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

A Thesis Progress Report Presented

by

Joanna M. Reuter

to

The Faculty of the Geology Department

of

The University of Vermont

November 14, 2003

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

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

______________________________ Advisor
Paul Bierman

____

____

____

Date Accepted: ____________________________

OVERVIEW

The core of my progress report is a field guide section that I prepared for the Southeast Friends of the Pleistocene trip, which was held October 17-19, 2003. During this trip, I made a 20 minute presentation about my work to a group of more than one hundred people perched on a bedrock terrace above the lower Susquehanna River. My progress report presentation will utilize the posters that I prepared for the trip.

The field guide includes background on the Susquehanna portion of my work, preliminary results, and discussion. For my progress report, I am providing an addendum which provides more details on my summer work, remaining work, and a timeline.

Long-term sediment-generation rates derived from ^{10}Be in river sediment of the Susquehanna River basin

Joanna M Reuter[1], Paul R. Bierman[1], Milan J. Pavich[2], Allen C. Gellis[2], Jennifer Larsen[1], and Robert C. Finkel[3]

[1] University of Vermont, [2] USGS, [3] Lawrence Livermore National Laboratory

Overview

We are using cosmogenic ^{10}Be measurements of quartz extracted from sediments of the Susquehanna River basin to address geomorphic questions of where and how quickly Earth's surface erodes. We seek to determine if long-term (10^4-10^5 year) rates of sediment generation, as inferred from cosmogenic ^{10}Be, correlate with GIS-measurable components of the present-day landscape, such as topography, relief, and precipitation. Such correlations, or a lack thereof, will provide insight into the tempo and pattern of landscape erosion and change.

Though we currently have results for only a small subset of the collected samples, the ^{10}Be-based sediment-generation rates (10-20 meters per million years) agree broadly with other erosion rate estimates for the Susquehanna basin.

Basin-scale sediment-generation rates from in-situ-produced ^{10}Be

The continual bombardment of Earth's surface by cosmic rays results in the production and accumulation of cosmogenic nuclides in near-surface materials. One such nuclide, ^{10}Be, is often measured in purified quartz (Lal and Peters, 1967). In an eroding landscape, quartz grains accumulate ^{10}Be as they approach the surface (Lal, 1991). When such grains enter a river system, they carry isotopic concentrations that record their near-surface exposure histories (Bierman et al., 2001; 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 integrated 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. Measurement of ^{10}Be in sediment provides sediment generation rates on a 10^3-10^6 year time scale, depending on the erosion rate and the associated sediment residence time in the basin.

Susquehanna River and sampled basins

The Susquehanna River drains >70,000 km^2 of the North American passive margin (Figure 1). The basin spans three major physiographic provinces: the Appalachian Plateaus, Valley and Ridge, and Piedmont. We sampled two groups of drainage basins. The first 26 samples were collected from USGS gage sites representing basins that range in size from 15 km^2 to 62,400 km^2 (Figure 1 and Figure 2). These gages have sediment yield records with which we can compare the ^{10}Be-estimated sediment-generation rates. The ^{10}Be data are relatively insensitive to land use impacts (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996), while the sediment yields may be affected by post-settlement land use (Trimble, 1977). The USGS gage samples are spread among each of the physiographic provinces, and most basins incorporate more than one lithology. Seven of these samples are north of the Late Pleistocene glacial margin, and an additional three sites, located on the mainstem Susquehanna and its major branches, are associated with basins that were partially glaciated. We currently have ^{10}Be activities for 15 of the samples from USGS gage sites, including 12 unglaciated basins and the three partially glaciated basins.

The second sample group consists of sixty small (3-10 km^2) basins. The small basins are unglaciated, span a range of mean basin slopes, and are scattered among the major physiographic provinces; each basin is mapped as a single lithology (Figure 1). Results from these basins will be used to assess relationships between basin-scale characteristics and sediment generation rates. Furthermore, data from these small, simple basins will aid in the interpretation of the larger, more complex USGS gage basins, where factors including multiple lithologies, glaciation, and mining must be considered.

Although we do not yet have ^{10}Be data for these small basin samples, observations of channel morphology provide insight about landscape behavior. At sizes between 3-10 km^2, the basins have well developed stream channels, most of which carried moderate flow during our sample collection visits in the relatively wet summer of 2003 (Figure 3). Of the basins we visited, few had exposed bedrock in the channel or lower valley walls near the sampling sites; the streams meander on a veneer of alluvium. A notable exception occurs in the vicinity of the Holtwood Gorge on the lower Susquehanna River. Tributaries entering directly into Holtwood Gorge have substantial exposed bedrock in their downstream reaches. Although the October 2003 SEFOP group will not have time to visit any of these streams, they are easily accessed by foot trails, and they are worth visiting independently. The waterfalls and local bedrock valley walls make these tributaries to Holtwood Gorge some of the most scenic small streams south of the glacial margin in the Susquehanna basin. It remains to be seen whether these basins are eroding more rapidly than more alluviated basins in the ^{10}Be data set.

The first 15 data points

The sediment-generation rate results presented here are preliminary; they were calculated using ^{10}Be production rates based on basin hypsometry under the assumption of equal quartz contribution from all parts of the basin. Fine tuning of this calculation will take place when data for the small basins are available, but the results presented here are a reasonable first estimate.

Table 1.

USGS Gage	Station ID	Basin area (km^2)	^{10}Be sediment generation rate (m/My)	Erosion rate inferred from sediment yield (m/My)	Percent of basin glaciated
Bald Eagle Creek below Spring Creek at Milesburg	1547200	686	16 ± 4	12	0
Bixler Run near Loysville	1567500	39	8 ± 2	9	0
Conestoga River at Conestoga	1576754	1217	18 ± 2	24	0
Cordorus Creek near York	1575500	575	14 ± 3	46	0
Dunning Creek at Belden	1560000	445	9 ± 1	8	0
Little Conestoga Creek near Churchtown	1576085	15	10 ± 1	400	0
Mill Creek at Eshelman Mill Road near Lyndon	1576540	140	11 ± 1	17	0
Raystown Branch Juniata River at Saxton	1562000	1958	9 ± 1	12	0
Sherman Creek at Shermans Dale	1568000	536	11 ± 2	12	0
Susquehanna River at Danville	1540500	29060	18 ± 2	19	93
Susquehanna River at Harrisburg	1570500	62419	34 ± 7	15	49
Swatara Creek at Harper Tavern	1573000	873	14 ± 2	30	0
West Branch Susquehanna River at Bower	1541000	816	19 ± 4	16	0
West Branch Susquehanna River at Lewisburg	1553500	17734	29 ± 4	16	17
Yellow Breeches Creek near Camp Hill	1571500	559	19 ± 4	18	0

The sediment generation rates calculated from ^{10}Be activities measured in unglaciated basin fluvial sediment range from 9 to 20 meters per million years (Figure 4 and Table 1). These results agree broadly with estimates of the erosion of the Susquehanna obtained using other methods including suspended sediment yield, saprolite production rates, thermochronologic data, and incision rates (see Pazzaglia, this volume).

In general, ^{10}Be-based erosion estimates and the sediment yield data for the same basins are correlated well, implying broadly consistent rates of sediment yield on decadal time scales and erosion on millennial timescales. However, two groups of basins deviate from the trend. (1) Basins influenced by continental glaciation have relatively low nuclide activities (or high calculated ^{10}Be sediment-generation rates). A lower nuclide concentration in sediment from glaciated basins is consistent with shielding by glacial ice and removal of the most highly irradiated portion of the soil and rock profile by glacial erosion. (2) Several of the basins in the southern part of the Susquehanna have ^{10}Be-inferred sediment generation rates in the 10-20 m/My range, but sediment yields that are much higher. While the basins with high sediment yields do have high percentages of agricultural land, not all of the basins with comparable percentages of agricultural land use have such high sediment yields.

The correlations explored thus far between ^{10}Be sediment-generation rates and basin characteristics are very weak. For example, ^{10}Be sediment-generation rates from the unglaciated basins appear to be uncorrelated to mean basin slope (Figure 5). The small size of the present data set limits our ability to apply multivariate statistical techniques, which will be used when the full data set is available.

References Cited

Bierman, P., Clapp, E., Nichols, K., Gillespie, A., and Caffee, M.W., 2001, Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport: New York, NY.

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

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

Granger, D.E., Kirchner, J.W., and Finkel, R., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments: Journal of Geology, v. 104, p. 249-257.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424-439.

Lal, D., and Peters, B., 1967, Cosmic ray produced radioactivity on the earth, *in* Sitte, K., ed., Handbuch der Physik: New York, Springer-Verlag, p. 551-612.

Trimble, S.W., 1977, The fallacy of stream equilibrium in contemporary denudation studies: American Journal of Science, v. 277, p. 876-887.

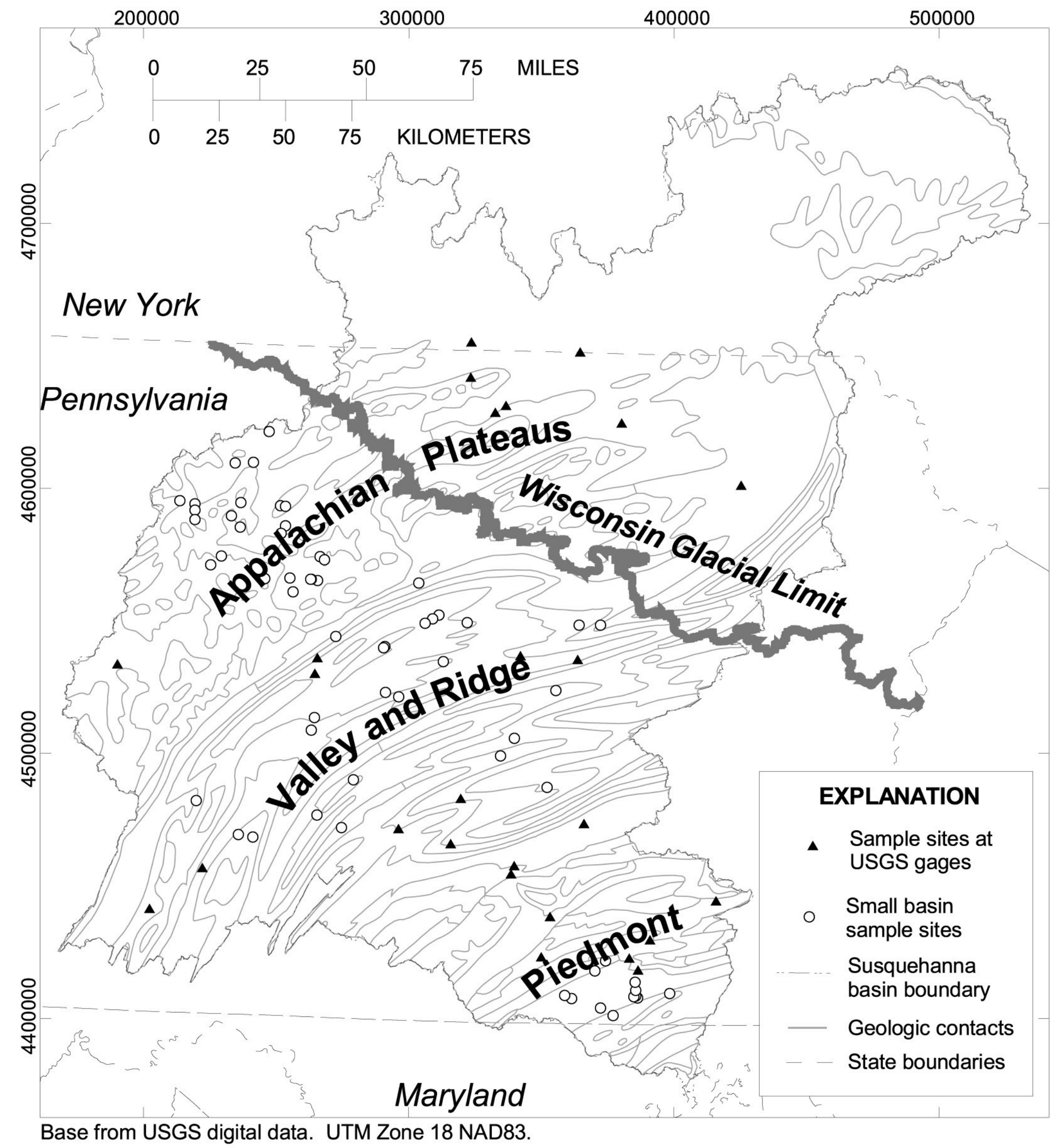

Figure 1. Map of the Susquehanna River basin. Geologic contacts (shown within the Susquehanna basin boundary) help to distinguish the major physiographic provinces: relatively flat-lying sedimentary rocks of the Appalachian Plateaus; folded sandstone, shale, and carbonate of the Valley and Ridge; and metamorphic, igneous, and sedimentary rocks of the Piedmont. Coordinates are UTM Zone 18.

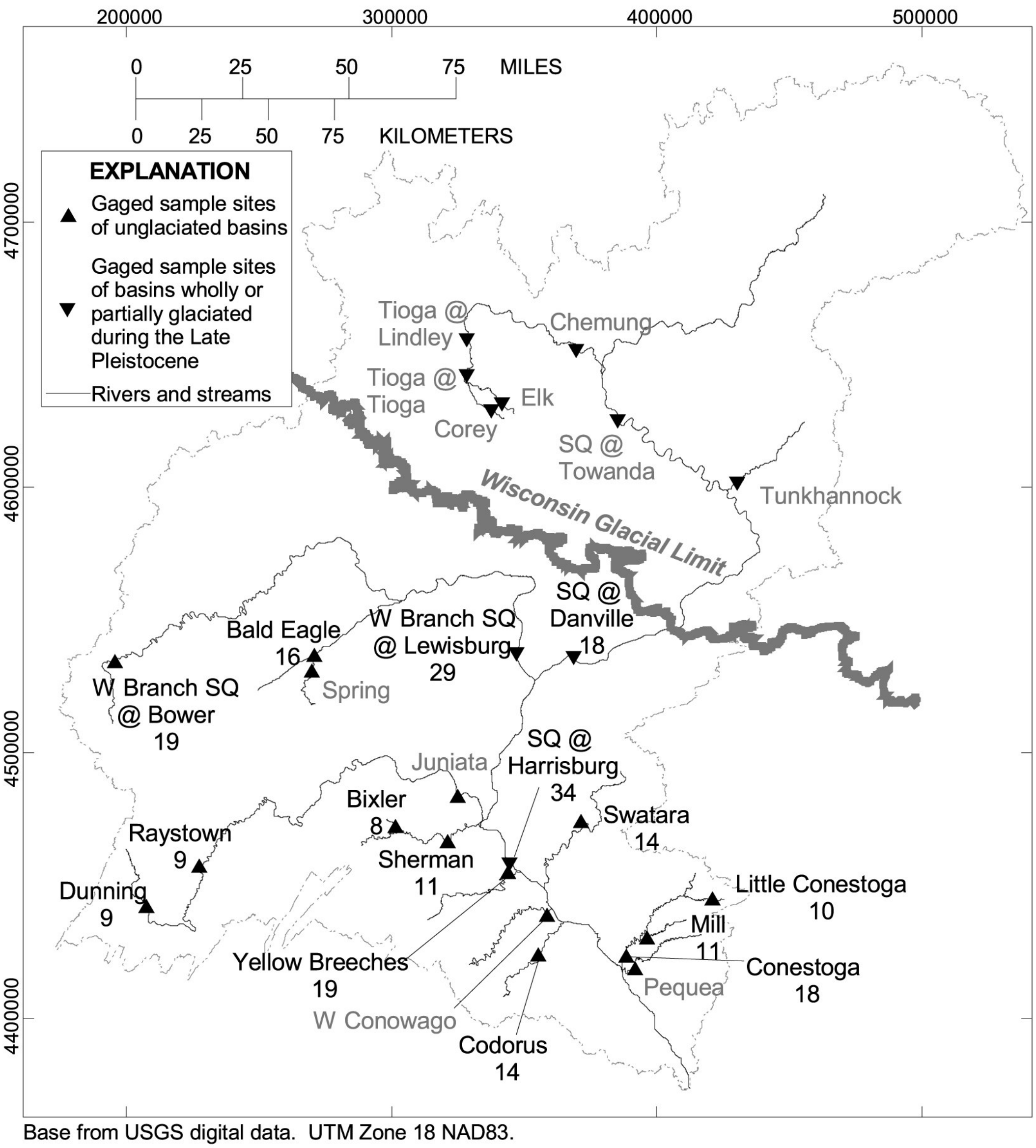

Figure 2. Map of the Susquehanna River basin showing USGS gages that were sampled. ^{10}Be sediment generation rates, in meters per million years, are shown where data are currently available. Susquehanna abbreviated as SQ.

Figure 3. Photo of the sample site for a 5 km^2 Piedmont basin, tributary to Tucquan Creek. Person on the right side of the photo is sieving sediment from the stream channel to obtain an appropriate grain size for analysis.

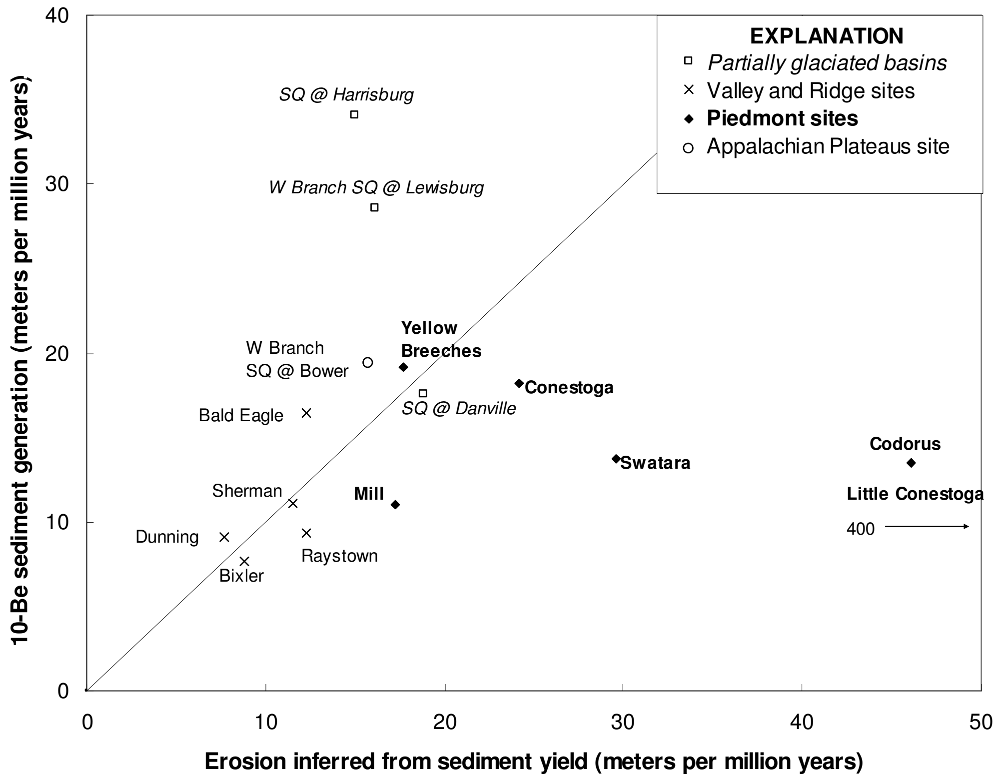

Figure 4. Scatter plot showing relation of sediment yield to ^{10}Be sediment generation rate, both expressed in meters per million years. Basins labeled in italics were partially glaciated during the Late Pleistocene. Basins labeled in bold are located at least partly in the Piedmont Province of the lower Susquehanna basin. Sediment yields were calculated by Allen Gellis and Milan Pavich (USGS).

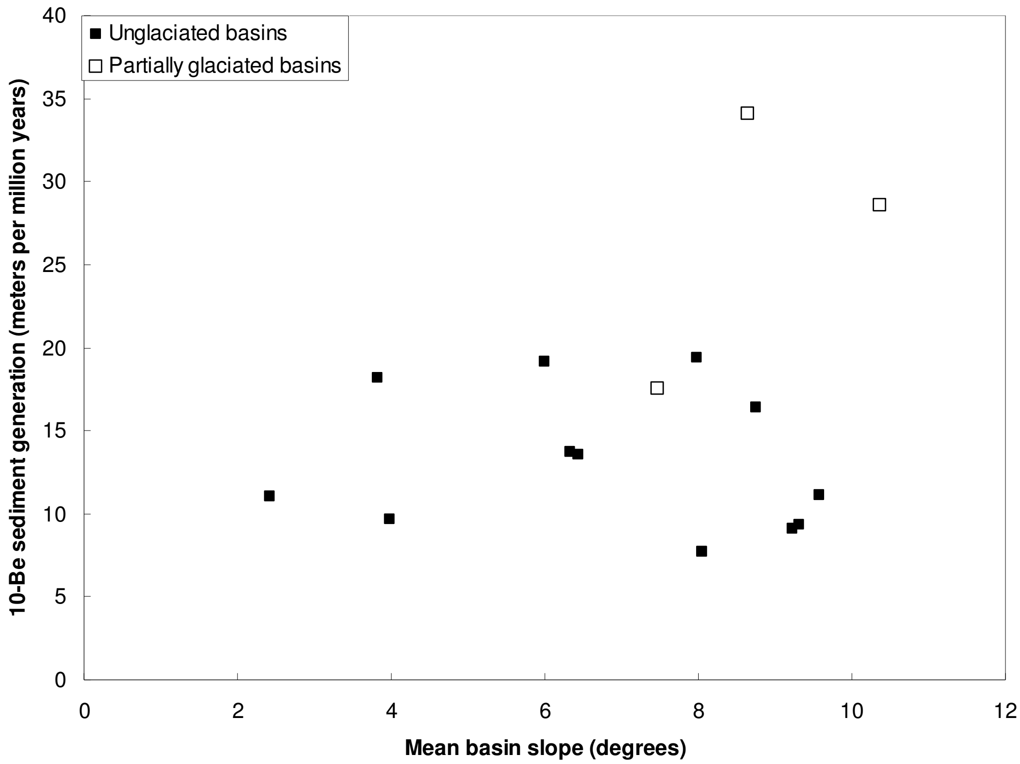

Figure 5. Based on the available data set, mean basin slope and ^{10}Be sediment generation rates for unglaciated basins appear to be uncorrelated.

SAMPLING THE SUSQUEHANNA BASIN

The most substantial progress since my proposal presentation has been in the selection of sampling sites within the Susquehanna basin, the collection of samples, and the preparation of quartz from these samples for ^{10}Be measurement.

Justification of Sampling Strategy

When selecting new sample sites to complement the existing samples from USGS gages, the following goals were important:

- To sample basins that can be used to assess the nature of the relationship between basin characteristics and sediment-generation rates.
- To sample basins for which relatively straightforward interpretations of sediment-generation rate can be made based on ^{10}Be. These basins can then be used to assist with the interpretation of the larger, more complex USGS gage basins.

The new sample basins are all south of the glacial margin, are spread among the three dominant physiographic provinces, are each mapped as a single lithology, and represent a range of mean basin slopes. These basins are dominantly in the 3-10 km^2 size range, which is a size that I selected for a number of reasons after considering a broad range of basin scales through GIS analysis. These reasons include:

- Basins of this size have well developed streams that serve to mix sediment from the basin. (Carbonate basins are an exception, but these were not sampled due to a lack of both quartz and a sizable stream channel where visited.)
- Numerous basins in this size range are mapped as a single lithology. Basins of a single lithology (in which the quartz distribution is assumed to be uniform throughout the basin) are more straightforward to interpret in terms of sediment generation rates than mixed-lithology basins.
- As basin size increases, the range of basin mean slope decreases (Figure A1). By working with relatively small basins, I was able to sample basins with mean slopes spanning a range of approximately 20º. This range is 2-3 times the range of mean slopes of sample basins from the Rio Puerco (New Mexico), Drift Creek (Oregon Coast Range), or the Great Smoky Mountains (North Carolina and Tennessee). This broad range should

assist in the identification of relationships between basin characteristics and sediment generation rates.

- The selection of all of the basins from a single limited size range means that I will have an adequate number of observations for multivariate statistics. Another statistical advantage is that most small basins are not nested and should therefore be statistically independent.

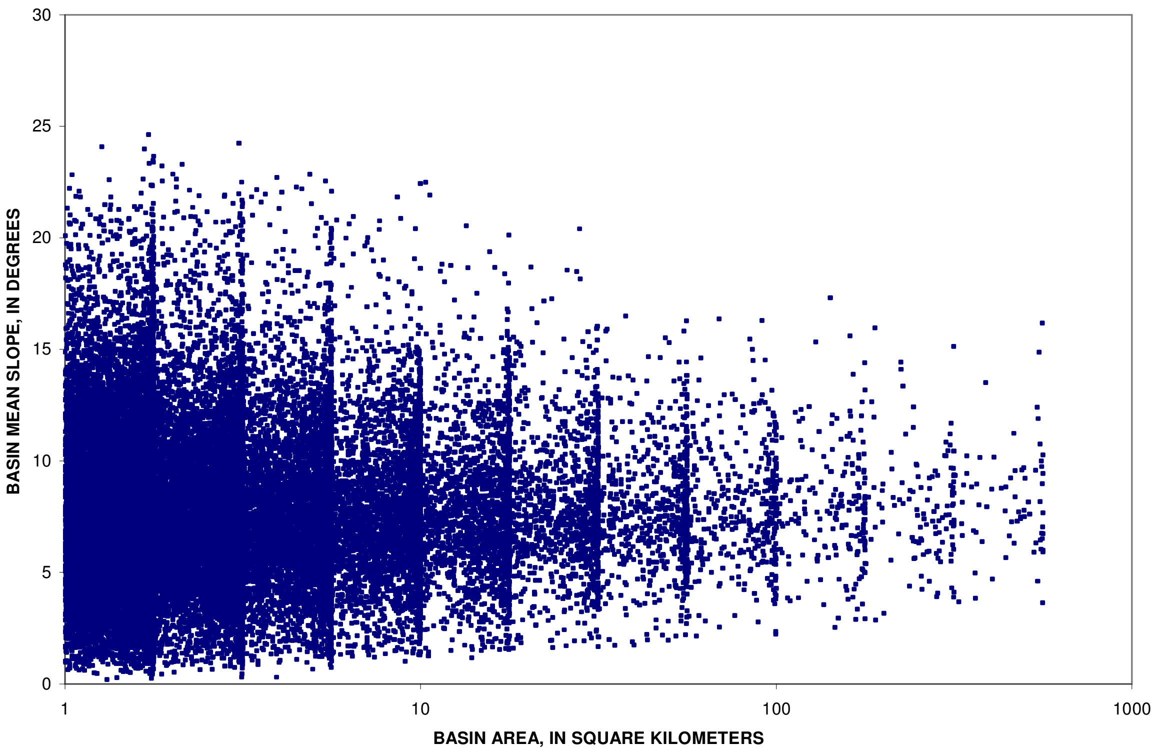

Figure A1. Each point represents a sub-basin of the Susquehanna River. As basin area increases, the range of mean slope decreases. Working with small basins allows for the selection of a broader range of characteristics than working with large basins. The vertical lines are artifacts of the basin size ranges that I specified when delineating basins.

Final basin selection involved visual examination of the 1:24,000 digital topographic maps so that undesirable features such as strip mines, dams, and excessive development could be avoided. Furthermore, I selected basins which appeared to have good chance of access; in particular, sites were mostly on public land and/or near a road crossing.

In selecting basins with a range of slopes, I focused primarily on basins with relatively uniform slope distributions (using the standard deviation of basin slope as an indicator). In addition, however, I selected a few basins with highly variable slopes. For a few of these basins, I took two samples: one in the low slope, upland portion of the basin and one in the steep, lowland portion of the basin.

In the Piedmont, I selected some basins that are direct tributaries of the mainstem Susquehanna near Holtwood Gorge and some that are more distant from the mainstem Susquehanna. As mentioned in the SEFOP guide, the direct tributaries to Holtwood are morphologically distinct from streams in the rest of the basins. In the downstream reaches of the Holtwood tributaries, extensive bedrock is exposed in the channel and waterfalls are common. Farther upstream, however, the streams more closely resemble "typical" Susquehanna streams, with a gentler gradient and alluvium in the stream valley. For one of these Holtwood tributary basins, I have two samples: one upstream of the high gradient reach, and farther downstream that incorporates the high gradient part of the basin.

Two Weeks of Sample Collection

With Eric Butler as field assistant, I spent approximately two weeks collecting samples in Pennsylvania from the basins that I had selected using GIS. At each site, we acquired a sample of sediment from the active channel. When water was available (as it was in most streams during this wet summer), we sieved the samples in the field to include the 250-850 micron size fraction. Depending on the quartz content of the sediment, we collected one or two gallon bags of sediment from each basin.

In addition to the sediment samples, we collected four upland bedrock samples where opportunities arose. Three of these samples are from a cluster of tors in the Appalachian Plateaus, and one is from a bedrock outcrop in the Valley and Ridge. These will provide minimum rates of erosion to compare to the sediment-derived rates.

Two Months of Cleaning Dirt

The process of extracting clean quartz from the raw sediment samples has occupied the bulk of my time since returning from the field in late August. With the help of Megan McGee, I have already cleaned quartz from almost all samples we collected. Standard procedures (http://geology.uvm.edu/morphwww/cosmo/lab/whatwedo.html) were modified slightly for these sediment samples. For each sample, the process involved (at a minimum) drying the samples, sieving them, wet sieving them, etching in hydrochloric acid (two eight-hour etches), etching in 1% hydrofluoric and nitric acid for 8, 14, and 24 hours, performing density separations with LST (a heavy liquid) to sink heavy minerals and float coal, and etching in hydrofluoric and nitric acid for 48 hours. The wet sieving step involves washing the 250-500 micron fraction in a 250 micron sieve; I added this step help to break up aggregates of grains that remained together during dry sieving. I am working exclusively with the 250-500 micron fraction for sediment samples largely because this size fraction is the most consistently abundant grain size available in my samples.

Samples are currently being processed by Jennifer Larsen in the next phase of the procedure: the isolation of beryllium and aluminum. As my quartz-cleaning work finishes, I will have more time to observe and participate in this process.

In February, I will travel to Lawrence Livermore National Laboratory to measure the ^{10}Be using the Accelerator Mass Spectrometer.

REMAINING WORK

Compilation and Analysis of Other ^{10}Be Data Sets

In the time after I finish quartz cleaning and before I have the full Susquehanna data set, I will focus my efforts on the compilation and analysis of other worldwide datasets, as discussed in my proposal. I began this work during the summer with the Rio Puerco, New Mexico, and Oregon Coast Range data, but I will refrain from presenting results until I have made additional progress.

Interpretation of ^{10}Be Results in Terms of Sediment Generation Rates

After ^{10}Be activities have been measured, the results are interpreted in terms of sediment generation rates. The results presented in the SEFOP guide for the USGS basins used a production rate weighted for altitude, but they assumed a uniform quartz distribution throughout the basins. However, most of these basins have more than one lithology. I will work to refine these sediment generation rate calculations through the pixel-by-pixel determination of production rate and the incorporation of lithologic data to estimate quartz contribution to the sample. If data from the small basins with two samples indicate that basins are eroding non-uniformly, then a model that involves weighting sediment contribution based on a hypothesized distribution of erosion rate within the basin may be used to constrain the range of erosion scenarios that are consistent with the data.

Basin Characteristics and Sediment Generation Rates

Using multiple regression and path analysis, I will assess the relationships between basin characteristics and sediment generation rates for the Susquehanna basins. The existence of significant relationships would allow for the estimation of sediment generation rates across the Susquehanna basin. Such estimates would need to be applied on a scale that is comparable to the scale of the sample basins, due to the effects of scale demonstrated in Figure A1. Several options for parsing the landscape into such units may be explored, including the use of moving windows of pixels or actual drainage basins. Estimates based on the small basin data could then be compared to the actual ^{10}Be results from the generally larger USGS basins. The extent to which this analysis can be taken may be limited by the strength of the correlations as well as by the nature of the sample basins. For example, the sample basins do not represent all elements of the landscape. However, the results of these analyses should help to assess whether it is possible to predict spatial pattern of erosion based on easily obtainable GIS characteristics of the present day landscape.

TIMELINE

Summary of work completed since proposal:

- Compiled Rio Puerco data and began analysis. Initial results were incorporated into a poster prepared and presented by Milan Pavich at INQUA.
- Developed Susquehanna sampling strategy based on GIS analysis.
- Collected 66 new samples from the Susquehanna River basin.
- Purified quartz from all remaining samples.
- Traveled with Paul to Drift Creek in the Oregon Coast Range to revisit sample sites and to meet with Tom Dunne, Liz Safran, and Rolf Aalto regarding ^{10}Be datasets.
- Presented for the Southeast Friends of the Pleistocene field trip.

Pre-Livermore trip work (November 2003 through January 2004)

- Present progress report.
- Update web page to include Susquehanna sample basins.
- Continue GIS analysis, extending analysis to worldwide basins.
- Complete path analysis for a subset of U.S. ^{10}Be sediment data for Geostatistics class.
- Submit abstracts for upcoming meetings.

Spring 2004

- Travel to Lawrence Livermore National Laboratory (early February) to measure ^{10}Be for all samples.
- Complete coursework requirements with the surface process seminar.
- Analyze new Susquehanna data.
- Begin writing thesis.
- Present at NE/SE GSA in March.
- Present at AGU in Montreal in May.

Summer 2004

- Finish writing thesis (target completion date: August 1).
- Defend thesis shortly after classes begin.