USING 10-Be TO DETERMINE SEDIMENT PRODUCTION AND TRANSPORT RATES ON STEEP HILLSLOPES IN VARIED TECTONIC AND CLIMATIC SETTINGS

A Thesis Proposal Presented

by

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to

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1.0 Abstract:

I will investigate the patterns and rates of sediment production and transport on steep (>20^o) hillslopes, using fieldwork and the analysis of ^{10}Be produced by cosmic-ray bombardment. My work will develop a new application for ^{10}Be that integrates measurements of hillslope-scale erosional processes into the broader scope of landscape evolution studied with ^{10}Be. The distribution of my study sites across varied geographic, tectonic, and climatic settings allows for a more general investigation of these factors' interactions and effects on hillslope-scale erosion and thus sediment production rates.

I have collected, along hillslope transects, one set of samples from a small basin in the Susquehanna River drainage, north-central Pennsylvania. I will continue my work this March with sample collection on the north island of New Zealand, and then later this summer in the Great Smoky Mountains, the Oregon Coast Range, and the central plateau of Madagascar. Four of my sites are underlain by sandstone; the fifth is underlain by granite. Three of my sites are located in passive margin tectonic environments, and two are located near active subduction zones.

I have carried out the initial steps of quartz purification for the majority my Pennsylvania samples, and further processing is pending lab completion. Measured ^{10}Be concentrations will be used along with simple box models to estimate rates of sediment production and subsequent transport of mass, down slope. My work will focus not only on resolving potential loci of sediment production, but also on how different grain sizes behave within a slope's soil profile. Statistical analyses will be used to test hypotheses regarding how slope, annual precipitation, uplift rates, and vegetation density may affect hillslope sediment production and transport rates.

2.0 Introduction:

The processes that shape landscapes are of fundamental importance to geomorphologists. These processes act on the scale of mountain ranges, drainage basins, hillslopes, and soil profiles. The measurement of cosmogenic nuclides, a technique developed over the last two decades, has allowed geomorphologists to better understand erosional processes and patterns for mountain ranges, drainage basins, and outcrops (Lal 1991; Gosse and Phillips, 2001; Bierman and Nichols, 2004). Much less work has focused on hillslope-scale sediment production and transport (Heimsath et al., 1997; Heimsath et al., 1999).

My thesis research will develop a new application for cosmogenic nuclides. I will use radionuclide abundances measured in samples of hillslope sediment, in conjunction with simple models of hillslope behavior, to better understand the patterns and rates of sediment production, as well as rates of sediment movement downslope. I will try to resolve what proportion of sediment is generated at the bedrock-soil contact beneath a hillslope's soil mantle vs. the proportion of sediment generated from bedrock along ridgelines above hillslopes. The improved understanding of hillslope processes that my research will develop, should allow for more robust interpretation of cosmogenic data derived from river sediments (most of which began as sediment on hillslopes). My measurements and findings will also be useful to those seeking to understand loci of landscape change over time.

3.0 Previous Work:

Cosmic ray bombardment of the Earth creates ^{10}Be in the first few meters below the surface (Lal and Peters 1967). The near-surface exposure history of a bedrock surface or grain of sediment can be determined by measuring ^{10}Be concentrations in quartz (Lal, 1991: Bierman and Steig, 1996). The near-surface residence time represented by the ^{10}Be concentration depends on erosion rate. For rapidly eroding sites, integration times might only be millennia (Duncan et al., 2001) and resulting ^{10}Be concentrations very low, 10^4 atoms per gram. For very stable sites, such as hyper-arid passive margins (Bierman and Caffee, 2002) and Antarctica (Nishiizumi et al., 1991), integration times may approach a million or more years resulting in extremely high ^{10}Be concentrations on the order of 10^6 to 10^7 atoms per gram.

The application of *in situ* produced cosmogenic radionuclides to quantify the rate of sediment generation and transport on steep hillslopes is a relatively new use for this isotopic technique (Heimsath et al., 2001; Heimsath et al. 2002). Heimsath has used ^{10}Be abundances in hillslope sediment to model the maintenance of a soil mantle through a balance between sediment production and hillslope erosion. This work did not track nuclide abundances as a function of movement downslope away from loci of sediment production. In contrast, Nichols et al. (2002) quantified sediment transport on moderately to shallowly sloping (~2^{o}) desert piedmonts in the eastern Mojave Desert but did not consider sediment production from bedrock. From the observation of a roughly linear relationship between distance from rangefront and nuclide concentration in piedmont sediment, they were able to demonstrate that sediment is uniformly dosed by cosmic rays as it is transported away from the mountain fronts (Figure 1). My research will test whether sediment on markedly steeper hillslopes displays the same pattern of increasing ^{10}Be concentration as sediment moves downslope away from ridgelines.

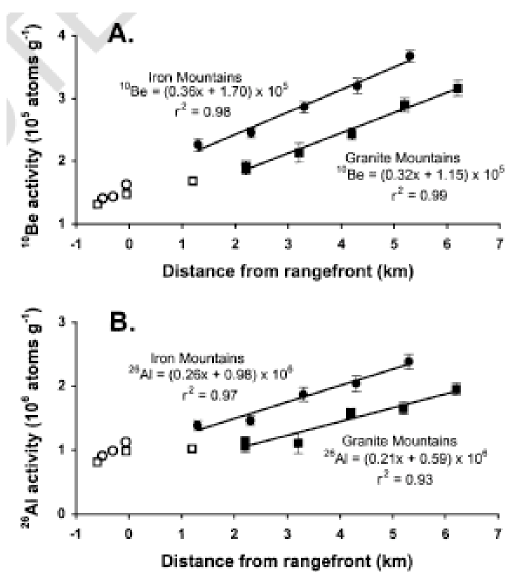

Figure 1. Plots from Nichols et al., 2002 showing increased nuclide concentration with increasing distance from rangefront. I will test whether sediment on steep hillslopes has the same relationship between increased nuclide concentration dosing and distance from ridgetops.

Sediment production and transport on steep hillslopes have been examined quantitatively using atmospherically produced ^{10}Be (McKean et al., 1993). Atmospheric ^{10}Be refers to nuclides produced in the atmosphere by nuclear reactions, deposited by rainfall, and adhered to soil grains, as opposed to the ^{10}Be created within soil grains that I will measure. These two types of ^{10}Be are separated in the lab by repeated acid etching of quartz grains to remove any surface-adhered ^{10}Be (Brown et al., 1991; Kohl and Nishiizumi, 1992; Gosse and Phillips, 2001). McKean et al.'s work on slopes with gradients up to 10^{o} showed a linear relationship between slope gradient and downslope sediment movement rate, which seems to support a dynamic equilibrium between sediment formation, soil transport (using slope geometry as a proxy), and soil loss. However, Roering et al. (1999) observe that many steeper, soil-mantled hillslopes may be convex near their divide, but become increasingly planar downslope. The authors propose that a nonlinear sediment transport model with a critical upper limit to slope gradient is needed to explain this tendency toward planar morphology on steep hillslopes. This problem of a linear vs. nonlinear relationship between gradient and sediment formation/transport is fundamental to an understanding of hillslope systems (Roering et al. 1999).

The rate at which sediment is produced from rock is key to understanding how soil mantles are maintained over a wide range of erosional, tectonic, lithologic, and climatic settings (Heimsath et al., 1997, Heimsath et al., 2002). Based on their work in Northern California and the Oregon Coast Range, Heimsath et al. (1997) have introduced the concept of a soil production function that uses hillslope shape (curvature) and the concentration of *in situ* produced cosmogenic radionuclides at the soil-bedrock contact to model the mass balance of soil production from bedrock and soil loss via surface erosion. While Heimsath et al. (1997) define their model as the soil production function, it should be noted that my work is focused on the inorganic sediment within a hillslope's soil mantle that is transported down slope. I am ultimately interested in the rate at which rock is weathered and becomes the sediment that eventually leaves the basin via stream and river channels. I refer to this rate in my work as the rate of sediment production. This difference between soil vs. sediment is primarily one of nomenclature, but is important for distinguishing my primary focus from that of previous authors.

Because cosmogenic radionuclides such as ^{10}Be can be used to constrain rates of sediment production (Heimsath et al., 2001; Heimsath et al., 2002) and trace transport down slope and into channel systems (Nichols et al., 2002), cosmogenic analyses are now often used to supplement and/or support previous work based on more traditional geomorphic techniques. For example, sediment yield estimates suggest that the Oregon Coast Range is in equilibrium as regards soil production driven by rock weathering and soil loss due to tectonically and climatically driven erosion (Reneau and Dietrich, 1991). Heimsath et al. (2001) and Bierman et al. (1998; 2001) used the cosmogenic nuclides ^{10}Be and ^{26}Al to estimate basin-scale erosion rates in the Oregon Coast Range so they could test the assumption (by comparision with sediment yield) that this is indeed an equilibrium landscape. Their cosmogenically-deduced conclusions supported Reneau and Dietrich's earlier assertion that the landscape was in equilibrium and allowed a clearer understanding of the spatial distribution of slope processes leading to that equilibrium.

Recently, cosmogenic radionuclides have been used in conjunction with other techniques, such as sediment budgeting and fission track dating, to provide a more complete picture of landscape evolution (Kirchner et al., 2001, Matmon et al. 2003; Nichols et al. 2005). For example, in the Great Smoky Mountains of the southern Appalachians, Matmon et al. found that late Cenozoic erosion rates calculated from cosmogenic nuclide concentrations agreed well with longer term exhumation rates determined from fission tracks and contemporary erosion rates deduced from modern sediment budgets. In contrast, Kirchner et al.'s controversial work in the Idaho batholith found that erosion rates measured with cosmogenic nuclides agreed well with rates from fission tracks, but were 17 times higher than rates measured through decadal scale budgets of sediment fluxes. It is possible that an understanding of erosion speed and locale on the slopes (such as the work I propose will accomplish) could help resolve these conflicts between basin-scale data integrating over different time frames.

4.0 Primary Objectives:

This study will use cosmogenic radionuclide analysis (^{10}Be) of sediment collected along hillslope transects and combined into amalgamated samples, as well as discrete samples of bedrock from ridge-top outcrops to:

- establish a new use of cosmogenic nuclides in the investigation of steep hillslope processes, thus contributing directly to our understanding of slopes as a key component of landscapes,
- determine nuclide activity in sediment contained in steep hillslope soil mantles as a function of depth and distance downslope,
- use these data to build simple box models of sediment production from rock and subsequent transport downslope,
- use nuclide data to determine whether sediment is generated primarily at ridges or whether the rate of sediment production changes downslope, and
- determine whether different sediment grain sizes have different nuclide

concentrations and thus behave differently within a slope's soil profile.

5.0 Work Plan:

I will collect samples from hillslopes in five different regions. Thus far, I have been able to collect samples from one hillslope in the Susquehanna River drainage in north-central Pennsylvania. This first round of field work was a good testing ground for my proposed methods, and a good opportunity to get a sense for the time required to sample an entire hillslope. I will continue applying, and refining, my methods in New Zealand (March), the Great Smoky Mountains (May), the Oregon Coast Range (June), and Madagascar (August). My study sites are quite varied both geographically and in terms of climatic and tectonic settings, but my work will be focused on the scale of hillslopes within these different environments. I will be working with at least one other geologist whose specialty is the larger scale processes for each site; they will be crucial in helping add context to my small-scale measurements.

5.1 Field Work: In November of 2004, Joanna Reuter and I conducted about a week of field work in north-central Pennsylvania, about three days of which were spent actively collecting hillslope transects. At least two other days were required to scout out a hillslope that would be suitable both in terms of logistics and in terms of proper gradient, elevation gain, and transect length.

Once we selected a hillslope, we used a hand level to calculate the height of the slope and to mark 30 meter intervals above stream level to use as potential transects (Figure 2).

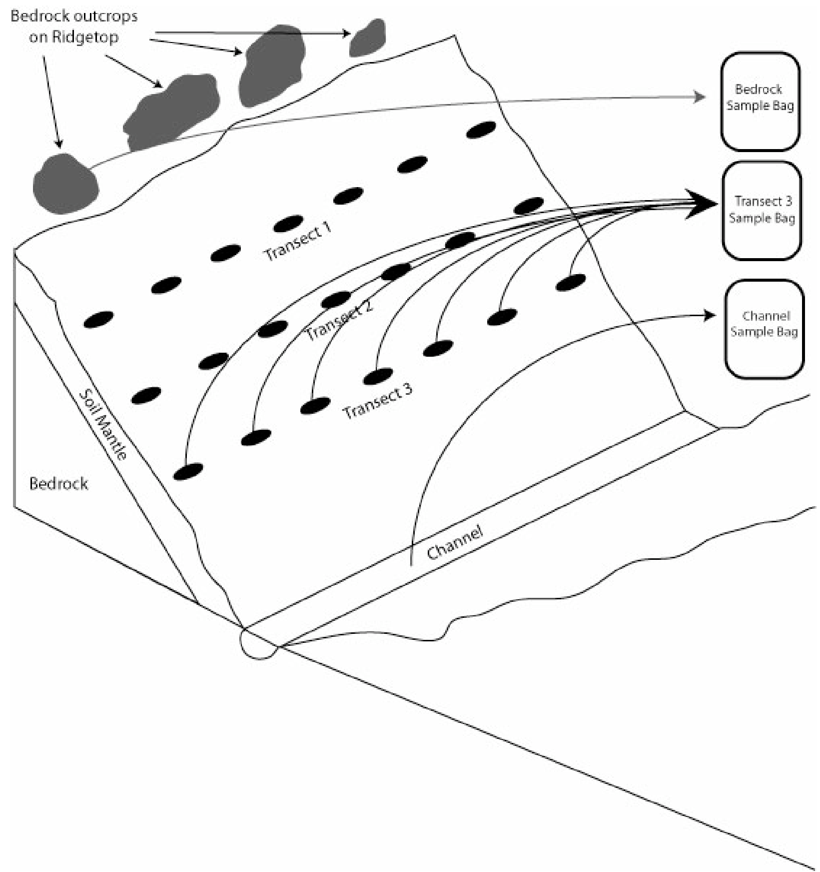

Figure 2. Schematic of hillslope sampling technique. Samples are collected from pits dug along hillslope transects and combined into amalgamated samples, one per transect. Discrete bedrock samples are collected along the ridgetop as potential sediment production loci. Channel sediment samples confirm basin-scale erosion rates and provide context for the hillslope data based on sediment from upstream hillslopes.

The actual process of collecting samples was more difficult than anticipated, primarily because the slope we chose was armored with a thick (5-50 cm) layer of coarse grain colluvial material that made digging pits a challenge. Once this colluvium was removed, we collected samples at 10 cm below the start of mineral soil horizons. The conditions in Pennsylvania did not allow for a more comprehensive sampling by depth. If possible at future sites, I will attempt to sample from the soil-bedrock contact in order to add another component to my soil production-transport box models. The most important controlling factors for such a sampling technique will be the thickness of the soil mantle and the ease with which pits can be dug.

In Pennsylvania, we collected samples from seven pits at 50 m intervals along four transects at 30, 60, 120, and 180 meters above stream level. We also collected two bedrock samples from outcrops along the top of the ridge above the slope, and we collected a sample from the stream channel below the slope. These bedrock and channel samples serve as potential beginning and end points for sediment as it moves down, and then off, hillslopes. By quantifying nuclide abundances in the rock along ridges above slopes and in bedrock beneath the soil mantle we will be better able to understand the balance of nuclides in sediment moving downslope and dominant sources for sediment's production (Clapp et al., 2000). For future sites, the number of pits along a transect may vary based upon the extent of different slopes, but the number of transects should not exceed six. The endpoints of transects were plotted using a Trimble Global Positioning System (GPS) unit with beacon correction, and for future transects each pit could be plotted in the same way. For Pennsylvania, it was not logistically possible to record the GPS location of each pit because of multipath problems and the time constraints of short November days. These GPS data are important not only for keeping track of sample locations, but they will also work well as reference points for DEM visualizations of my hillslopes that could be created using Geographic Information Systems (GIS).

5.2 Lab work: My samples from the Susquehanna River basin have already undergone the first step in processing at the University of Vermont using standard techniques (Kohl and Nishiizumi, 1992; Bierman and Caffee, 2001). I will further isolate the quartz that I have etched through density separation. Pending lab completion, I will assist Jennifer Larsen in the isolation of ^{10}Be in the cosmogenic laboratory to prepare my samples for isotopic measurement by accelerator mass spectrometry at the Lawrence Livermore National Laboratory in Livermore, California.

5.3 Data analysis: First, nuclide concentrations for each sample will be plotted against that sample's distance down slope away from the ridgeline to see if such concentrations increase down slope as expected from the work of Nichols et al. (2002). Then, simple box models (developed previously) will be used to analyze the measured nuclide concentrations. Transport rates of hillslope sediments have been modeled using fluxes of both nuclides and sediment into and out of defined boxes (Figure 4) distributed down a slope (Nichols et al. 2002).

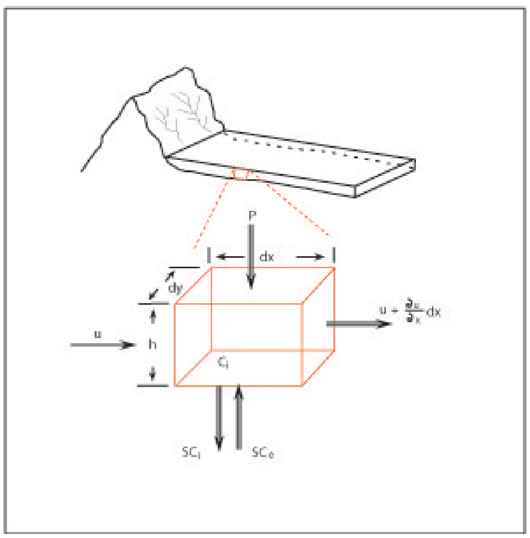

Figure 4. Schematic of transport boxes in a low angle piedmont environment. The piedmont is divided into transport boxes of length, dx, width, dy, and height, h. The double stemmed arrows represent inflows and outflows of nuclides. P is average production during transport, SCe is erosion from piedmont beneath ATL, SCi is deposition to the piedmont beneath the Active Transport Layer (ATL), u is the flux from up-gradient, and u + (Du/Dx)dx is the flux out of element box (Nichols et al., 2002). I will test whether this same model of flux is appropriate on steep gradients.

5.4 Hypothesis testing: First, I will test at five different sites, whether there is a positive relationship between nuclide concentration and distance down slope as predicted by the work of Nichols et al. (2002) and by the common sense assumption that sediment is systematically irradiated, as it moves down hillslopes, and thus contains more ^{10}Be downslope than upslope. Second, the geographic distribution of my study sites allows for statistical analysis of hillslope behavior as related to tectonic and climatic differences. I predict distinct differences in hillslope behavior between my study sites located in passive tectonic settings and those found in active settings. Since these sample sites can be divided into two populations, a t-test may be used to investigate whether statistically significant differences exist between the two settings for such characteristics as slope, ^{10}Be concentration, bedrock to soil conversion speed, and sediment transport rate.

Differences for other variables such as uplift rate (tectonic or isostatic), precipitation, temperature, and vegetation exist on a continuum, and are therefore not suited for statistical analysis using t-tests. However, regression analyses of hillslopes' sediment production rate and these variables may reveal trends. I will test my prediction that higher uplift rates and higher levels of precipitation will both increase rates of sediment production and transport; regression analyses will help me either support or refute these assertions.

Regression analyses will also help elucidate differences caused by variables such as vegetation density and type for which simple predictions of effect are difficult. It is possible that high levels of vegetation could slow sediment transport rates by adding effective root cohesion to slopes (Roering et al., 2003). However, vegetation could also increase rates of sediment transport and production through stochastic processes like tree-throw (Heimsath et. al, 2001). Regression plots of sediment production and transport rates versus vegetation density or type may clarify these relationships.

6.0 Timeline:

	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05
New Zealand Fieldwork			xxxxxx	xxxx		
Smoky Mountains Fieldwork					xxxxx	
Oregon Fieldwork						xxxxx
Madagascar Fieldwork						
Quartz Making at UVM (pending lab availability)	xxxxxxxxxx	xxxxx				
Sample Processing and Analysis						
Proposal Writing	xxxxxxxxxxxxxxxxxxxx		xxxx			
Proposal Defense			7-Mar			
Progress Report Writing						
Progress Report Defense						
Modeling and Data Analysis						
Thesis writing						
Thesis defense						

	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Jan-06	Feb-06	Mar-06	Apr-06
New Zealand Fieldwork										
Smoky Mountains Fieldwork										
Oregon Fieldwork										
Madagascar Fieldwork		xxxxxxxxxx								
Quartz Making at UVM (pending lab availability)	xxxxxxxxxx		xxxxxxxxxx	xxxxxxxxxx						
Sample Processing and Analysis					xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx			
Proposal Writing										
Proposal Defense										
Progress Report Writing	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx							
Progress Report Defense				??	??					
Modeling and Data Analysis								xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx
Thesis writing										xxxxxxxxxx
Thesis defense										

	May-06	Jun-06	Jul-06	Aug-06	Sep-06	Oct-06	Nov-06	6-Dec
New Zealand Fieldwork								
Smoky Mountains Fieldwork								
Oregon Fieldwork								
Madagascar Fieldwork								
Quartz Making at UVM (pending lab availability)								
Sample Processing and Analysis								
Proposal Writing								
Proposal Defense								
Progress Report Writing								
Progress Report Defense								
Modeling and Data Analysis	xxxxxxxxxx							
Thesis writing	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx	xxxxxxxxxx		
Thesis defense							??	??

7.0 Study Sites:

My study sites were selected primarily because they are contained within basins with ^{10}Be-quantified erosion rates (Figure 5). This provides context for my data, and allows me to add to the overall understanding of landscape change within previously studied basins (Table 1).

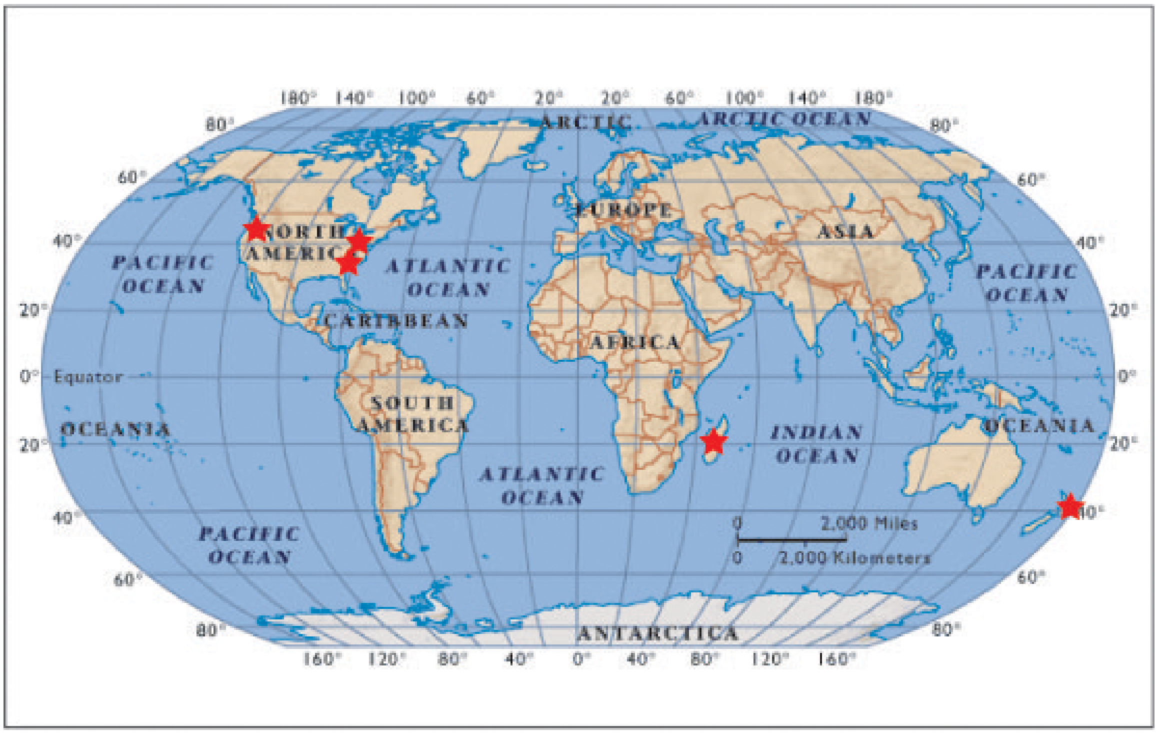

Figure 5. Geographic distribution of study sites shown by stars.

7.1 Susquehanna River Basin: Phanerozoic mountain building events, followed by rifting in the Triassic/Jurassic created the passive margin that the Susquehanna River drains today (Schultz, 1999). The Susquehanna Basin climate is humid and temperate, with mean annual precipitation ranging from about 0.8 to 1.3 meters, depending on location (Daly and Taylor, 1998). My samples were taken from within the Appalachian Plateau physiographic region of the Susquehanna Basin, which is underlain by relatively undeformed sedimentary bedrock, largely sandstone and shale. Erosion rates for the Susquehanna Basin, based upon ^{10}Be concentrations in river sediment, range from 4-54 m My^{-1} (Reuter et al., in preparation).

7.2 Oregon Coast Range: The Oregon Coast Range is a tectonically active, deeply dissected mountain range that runs north-south in western Oregon. The climate is temperate and wet with >2 m of precipitation annually (http://www.wrh.noaa.gov/images/pqr/prec_OR.gif; 3/05), and is underlain by a relatively undeformed sequence of lithic Eocene turbidite sandstone, the Tyee Formation (Snavely et al., 1964; Lovell, 1969; Heller et al., 1985). This bedrock is extensively weathered and fractured with saprolite depths of several meters in some places (Heimsath et al., 2001). Rock uplift rates have been estimated at between 30 and 230 m Ma^{-1} through the dating of marine terraces (Kelsey and Bockheim, 1994; Kelsey et al., 1994). Erosion rates for the Drift Creek basin within the Oregon Coast Range have been measured at 125-130 m My^{-1} (Bierman et al., 2001), consistent with but not mandating approximate equilibrium between uplift and erosion (Reneau and Dietrich, 1991).

7.3 Great Smoky Mountains: The Great Smoky Mountains, located between North Carolina and Tennessee, contain the highest peaks of the southern Appalachian Mountains. Mean annual precipitation ranges from 1.4 to 2.3 m, depending on elevation (http://www.nps.gov/grsm/gsmsite/natureinfo.html; 2/05). The Great Smoky Mountains are built of medium grade, metamorphosed sedimentary rocks of Neoproterozoic to early Cambrian age with isolated areas of Mesoproterozoic gneiss (King et al., 1968). This area has not been tectonically active since Late Paleozoic orogenic events formed the Appalachian Mountains (Blackmer et al., 1994; Boettcher and Milliken, 1994; Friedman and Sanders, 1982; Pazzaglia and Brandon, 1996). Erosion rates for the Great Smoky Mountains are on the order of 27 +/- 4 m My^{-1} (Matmon et al., 2003), far less than those during the Appalachians' Paleozoic mountain building events, which were $>10^2$ m My^{-1} (Pavich, 1985; Zen, 1991; Huvler, 1996).

7.4 Waipaoa River Basin, North Island, New Zealand: The Waipaoa River drains into Poverty Bay on the east coast of New Zealand's North Island. Annual rainfall averages 1.5 m (http://baby.indstate.edu/gomez/margins.html; 2/05). The bedrock in the basin's headwaters is composed of highly crushed Cretaceous and Paleocene mudstones and argillites (DeRose et al., 1998), while the lower Waipaoa is underlain by poorly consolidated sandstone and mudstones of Miocene and Pliocene age (Gage and Black, 1979). This basin is situated within the active forearc margin of the Hikurangi subduction margin, and is undergoing broad regional uplift on the order of 0.5-1.1 mm/yr (Berryman et al., 2000). Long-term sediment yields for the Waipaoa River Basin and its tributaries have been estimated to be as high as 1700 m My^{-1} (Hicks et al., 2000).

7.5 Central Madagascar Craton: The central plateau of Madagascar ranges in elevation from 1000 to 2000 m with local relief between flat valleys and convex hillslopes of 100 to 500 m (Wells and Andriamihaja, 1993). Annual rainfall ranges from 100-200 cm, which is intermediate between the much wetter eastern rain forest and the arid southwest of the island (Donque and Rabenjy, 1972). The craton is composed of granites, migmatites, gneisses, and schists that are commonly covered by a thick lateritic regolith (Wells and Andriamihaja, 1993). No erosion rate data are available yet; samples that would provide this information have been waiting for lab completion so they can be processed.

Table 1. Geographic locations and tectonic/climatic differences between study sites.

Location	Tectonic Setting	Lithology	Precipitation ($m\ yr^{-1}$)	Erosion ($m\ My^{-1}$)
Susquehanna Basin, PA, USA	ancient orogeny, now passive margin	sandstone	0.8-1.3	4.0-54
Waipoa Basin, Gisborne, NZ	active subduction	sandstone/ mudstone	1.5	1700
Great Smoky Mountains, NC, USA	ancient orogeny, now passive margin	sandstone	1.4-2.3	27 +/- 4
Oregon Coast Range, OR, USA	active subduction	sandstone	1.5	125-130
Madagascar Highlands, Madagascar	stable craton	granite/gneiss	1.0-2.0	*in progress*

8.0 Expected Outcomes

I will be carrying out my hillslope work within basins with documented background erosion rates (Reneau and Dietrich, 1991, Reuter et al., *in review*, Matmon et al., 2003; Cox et al., *personal communication*; Reusser et al., *personal communication*). This nesting of my work within the study sites of others offers both practical and theoretical advantages. Background erosion rates will be useful in providing context for the rates that I measure, and they will allow me to judge whether the hillslopes I selected are representative of the basins as a whole in terms of erosion rate.

Working within previously studied basins also provides the opportunity to create a more comprehensive understanding of erosion for entire areas. For example, in the Oregon Coast Range, it has been shown that average bedrock lowering rates of 70 to 125 $m\ Ma^{-1}$ (Reneau and Dietrich, 1991; Bierman et al., 2001) are in approximate equilibrium with rock uplift rates of between 30 and 230 $m\ Ma^{-1}$. The maintenance of a thick soil mantle on steep slopes in the Oregon Coast Range then implies that soil production is keeping pace with soil lost to tectonically-driven erosion. The use of cosmogenic radionuclides to determine slope-scale erosion rates will allow me to quantifiably test that implication. Furthermore, the interplay between climate, tectonics, and erosion will also be addressed through my collection of samples from hillslopes that are geographically, climatically, and tectonically varied. For example, my work will suggest whether hillslope-scale erosion rates are as sensitive to tectonic forcing as basin-scale rates of erosion (Reuter et al., 2004), and it may introduce new components to the picture such as climatic and vegetation controls on hillslope sediment production and erosion.

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