian Piedmont. Analysis of each of these studies as one synthetic southern Appalachian dataset may help us understand better how the orogen as a whole has behaved on a millennial to million year time scale.

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