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

A Progress Report

by

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to

The Faculty of the Geology Department

of

The University of Vermont

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

The following members of the Thesis Committee
have read and approved this document
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Date Accepted: __________________________

Abstract:

I seek to quantify sediment production and transport rates on steep, soil-mantled hillslopes. Specifically, I am using the activity of ^{10}Be produced by cosmic ray bombardment, measured in both discrete and amalgamated transect samples of hillslope sediment (an extension of the method of Nichols et al., 2002, 2005), in conjunction with simple models of hillslope behavior, to understand better the patterns and rates of sediment production, as well as rates of sediment movement downslope. I have collected suites of samples (n = 96) from hillslope transects across varied climatic and tectonic settings. Most of these samples have been processed and I now have data for the first 51. These initial data clearly show that the spatial distribution of ^{10}Be in hillslope soil is systematic and thus interpretable. Nuclide concentrations indicate the extent of soil stirring and are consistent with down-slope soil transport.

Sample sites include north-central Pennsylvania, New Zealand's North Island, Great Smoky Mountains National Park, the Oregon Coast Range, and the central plateau of Madagascar. Field and isotopic data from these hillslope samples is being considered along with cosmogenic data from river sediment samples collected near each site. This pairing provides context for the results of my new application of cosmogenic nuclides, and adds breadth and depth to the relevancy of this work and that of our collaborators. The importance of the link between hillslope processes and inferred basin-scale erosion rates is often cited (Bierman and Steig, 1996; Brown et al., 1995; Matmon et al., 2003), but rarely explored quantitatively (Heimsath et al., 2005). My project is explicitly making this link.

During the upcoming summer and fall, my primary focus will be collaboration with other researchers to develop the simple models needed to translate raw ^{10}Be abundances into meaningful sediment production and transport rates. The recent receipt of a grant from the National Center for Airborne Laser-swath Mapping (NCALM) for high-resolution topographic mapping of my intensively sampled, Great Smoky Mountains field site will afford the opportunity for me to develop additional curvature-based topographic models for sediment transport. These models can then be compared to the simple, nuclide-based models I develop for the Smoky Mountain site in order to enrich our understanding of the link between hillslope processes and landscape morphology.

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 cosmogenic research has focused on hillslope-scale sediment production and transport (Heimsath et al., 1997; Heimsath et al., 1999; Heimsath et al., 2005).

My thesis develops a new application for cosmogenic nuclides. I am using radionuclide abundances measured in samples of hillslope sediment, in conjunction with simple models of hillslope behavior, to understand better the patterns and rates of sediment production, as well as rates of sediment movement downslope. This improved understanding of hillslope processes should allow for more robust interpretation of cosmogenic data derived from river sediments (since most of these grains began as sediment on hillslopes).

Significance and Context of Research:

Gravity-driven soil diffusive processes, such as soil creep, have long been considered important for sediment transport during the evolution of soil-mantled landscapes. Early observational studies defined a proportional link between slope gradient and rate of soils' downslope transport, with those components eventually reaching dynamic equilibrium (Gilbert 1877, 1909). Gilbert assumed a uniform soil thickness and a uniform rate of soil production, requiring soil flux to increase with distance from the top of the slope. Consequently, a slope's gradient must increase linearly downslope – creating a convex upward profile – to provide the necessary transport capacity (Gilbert, 1909). This inferred linear relationship between gradient and soil transport has been the basis for many soil-transport laws and hillslope evolution models (e.g., Carson and Kirkby, 1972).

Recently, soil-transport laws have been divided into two distinct populations (Dietrich et al., 2003, Heimsath et al., 2005). A linear diffusion law that is based on morphometric observations of convex, soil-mantled hillslopes continues to rely on an assumption of steady-state erosion and has limited field support (Gilbert 1877, 1909; Fleming and Johnson, 1975; McKean et al., 1993; Roering et al., 2002; Schumm, 1967; Small et al., 1999). McKean et al. (1993), in particular, were able to demonstrate a proportional relationship between soil flux and gradient by tracking meteoric ^{10}Be concentrations downslope. A non-linear diffusion law has been proposed more recently (Anderson, 1994; Howard, 1994; Roering et al., 1999; Heimsath et al., 2005), and supported primarily through high-resolution topographic modeling (Roering et al., 1999; Roering and Gerber, 2005). With the exception of Heimsath et al. (2005), most work on soil-transport laws has lacked strong, fieldwork-based quantification of soil generation and flux rates.

This project uses intensive field sampling, and subsequent analysis of ^{10}Be produced in quartz, to create simple, quantitative models for soil flux down hillslopes based on combined soil and isotope flux balances. These models are meant to stand alone, or they can be considered in the context of more complex observational models based on topography and assumed transport laws. My research will contribute to the understanding of hillslope behavior directly as well as contributing to the discussion of basin-scale landscape evolution where hillslope processes are often cited as important, but are rarely addressed in a quantitative manner.

Review of Primary Objectives:

This study uses 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.

Work Completed To Date:

Field Work: Since my proposal presentation in March of 2005, I have completed four additional rounds of fieldwork in New Zealand, the Great Smoky Mountains, the Oregon Coast Range, and Madagascar with a final sample tally of 96 (Table 1).

Table 1. General site characteristics.

Location	Average slope (degrees)	# of Transects	Transect Length (meters)	# of Samples
Pennsylvania	25	4	300	12
New Zealand	20	4	300	14
Great Smoky Mountains, TN	5-10	4	300	45
Oregon Coast Range	10-15	4	100	17
Madagascar	15-20	4	300	8

In each of these locations, the same sample collection scheme was followed (as outlined in my proposal), with minor modifications related to sample site morphology and enrichment of the project's statistical design as suggested by faculty during my proposal.

The most significant of these modifications was the collection of enough soil from each pit along a mid-slope transect in the Smoky Mountains to test for internal variance across the slope. By comparing and averaging the isotope concentrations of these seven samples, we test the validity of our physical mixing of samples across transects to obtain an average value for nuclide activity. In the Smoky Mountains, four samples were collected at different depths in each pit: 1) A-horizon centered at 10 cm (sample ID = Ah), 2) top of the B-horizon centered at 30 cm (Bt), 3) bottom of the B-horizon centered at 50 cm (Bb), and 4) clasts from 60 cm (clasts).

Our sample collection strategy proved flexible when our target hillslope in the Oregon Coast range was inaccessible because Drift Creek was running at a higher stage than anticipated and could not be crossed. We were able to locate a smaller, but more accessible slope, and we scaled down our transect length and spacing accordingly. While collecting samples on this smaller scale was not included in the original sampling plan, it provides an opportunity to evaluate the consistency of soil diffusion processes across different length scales.

Fluvially-transported sand samples were collected from small hillslope drainages adjacent to sampled transects in the Smoky Mountains, the Oregon Coast Range, and Madagascar. These samples will allow me to compare ^{10}Be activities on slopes and in channels in order to understand better the relationship between these two geomorphic elements. I will also be able to compare inferred hillslope transport rates to erosion rates for these small catchments. These spatially limited process rates will be compared to basin-scale erosion rates inferred from streams within each hillslope's large drainage basin.

Most recently, Paul Bierman and I returned to my Great Smoky Mountains field site to examine the new isotopic data in the field, develop field-based hypotheses for testing, and resurvey the locations of each sample pit using Trimble ProXH GPS units. We were successful in relocating every pit and measuring the location of each with a precision of 10-20 cm (Figure 1A). These high resolution GPS data will serve as reference points for a high-resolution Airborne Laser Swath Mapping (ALSM) mission that will be flown by the National Center for Airborne Laser-swath Mapping (NCALM). This mission will be paid for through a seed grant that I was awarded in April. The product of this ALSM will be 10 to 20 cm vertical resolution topographic data at meter scale grid points for the entire surface of the hillslope I sampled. These data will be necessary for any topographic models that we might develop to complement our isotope and mass balance models (see "Remaining Work").

In addition to collecting GPS locations for each sample pit, we also measured soil depth-to-bedrock by driving a metal rod into the soil mantle adjacent to each soil pit location (Figure 1B).

a)

b)


Figure 1. Field techniques from our recent round of fieldwork in the Great Smoky Mountains, TN. a) Trimble ProXH GPS unit setup for collecting 10-20 cm resolution GPS data for each soil pit on the Great Smoky Mountains hillslope. b) In addition to collecting GPS data, we drove a metal rod into the soil adjacent to each pit to determine the depth of the soil-bedrock contact.

These depth measurements will be useful when considering soil mass balance during modeling, and for comparing our ^{10}Be concentrations to those used by Heimsath et al. (1997) in defining their soil production function.

Lab Work: I have purified quartz (Kohl and Nishiizumi, 1992) from all of my samples, except those from New Zealand, which, because they lack sufficient coarse quartz, will be reserved for the analysis of meteoric ^{10}Be. Jennifer Larsen has isolated ^{10}Be from my Great Smoky Mountains, Madagascar, and Pennsylvania samples, and samples from the Oregon Coast Range are queued for processing in the cosmogenic laboratory at UVM. During April 2006, I measured ^{10}Be nuclide activity for all but one of my samples from the Great Smoky Mountains and Madagascar using the accelerator mass spectrometer (AMS) at Lawrence Livermore National Lab (LLNL) in Livermore, California.

Preliminary Data Analysis:

I am currently at the observational and organizational stage with regards to data collected during a trip to Lawrence Livermore National Lab in early April. However, even simple statistical observations of these data from the Great Smoky Mountains and Madagascar reveal systematic patterns in ^{10}Be concentrations, which will allow more detailed modeling of hillslope processes in the near future.

Great Smoky Mountains, TN:

Based on our sampling strategy, ^{10}Be concentrations for the Smoky Mountains can be analyzed for 1) depth relationships, 2) spatial variations across the hillslope, 3) downslope patterning, and 4) grain size relationships.

No consistent relationship between ^{10}Be and depth was observed in our data suggesting the soil mantle is well-mixed at least to a depth of 70 cm (Figure 2).

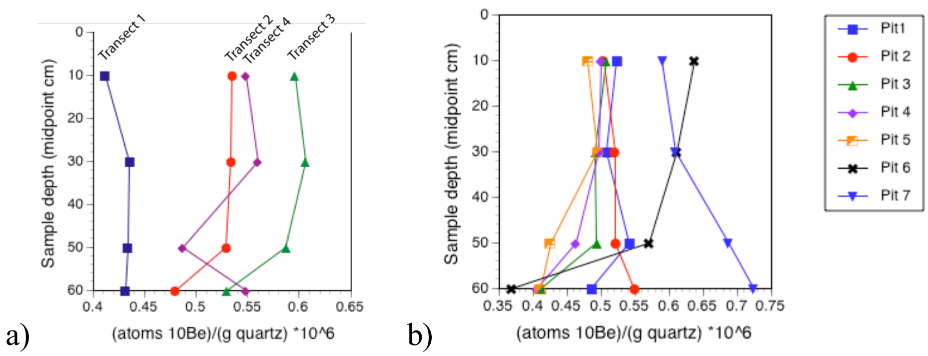

Figure 2. Plots of depth vs. [^{10}Be] (atoms/g) for a) amalgamated soil pit samples from each transect starting at the top of the slope with Transect 1, and b) for discrete samples from each soil pit along Transect 2. No consistent relationship between sample depth in soil profile and [^{10}Be] can be inferred from these plots, implying thorough mixing of the soil mantle both downslope and across slope. Mixing of the soil to a depth of 60-70 cm is likely achieved by tree throw events. Observed tree root wads had average thicknesses at least equal to the sampling depth of our pits.

Observations of extensive tree throw in the field supports the inference of thorough and spatially extensive soil mixing to a depth of 60-70 cm. Root wads frequently had thicknesses of 50-70 cm incorporating clasts from the transition between the B- and C-horizons (Figure 3).

Figure 3. Rootwads in the Great Smoky Mountains have average thicknesses (from base of the tree to the base of the wad) of 60-70 cm (n=18), and appear to be the primary agent of soil mixing. Integrated over time, an entire hilllslope's soil mantle can be overturned by random, but overlapping tree throw events.

In the Great Smoky Mountains, the presence of well-defined soil horizons does not distinguish active transport layers from stable subsurface layers (in contrast to the findings of Nichols et al., 2002), and requires that the formation of soil horizons takes place at a rate faster than soil transport processes.

Spatial variance between pits along slope parallel transects was tested for at each depth along transect 2 (MJGS3A-G). A maximum variance of 3.5 x 10^5 (atoms ^{10}Be)/g was observed between pits for clasts at a depth of 60cm (Figure 4).

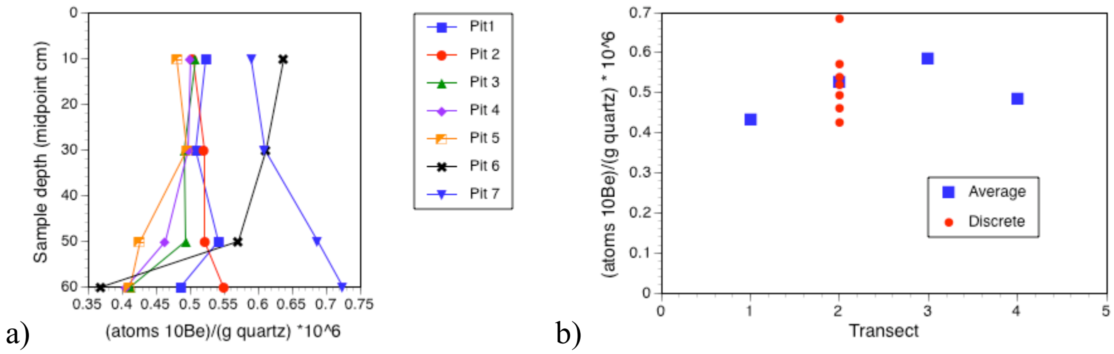

Figure 4. (a) Spatial variance of [^{10}Be] between samples collected at different depths in pits along transect 2. Variance increases with depth with the maximum variance occurring between clasts at a depth of 60 cm in pits 6 and 7. Physical mixing of samples for each transect reduces the variability of our transect data. (b) Plot of [^{10}Be] from samples amalgamated from the bottom of the soil B-horizon (sample depth midpoint = 50 cm) for each transect including both the concentrations for discrete pits along transect 2 and a arithmetic mean for those pits' concentrations. The mean plots in line with the trend observed between transects 1 and 3 suggesting that physical and mathematical amalgamation have the same result.

Despite the observed variance between pits along transect 2, arithmetic means for each sample plot in line with observed trends for the other transects' physically mixed samples (Figure 4b). This relationship between mean concentrations for transect 2 and physically averaged concentrations for transects 1, 3, and 4 confirms our assumption that amalgamation of samples from seven pits along transects sufficiently accounts for the idiosyncratic nature of different grains' histories across the slope.

^{10}Be concentrations from three distinct depths and from clasts (collected at the 60-70 cm depth) at each transect show that grains are undergoing systematic cosmic-ray dosing (as indicated by the increase in ^{10}Be concentration) as they move downslope (Figure 5).

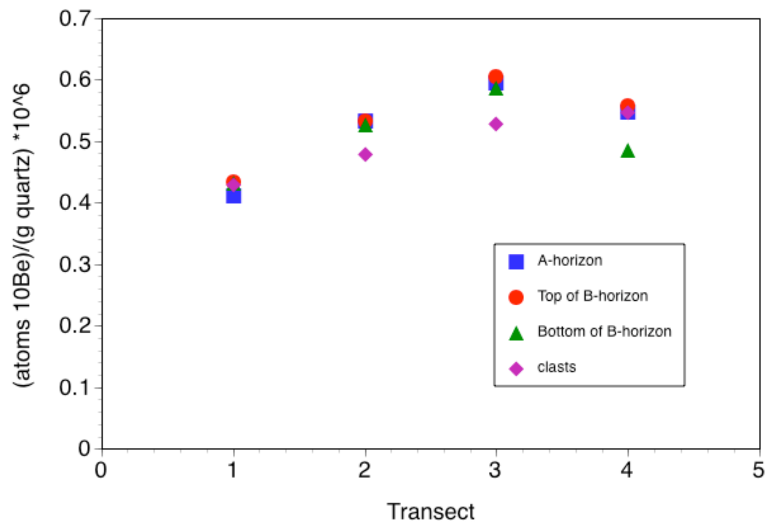

Figure x. ^{10}Be concentrations (atoms/g) for each sample type for transects 1 (top of slope) to transect 4 (bottom of slope). The relationship between ^{10}Be concentrations and downslope position is linear from transects 1-3; a systematic decrease in concentration occurs for all sample types except for clasts at transect 4. Clustered plots of soil samples (squares, circles, triangles), with the exception of the lower B-horizon from transect 4, indicate a thoroughly mixed soil mantle to a depth of ~60 cm. Clasts (diamonds) do not cluster with the smaller grain-sizes for two out of the four transects suggesting a different mixing history for these larger grains.

The increase in nuclide concentrations is linear between transects 1-3, but a systematic drop in ^{10}Be concentrations occurs for the smaller grain-size fractions (squares, circles, triangles) at transect 4. Concentrations for larger clasts (diamonds) increase linearly downslope from transect 1-4. The smaller grain-size fractions plot in clusters for each transect (with the exception of transect 4), which implies that the smaller soil grains are well-mixed through the sampling depth of ~60 cm. The larger clasts do not cluster with the smaller grain-sizes for two out of the four transects, which suggests a different mixing and transport history for larger grains. This difference in ^{10}Be concentrations for small vs. large grain-size fractions has been observed before in the river sediments of the Great Smoky Mountains (Matmon et al., 2003).

Amparafaravola, Madagascar:

Despite the absence of one data point (60 cm depth on transect 4) from my Madagascar hillslope (which is pending the next trip to LLNL), a pattern between downslope position and ^{10}Be concentrations is clear from the data (Figure 6).

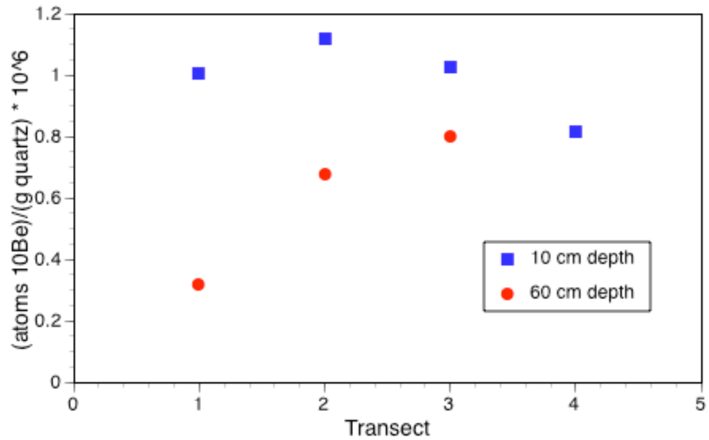

Figure 6. ^{10}Be concentrations (atoms/g) vs. downslope position for two sample depths from the central plateau of Madagascar. Data from 60 cm depth at transect 4 is pending at LLNL. In comparison to a similar plot from the Great Smoky Mountains, TN, ^{10}Be concentrations are greater, and samples of similar grain-size from different depths do not cluster indicating that the soil is not well-mixed.

The dosing pattern for samples moving from upslope to downslope positions appears different for Madagascar than for the Smoky Mountains, but the Madagascar data are systematic, nonetheless, and are therefore amenable to modeling. Disparate ^{10}Be concentrations for each transect's sample depths suggest that mixing processes are not as effective in Madagascar as they are in the Smoky Mountains. The absence of deep-rooting vegetation from this region of Madagascar is a possible explanation, and I did not see any evidence for 10-60 cm scale turnover while collecting these samples. Further consideration of these data will occur when this dataset is complete.

Remaining Work:

Lab Work: The processing of my samples for analysis of meteoric ^{10}Be activity will be carried out this spring and summer under the guidance of Adam Hunt, a doctoral student in Chemistry who has tested and adopted the method at UVM. Analysis of meteoric ^{10}Be (in contrast to *in situ*-produced ^{10}Be) has been shown as a useful technique for determining erosion rates and soil transport rates when samples are not quartz-rich (Brown et al., 1988; McKean et al., 1993). We will be using this analysis for our New Zealand samples, which are derived from mudstone, and for a limited number of samples that are also being analyzed for *in situ*-produced ^{10}Be. These paired meteoric/*in situ* samples will allow us to compare rates derived from both types of ^{10}Be concentrations.

Another trip to LLNL will be necessary before the completion of my thesis so that the remainder of my samples can be measured for ^{10}Be activity.

Modeling Approach:

Consideration of generalized hillslope mass transport equations is necessary to convert measured ^{10}Be concentrations into soil production and transport rates (cf., McKean et al., 1993; Heimsath et al., 1997; Heimsath et al., 1999; Small et al., 1999; Heimsath et al., 2005). Gilbert (1909) and Davis (1892) were the first to describe soil transport in terms of a linear diffusion function, where the sediment flux, q_s, is proportional to gradient, ∇z, such that $q_s = -K\nabla z$; here K is equivalent to a diffusion coefficient with dimensions (length)^2 (time)$^{-1}$. This diffusion function can be inserted into a mass conservation equation for a soil mantle (variables defined in Figure 7a, Heimsath et al., 1997), which gives

$$\rho_s \frac{\partial h}{\partial t} = -\rho_r \frac{\partial e}{\partial t} - \nabla \cdot \rho_s \bar{q}_s \qquad (1)$$

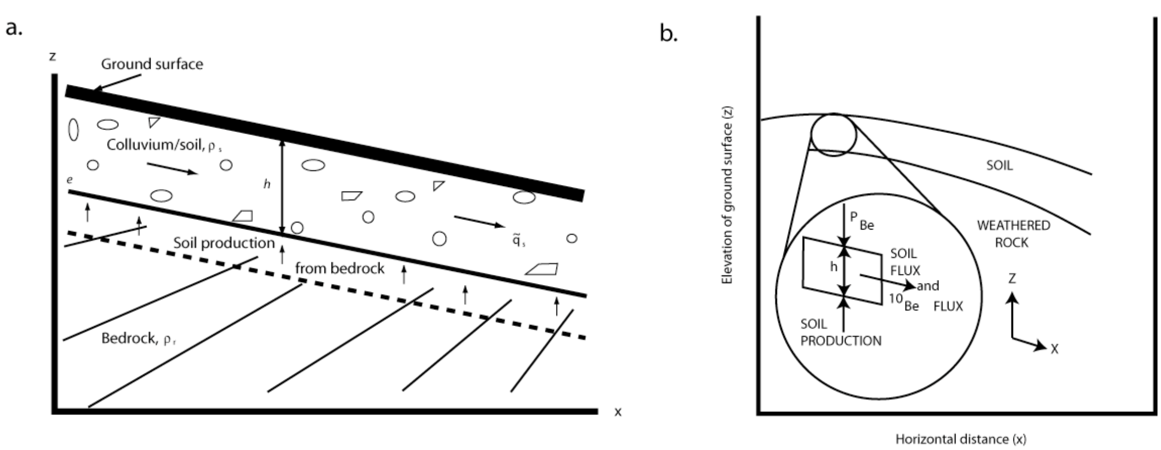

Figure 7. Models for soil flux with conservation of mass; a) the conservation of mass equation for soil thickness *h* (equation 1) states that the change in soil mass with time, *t*, is equal to the conversion of bedrock to soil due to lowering of the bedrock-soil interface less the divergence of transported soil mass. The area shown between the base of the soil at elevation *e* and the dashed line is the amount of bedrock that would be converted to soil over some specified time interval, *t*. ρ_s and ρ_r are the densities of soil and bedrock respectively (Heimsath et al., 1997); b) conservation of mass and isotopes includes ^{10}Be introduced through soil production from bedrock and through *in situ* production within the soil. Loss of mass/isotopes at a given point due to downslope transport is balanced by flux of mass/isotopes from upslope positions (Modified from McKean et al., 1993). In all cases, loss of ^{10}Be by decay is assumed to be negligible as the time scale of sediment production and transport (10^3 to 10^4 y) is one to several orders of magnitude less than the half-life of ^{10}Be (1.5 My).

This mass balance approach can be modified to consider the flux of ^{10}Be (Figure 7b, modified from McKean et al., 1993), where soil production adds both mass and ^{10}Be produced in the bedrock to the soil mantle; ^{10}Be is also added to the soil mantle by *in situ* production in the soil. Soil flux, q_s, downslope includes both soil mass and ^{10}Be. Loss of mass and isotopes at a given point by downslope flux is balanced by an equal flux of material from upslope (continuity).

Both models, considered above, for mass balance within the soil mantle assume steady-state soil thickness, *h*, at any given point, which means that $\partial h/\partial t = 0$ (Dietrich et al., 1995; Heimsath et al., 1997). This assumption in conjunction with the substitution of a linear diffusion function into equation (1) gives

$$\frac{\partial e}{\partial t} = -\frac{\rho_s}{\rho_r} K \nabla^2 z \qquad (2)$$

Equation (2) allows topographic curvature, $\nabla^2 z$, to be used as a proxy for soil production, $\partial e/\partial t$, across a hillslope. Using this relationship, we can both develop predictive models for soil transport/production using high-resolution topographic data from ALSM, and we can use soil transport functions modeled from ^{10}Be concentrations to test Gilbert's (1909) primary assumption that soil flux is directly proportional to gradient (cf., Roering et al., 1999; Heimsath et al., 2005).

Timeline:

<u>*Work Completed To Date:*</u>

- November, 2004: Collection of Pennsylvania samples. Begin sample preparation.
- March, 2005: Proposal defense and collection of New Zealand samples.
- May, 2005: Collection of Great Smoky Mountain samples.
- June, 2005: Collection of Oregon Coast Range samples and review of Heimsath et al. paper on soil diffusion processes for *Geology* (paper accepted with minor revisions).

- August, 2005: Collection of Madagascar samples.
- December, 2005: Applied for NCALM grant for high-resolution topographic mapping of Great Smoky Mountains field site.
- March, 2006: Sample preparation completed.
- April, 2006: Awarded NCALM grant. Carry out initial AMS measurements of sample nuclide concentrations at LLNL.
- Continued research and background reading.
- Returned to the Great Smoky Mountains to locate more precisely transect pits using higher resolution GPS units.
- Trip to Williamstown with Paul Bierman to discuss Ronadh Cox's cosmogenic data from lavakas in Madagascar, and how my hillslope data are relevant to her research questions.

Spring 2006:
- Present progress report oral defense.
- Sample preparation for measurement of meteoric ^{10}Be.
- Statistical analysis of samples already measured at LLNL.
- Begin development of simple models describing sediment production and transport on hillslopes using recently acquired nuclide concentrations.

Summer 2006:
- Continued meteoric sample preparation.
- Continued modeling, with the addition of high-resolution topographic data from NCALM flights over Smoky Mountains field site.
- Continued research and reading.
- Begin writing sections of my thesis.
- Prepare abstract for GSA annual meeting.
- Possibly another trip to LLNL?

Fall 2006:
- RA supported.
- Continue with data analysis.
- Present poster for GSA annual meeting.
- Submit abstract for AGU meeting.
- December, 2006: Finish writing thesis and present thesis oral defense. Present poster at AGU.

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