BASIN-SCALE ANALYSIS OF LONG-TERM SEDIMENT-GENERATION RATES DERIVED FROM ^{10}BE IN RIVER SEDIMENT: THE SUSQUEHANNA RIVER BASIN AND BEYOND

A Thesis Proposal Presented

by

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to

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of

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

_____________________________ Advisor
Paul Bierman

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Date Accepted: ___________________________

ABSTRACT

My Masters research applies a combination of techniques (cosmogenic nuclide analysis of sediment, GIS, and multivariate statistical analysis) to address fundamental geomorphic questions of where and how quickly Earth's surface erodes. My work consists of two nested components. One component involves the acquisition of a new suite of nuclide measurements in sediments from the Susquehanna River basin, which drains >70,000 km^2 of the North American passive margin. These data will complement ten other data sets (collected by my advisor, Paul Bierman, and collaborators) from a variety of tectonic and climatic settings. These data sets, which have not yet been rigorously analyzed in the context of basin-scale parameters, are the foundation for the broader component of my research. I will use GIS analysis to investigate the relation between ^{10}Be activity (a proxy for erosion rate) and landscape-scale parameters in the existing data sets (Fig. 1, Table 1). I seek to determine if long-term rates of sediment generation, as inferred from cosmogenic ^{10}Be, correlate with GIS-measurable components of the present-day landscape. Such correlations (or a lack thereof) will provide insight into the tempo and pattern of landscape erosion and change.

INTRODUCTION

The quest to understand the development of landscapes, including controls on erosion and sediment generation, is fundamental to geomorphology. This is neither a new task, nor a simple one. For many years, researchers have sought correlations between erosion and spatial landscape characteristics; relationships have been identified or hypothesized, for example, between denudation and relief (Ahnert, 1970), sediment yield, precipitation, and vegetation (Langbein and Schumm, 1958), lithology and topography (Hack, 1960), and climate and tectonics (Molnar and England, 1990).

My approach also seeks correlations between erosion rates and landscape-scale parameters, but it considers broad spatial and temporal scales, and it utilizes modern analytical tools including ^{10}Be analysis of sediment, GIS, and multivariate statistics.

Fundamentals of Cosmogenic Nuclide Analysis of Sediment

The continual bombardment of Earth's surface by cosmic rays results in the production and accumulation of cosmogenic nuclides in near-surface materials (Lal and Peters, 1967). ^{10}Be and ^{26}Al are particularly useful nuclides. In addition to being relatively long-lived nuclides (half life of 1.52 x 10^6 years for ^{10}Be and 710,000 years for ^{26}Al; http://www.webelements.com), they are produced in quartz, which is geologically abundant (Nishiizumi et al., 1986). In an eroding landscape, cosmogenic nuclides accumulate as rock and soil approach the surface (Lal, 1991). As grains of quartz enter a river system, they function as dosimeters, carrying isotopic records that reflect their near-surface exposure histories (Bierman et al., 2001a; Brown et al., 1995). Rivers collect, transport, and mix grains from various parts of the basin. The abundance of cosmogenic nuclides in stream sediments reflects the cosmic ray dosing and thus, by inference, the erosional history of the basin. For example, slowly eroding basins have relatively high nuclide activities because quartz grains, on average, have spent a long time near the surface.

Interpretation of nuclide activities in terms of sediment-generation rates relies on several assumptions and takes into account basin altitude and latitude (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). Previous studies document efficient sediment mixing and suggest that ^{10}Be provides a valuable tool for assessing basin-scale sediment-generation rates (Clapp et al., 2001; Clapp et al., 2000; Matmon et al., 2003; Schaller et al., 2001).

Motivation and Significance

Estimates of erosion rates traditionally have been based on contemporary measurements of sediment yield data; such data are often limited in length of record (years to decades) and may be confounded by land use signals and episodic sediment delivery (Kirchner et al., 2001; Meade, 1969; Trimble, 1977). Thermochronologic methods, such as fission track and (U-Th)/He thermochronometry, also provide information about exhumation rates, but such results generally address much longer time scales (10^6-10^8 years). ^{10}Be-derived sediment-generation rates provide a complementary data set for an intermediate (10^3-10^6 year) time scale; these data are largely insensitive to current land use (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996).

In a spatial context, current research in diverse geographic regions reveals a more complex view of controls on erosion than was identified in some earlier studies that focused on mid-latitude basins of the U.S. (e.g., Ahnert, 1970; Montgomery and Brandon, 2002). The ^{10}Be data sets that I will analyze span a range of climatic and tectonic settings (Fig. 1); within each region, data are organized by nested basins. By applying a consistent approach to varied geographic regions, I hope to ascertain whether correlations exist between erosion and basin-scale parameters, and whether relations can be generalized between geographic regions. The results of GIS and multivariate statistical analysis will provide insight regarding the relative importance of climate, tectonics, topography, biota, and lithology in determining sediment-generation rates.

Because sediment-generation rates obtained from ^{10}Be analysis of river sediment provide information about a 10^3-10^6 year time scale, these rates can be used to put historic measurements of sediment yield into perspective (Kirchner et al., 2001). Samples collected thus far from the

Susquehanna basin are from sites where contemporary USGS sediment-yield data are available. Collecting and analyzing such samples provides a means of assessing whether present-day sediment yields are similar to long-term ^{10}Be sediment-generation rates. Such a comparison may reveal the degree to which humans have changed sediment yield. While one might expect recent sediment yield to be elevated due to human land use practices, Kirchner et al. (2001) and Schaller et al. (2001) found the reverse--that background erosion rates derived from ^{10}Be were slightly to many times higher than current erosion rates derived from sediment yields. They interpret such differences as reflecting episodic sediment delivery and the lingering effects of glaciers, respectively. In contrast, Matmon et al. (2003) inferred temporally uniform erosion rates (over 10^8-10^0 years) when comparing ^{10}Be to sediment yield and thermochronologic data. The Susquehanna results will provide another valuable data set to assess such relationships, in particular because the first samples are from sites with suspended sediment records.

^{10}BE FROM SUSQUEHANNA RIVER BASIN SEDIMENTS

This spring, I will obtain ^{10}Be data for 22 sand-dominated samples that USGS collaborators collected from USGS streamgage stations in the Susquehanna River basin. Sample preparation includes separation of quartz and standard processing procedures in the UVM cosmogenic lab (Bierman and Caffee, 2001), followed by AMS analysis at Lawrence Livermore National Laboratory. I will use the results from the existing samples, in combination with GIS analysis of basins, to determine strategic locations for additional samples, which I will collect and analyze during the summer of 2003. Furthermore, I have the flexibility to utilize field time to address relevant geologic and land use questions that arise from the preliminary data.

The Susquehanna River Basin: Physical Setting

The Susquehanna River drains approximately 71,190 km^2 of New York, Pennsylvania, and Maryland and extends across several major physiographic provinces (Fig. 2). The Susquehanna River's headwaters are in the Appalachian Plateaus; the river continues through the Valley and Ridge, where the mainstem river passes through several water gaps. The lower basin is part of the Piedmont, which the river crosses before draining into Chesapeake Bay. Clastic and carbonate Paleozoic sedimentary bedrock dominates much of the highlands, while metamorphic rocks are present in the Piedmont. The Taconic, Acadian, and Alleghanian orogenies affected the region, with the Alleghenian being the most directly responsible for the structural deformation of Valley and Ridge (Barnes and Sevon, 2002). Rifting in the Late Triassic led to the opening of the Atlantic Ocean, leaving the Susquehanna region as part of the North American passive margin (Barnes and Sevon, 2002). About half of Susquehanna River basin has been glaciated (Fig. 2), and the mainstem of the river experienced major outburst floods during glacial retreat (Stranahan, 1993). Historic human impacts, including logging, farming, dam building, and mining (Meade, 1969; Stranahan, 1993), have undoubtedly changed sediment dynamics in the Susquehanna basin during the last three centuries.

Interpretation of Cosmogenic Nuclide Activities in Susquehanna Sediment

After ^{10}Be activities have been measured, the results will be interpreted in terms of sediment-generation rates. Standard corrections will be applied to account for basin latitude and altitude (Brown et al., 1995; Lal, 1988). The impact of shielding will also be considered; snow and ice cover, in particular, require consideration because they reduce the penetration of cosmic rays into the ground (and to the quartz), although such corrections are typically less than 10%. The Susquehanna data set will present several new opportunities and challenges for the interpretation of nuclide activities in terms of sediment-generation rates. The Susquehanna River basin is larger than any of the other basins for which we have data. As a result, issues associated with temporary sediment storage (such as nuclide decay during burial in terraces) may be non-trivial. In addition, about half of the Susquehanna basin (dominantly the North Branch) has been glaciated. Finally, quartz is not homogeneously distributed in bedrock throughout the basin. Mass-balance and nuclide-balance models, in combination with a sampling strategy involving nested basins, will aid in the interpretation of results. The first-hand knowledge that I will develop of Susquehanna ^{10}Be data interpretation will help me critically assess data sets that I will be using for the broader, GIS-based component of my research.

SPATIAL ANALYSIS OF WORLDWIDE COSMOGENIC SEDIMENT DATA SETS

I will apply my Geographic Information Systems skills to analyze spatial relationships in cosmogenic nuclide data sets from geographically diverse regions (Fig. 1, Fig. 3). Topography, physiography, geology, land use/land cover, and climatic factors can be mapped and analyzed in a GIS environment; these are also landscape characteristics that are likely to influence sediment-generation rates on various time scales. For example, work by Matmon et al. (2003) in the Great Smoky Mountains demonstrates that slope is well correlated with sediment-generation rates but relief is not.

I plan to explore the data both qualitatively and statistically, using my GIS experience and programming skills to extract, manipulate, summarize, and view GIS data. I will utilize multivariate statistical techniques to explore data matrices for correlations between basin-scale parameters and cosmogenic nuclide data (Table 1).

GIS Data Acquisition, Processing, and Analysis

Vast amounts of digital spatial data are in existence; many important data sets are available free of charge from the internet. However, the availability of GIS data layers of an appropriate resolution will place some constraints upon the scope of analysis. The analysis design works within the framework of the available GIS layers. Within-region comparisons can draw upon sometimes extensive collections of data sets that are available within the appropriate political (country or state) boundary, even though comparable data sets may not be available in other regions. Between-region comparisons require comparable data layers (in terms of resolution and quality) from each region, so these will be limited by the coarsest-scale data available to all regions under consideration. A special case of the between-region comparisons will be the U.S. basins, for which a number relatively high resolution data layers with uniform standards are available.

USGS collaborators have compiled GIS data for the larger U.S. basins (Susquehanna and Rio Puerco) for which we have or will have cosmogenic data. As a result, I can focus my attention on data analysis rather than data compilation. The acquisition of GIS data for basins outside of the United States will present more of a challenge. At a minimum, global digital elevation models and climatic data are available in digital form, but generally at a coarser resolution than in the United States.

Availability of uniform, digital data for the United States:

- DEM (Digital Elevation Model): Digital elevation data are available for the coterminous United States with 10 meter or 30 meter horizontal grid cells (depending on location). 7.5” quadrangles are free (http://www.gisdatadepot.com). The USGS also provides a seamless version of the data, the National Elevation Database (NED;

http://gisdata.usgs.net/NED/default.asp). Data from the NED for the Rio Puerco and the Susquehanna will be available for this project without a fee.

- DRG (Digital Raster Graphics): Scanned images of USGS topographic quadrangles are available for the entire country, though free online availability varies on a state-by-state basis (http://www.dragonbbs.com/members/1117/drg.html). These are useful for pinpointing sample locations when GPS data not available, and they will be used to confirm or correct the DEM-based drainage basin delineation.
- NLCD (National Land Cover Data): This is a grid-based classification of land cover from 1992 Landsat satellite data; it provides nation-wide coverage and was processed with consistent methods (http://landcover.usgs.gov/natllandcover.html).
- Physiography: A national coverage of U.S. physiographic provinces is available (http://water.usgs.gov/lookup/getspatial?physio).
- Climate: The National Weather Service maintains a network of weather stations, and data from these stations can be averaged over time and contoured to provide information about spatial distribution of rainfall, for example. Raw data and contoured/gridded products exist for the entire country (http://www.ncdc.noaa.gov/oa/ncdc.html, http://www.ocs.orst.edu/prism/prism_new.html), but I am not aware of a source that provides the nation-wide data (either raw or processed) free of charge.

Availability of digital spatial data on a regional basis in the United States:

- Geology: Geologic maps with an appropriate resolution for this project are available in digital form on a regional basis, often at the state level. Collaborators at the USGS have compiled a uniform geologic map for the Susquehanna (Fig. 2). All other U.S. basins of interest are contained within a single state.

- Historic streamflow and sediment load: Discharge and flow recurrence data can be obtained for basins using the USGS streamgage network. The initial Susquehanna samples were collected at USGS gage locations.
- A variety of other data sets may be available on a regional basis. For example, the state of Oregon provides free contoured precipitation data, and an ecoregion coverage is available for the Susquehanna.

Digital elevation models are of particular importance in executing data analysis because they are the basis from which stream networks and drainage basins are delineated. After delineating drainage basins based on the topography, basin-scale parameters for the nested sample basins can be summarized and displayed. I can also extract and display longitudinal river profiles (Fig. 4) as well as slope profiles. I will draw upon my programming skills (in Perl and Avenue) in order to streamline repetitive data processing steps; I anticipate that I will also become competent with Visual Basic, which will allow for programming in the ArcGIS environment.

When considering numerous basin-scale factors, a common approach is to reduce landscape-scale attributes to metrics and to apply multivariate statistical techniques such as multiple regression and principal components analysis (e.g., Panfil and Jacobson, 2001). Multivariate statistical techniques provide a way to investigate correlations between basin-scale parameters and cosmogenic nuclide data (Table 1). I am currently enrolled in an applied multivariate statistics course.

I will perform GIS and statistical analysis on the Drift Creek from the Oregon Coast Range as a pilot study (Fig. 3-5). This is a good basin with which to begin because of the small basin size (approximately 180 km^2), because the region has received fairly extensive geomorphic study (Anderson et al., 2002; Dietrich and Dunne, 1978; Heimsath et al., 2001; Montgomery, 2001; Reneau and Dietrich, 1991; Reneau et al., 1989), and because independent evidence suggests that the basin is in topographic steady state (Montgomery, 2001). The small basin size facilitates rapid data processing as I work out the kinks of the data processing and reduction while transitioning to an ArcGIS environment (rather than ArcView 3.3). I will also experiment with various ways to parameterize aspects of the landscape.

BUDGET AND FUNDING

I have analytical support and travel support for the Susquehanna samples from the USGS that will amount to approximately $20,000. Furthermore, I will be executing data analysis on samples that were collected and analyzed under the auspices of a variety of previous grants totaling over half a million dollars. I will perform GIS analysis on a new Dell Precision Workstation which was purchased with university, departmental, and grant funding.

A Graduate Teaching Fellowship provided salary support for the 2002-2003 academic year. Work during summer 2003 will be funded by a Graduate College Summer Research Fellowship. I was awarded an NSF Graduate Research Fellowship, which will provide salary and tuition beginning in fall 2003. I also submitted an application, which is still under consideration, for the Howard Award from the GSA Quaternary Geology and Geomorphology Division.

TIMELINE

Fall 2002 (Graduate Teaching Fellowship)

- Started background reading and research.
- Traveled to Washington, D.C. to meet Milan Pavich (USGS collaborator) and to assist with fieldwork on the Potomac River.
- Submitted application to the NSF Graduate Research Fellowship Program.
- Submitted request for Dell Precision Workstation.

Spring 2003 (Graduate Teaching Fellowship)

- Received NSF Graduate Research Fellowship.
- Received Graduate College Summer Research Fellowship.
- Submitted application for the GSA Quaternary Geology and Geomorphology Division's Howard Award.
- Purified quartz for preliminary Susquehanna samples; will travel to Lawrence Livermore National Laboratory prior to summer field work.
- Took coursework in applied multivariate statistics.
- Setup Dell workstation and began GIS data acquisition and analysis for Drift Creek, Susquehanna, and Rio Puerco basins.
- Wrote and will defend proposal.

Summer 2003 (Graduate Collage Summer Research Fellowship)

- Develop Susquehanna sampling strategy based on GIS analysis and results from preliminary cosmogenic samples.
- Travel to the Susquehanna for field work and sample collection.
- Continue GIS analysis.
- Purify quartz from new samples.

Fall 2003 (NSF Graduate Research Fellowship)

- Analyze field data.
- Continue intensive GIS analysis, extending analysis to worldwide basins.
- Write and present progress report.
- Present at GSA.
- Begin writing thesis.

Spring and Summer 2004 (NSF Graduate Research Fellowship)

- Complete data analysis.
- Write and defend thesis.
- Present at AGU.

APPLICATIONS AND EXTENSIONS

The results of analysis of cosmogenic nuclide data in the context of basin-scale parameters will provide insight regarding the relative importance of climate, tectonics, topography, biota, and lithology in determining sediment-generation rates. These results will be relevant to a variety of practical needs, such as estimating reservoir lifetimes or understanding disturbance regimes experienced by aquatic organisms. In addition, the EPA is in the process of developing Total Maximum Daily Loads (TMDLs) for sediment, a task for which an understanding of current rates of sediment generation and transport relative to background rates is important. Results from my GIS work regarding whether basin-scale characteristics reflect and might be used to predict long-term rates of sediment generation will be relevant to TMDL development. Long-term sediment-generation rates, and how they relate to characteristics of drainage basins, are clearly of great academic and practical interest.

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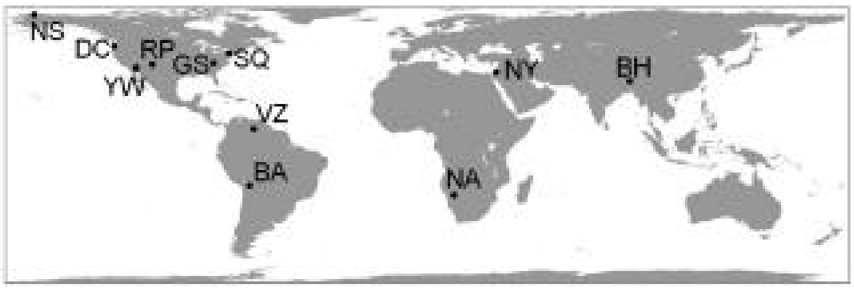


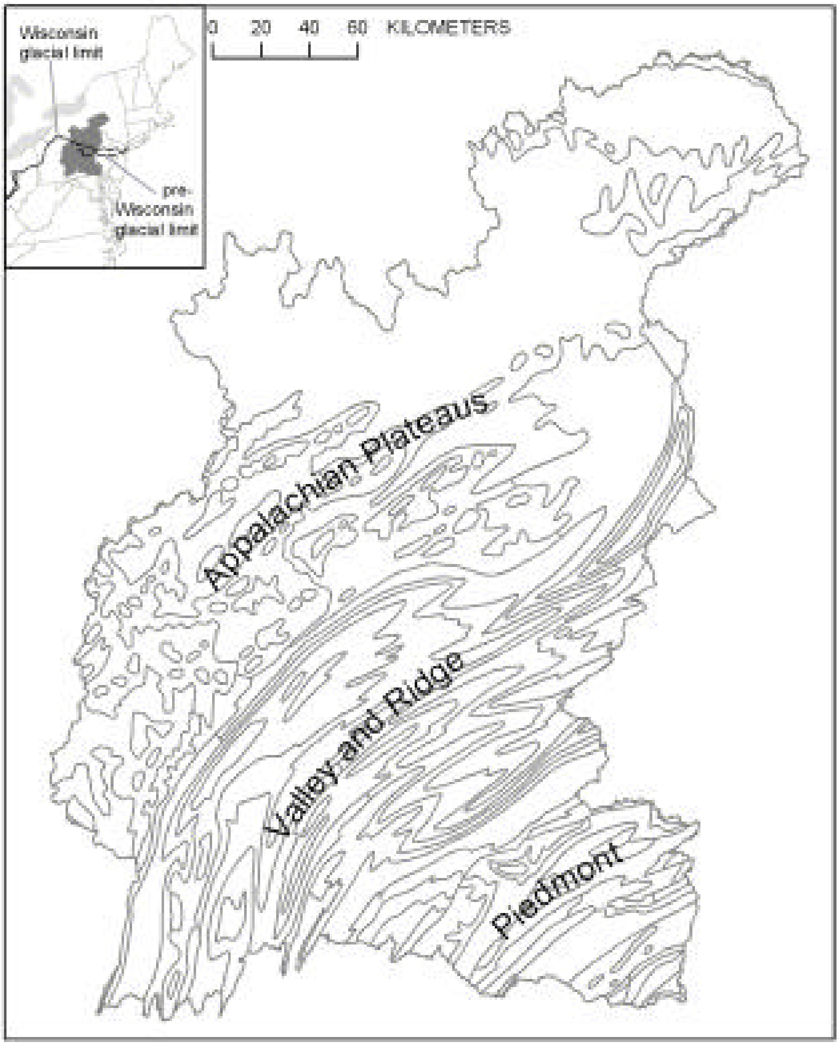
EXPLANATION

NS: North Slope, Alaska
DC: Drift Creek, OR (Bierman et al., 2001)
SQ: Susquehanna River
GS: Great Smoky Mtns. (Matmon et al., 2003)
YW: Yuma Wash, AZ (Clapp et al., 2002)
RP: Rio Puerco, NM (Clapp et al., 2001; Bierman et al., 2001b)
VZ: Venezuela
BA: Bolivian Andes
NA: Namibia
NY: Nahal Yael, Israel (Clapp et al., 2000)
BH: Bhutan

Figure 1. World map showing distribution of ^{10}Be data sets. I will analyze the data in the context of basin-scale parameters using a GIS approach. Collection and ^{10}Be analysis of Susquehanna samples is also part of this project.

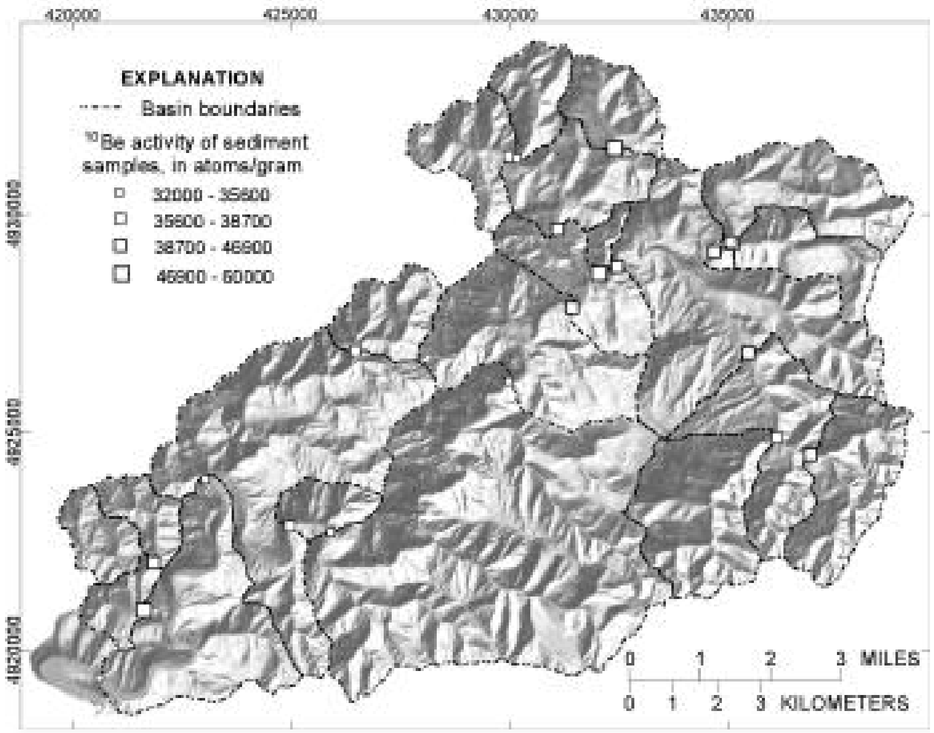
Sediment sample properties			^{10}Be activity
			Interpreted sediment generation rate
			Grain size fraction used in analysis
Basin properties	Digital elevation model (DEM)		Basin area
			Slope
			Curvature
			Aspect
			Relief
		Stream network properties	Network length (by stream order)
			Sinuosity
		Longitudinal profile geometry	Concavity
	Geology		Lithology
			Rock strength
	Physiography		Area of represented physiographic provinces
	Ecoregion		Area of represented ecoregions
	Land use/land cover		Area of land cover types
Region properties	Tectonics		Tectonic setting
	General climate		Rainfall
			Temperature

Table 1. Hierarchy of data types that will be analyzed with a multivariate statistical approach. The basin properties will be derived from GIS layers; the layers that are listed are readily available for U.S. basins. This is not a comprehensive list; other data (such as hydrologic data and sediment yield from USGS gages) will be available for some sample sites. Most data types will be further parameterized (e.g., as averages, indices, or values based on recurrence intervals).



Base from USGS digital data. Albers.

Figure 2. Inset map shows the Susquehanna River basin in gray; lines show southern extent of Wisconsin and pre-Wisconsin glaciation. Geologic contacts highlight the differences between the major physiographic provinces of the Susquehanna basin: the Appalachian Plateaus, the Valley and Ridge, and the Piedmont.

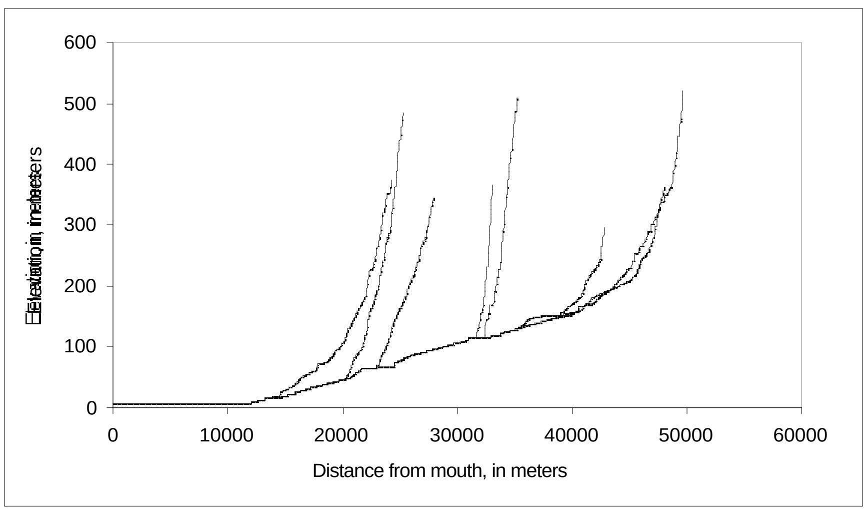


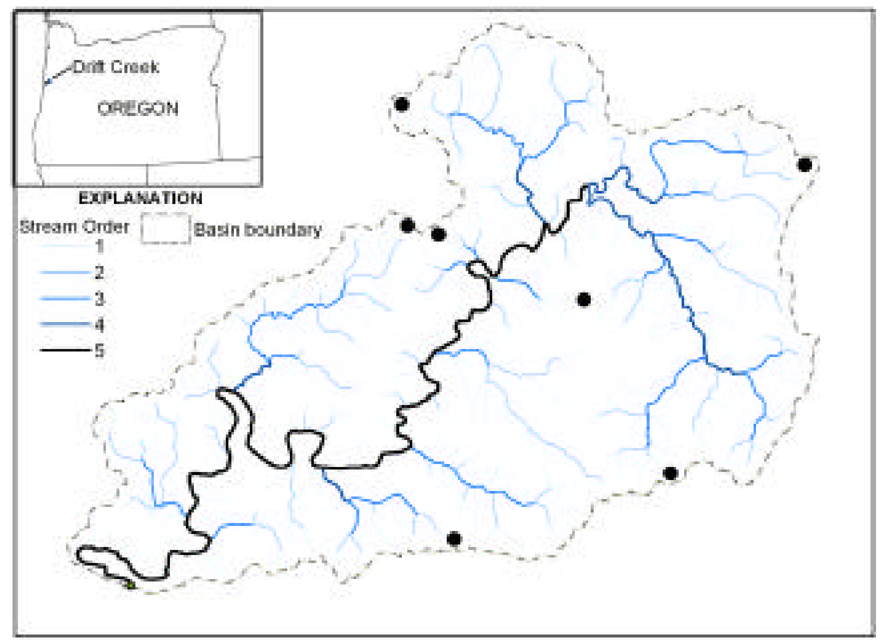
Base from USGS digital data. UTM Zone 10.

Figure 3. [left] Shaded relief map of the Drift Creek basin, Oregon Coast Range. ^{10}Be data demonstrate the nested-basin sampling approach. These data, collected by Bierman and others, have undergone cursory data analysis (Bierman et al., 2001a), but have not been rigorously analyzed in the context of basin characteristics. I will explore these data in more detail using GIS and multivariate statistical techniques.

Figure 4. [below left] Longitudinal profiles of Drift Creek tributaries. Black dots in fig. 5 represent the source of each profile.

Figure 5. [below] Drainage network for Drift Creek derived from merged 10 meter DEMs with the TauDEM ArcGIS extension, which allows for more sophisticated delineation of the drainage net relative to standard ArcView grid functions (Tarboton and Ames, 2001). Black dots are the source locations for the longitudinal profiles shown in fig. 4.





Base from USGS digital data. UTM Zone 10.