Using ^{10}Be To Constrain The Spatial and Temporal Pattern of Bedrock Channel Incision

A Progress Report

by

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to

The Faculty of the Geology Department

of

The University of Vermont

May, 2003

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 before it was circulated to the faculty:

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Paul R. Bierman

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Date Accepted:__________________________

1.0 Abstract

^{10}Be analysis of 41 samples collected from a flight of fluvially carved bedrock terraces along the Susquehanna River in southeastern Pennsylvania indicate that the river has episodically incised nearly 20 meters during the middle to late Pleistocene. The majority of these samples are from the lowest two terrace levels, and indicate that these two surfaces have model ages corresponding to the Late Wisconsinan glacial period in Pennsylvania. Results from regression modeling, analysis of model age variance between samples collected 10-15 meters apart, and field observations suggest that the lowest strath terrace (mean model age = ~14 ky) was cut/formed rapidly, possibly by post glacial outburst floods following the Last Glacial Maximum. In contrast, the range of model ages along the level 2 strath, regression analysis of model age vs. distance downstream, and small-scale sample replication support a model of knickpoint propagation through the gorge during Wisconsinan advance and deglaciation. Nuclide activity and model ages for two samples collected at higher elevations in the gorge are in sequence (highest sample = oldest; lowest sample = youngest) confirming the assumption that bedrock surfaces higher in the gorge have experienced a longer period of exposure.

During this upcoming summer, I will conduct one final field session to recheck all sample sites and finish any remaining work in the gorge. I plan to work with several researchers in constructing models capable of estimating fluctuation in discharge and sediment load, as well as isostatic rebound during the middle to late Pleistocene, in order to better constrain the spatial and temporal roles of these agents in the erosion of Holtwood Gorge.

2.0 Introduction:

The spatial and temporal pattern by which large rivers around the globe erode through bedrock is poorly constrained (e.g.,Tinkler and Wohl, 1998), a problem for geomorphologists who wish to understand the timing and rate of bedrock fluvial incision. Quantitatively understanding fluvial incision is important because it reflects the interaction between climate, solid Earth-, and surface-processes (Bull, 1990; Engel et al., 1996; Pazzaglia and Gardner, 1994). The measurement of cosmogenic nuclides, produced in situ, now allows for the dating of bedrock erosional surfaces, such as fluvially sculpted strath terraces (Lal, 1991; Lal and Peters, 1967). I am using ^{10}Be to decipher the spatial and temporal pattern by which the largest river draining the East coast of North America, the Susquehanna, erodes through rock (Figure 1). The striking flights of bedrock terraces preserved within Holtwood gorge (Thompson and Sevon, 2001) along this passive margin river offer a unique opportunity to investigate quantitatively the history of fluvially sculpted surfaces, prerequisite to understanding when, how, and why rivers incise hundreds of meters through rock.

3.0 Primary Objectives and Overarching Questions:

My goal is to determine whether measured nuclide activities along and between the three well-defined Susquehanna River strath terraces are consistent with my extensive field mapping and accepted explanations for the genesis of river terraces (e.g., Bull, 1990). Specifically, does nuclide activity increase with elevation above the modern river? Does nuclide activity increase downstream along a single terrace, the expected result of knickpoint retreat? Do spatial replicates yield similar results? My study uses cosmogenic nuclide analysis and interpretive modeling of >80 samples collected from within the Susquehanna River basin in order to:

- quantify the nuclide activity and model the exposure age of at least three levels of river terraces within the lower reaches of the Susquehanna River,
- calculate both the vertical and longitudinal rate at which the Susquehanna River incised bedrock during the carving of Holtwood Gorge,
- determine whether this incision can be correlated to otherwise documented changes in climate and resulting effects, as well as glacial isostasy throughout the Pleistocene,
- refine this new application of cosmogenic nuclides by investigating the spatial pattern of nuclide activity at various scales on bedrock fluvial landforms in order to understand better the dynamics of erosion and exposure in passive margin, bedrock river systems.

4.0 Significance of Research

Bedrock channel systems are of critical importance to the understanding of landscape evolution in that they are the communicators of boundary conditions, such as fluctuations in base level and/or land level, climate change, and tectonics across landscapes (Whipple et al., 2000). Lithologic and hydrologic characteristics of these bedrock systems govern the response time to such external changes throughout a drainage network and raise numerous questions regarding active erosional processes, timing and rates of incision, and ultimately, what combination of conditions compel rivers to incise through bedrock.

Most studies of bedrock channel processes have focused on rivers in active tectonic settings where modern land uplift is accompanied by rapid rates of river incision (e.g., Burbank et al., 1996). In contrast, little work considers river incision into bedrock on a passive margin. In order to address this lack of knowledge and understanding, my study focuses on the Susquehanna River which drains the central Appalachian Mountains. Many rivers draining the North American passive margin (the Susquehanna, Potomac, Rappahannock and James) have incised deep into bedrock as they cross the fall zone, separating the Appalachian Piedmont from the coastal plain (Pazzaglia et al., 1998). Gorges carved into the lower reaches of these rivers typically display spectacular flights of bedrock terraces which, if dated, provide an opportunity to address some of the overarching questions regarding the timing, rate, and ultimate cause of bedrock fluvial incision.

In order to accomplish this task, I will employ a new dating technique capable of estimating the duration of time a bedrock terrace has been exposed at Earth's surface since fluvial erosion ceased. Cosmogenic exposure age dating utilizes rare isotopes produced and accumulated within exposed rocks and sediment by the continual cosmic ray bombardment of Earth's surface (Lal and Peters, 1967). Technological advances in accelerator mass spectrometry (AMS) over the past decade allow me to measure nuclide abundance of ^{10}Be and ^{26}Al and calculate model exposure ages of bedrock samples collected from strath terraces preserved within Holtwood Gorge along the Susquehanna River. Only three studies using cosmogenic nuclides have been conducted on bedrock terraces, all in the tectonically active Himalayas (Burbank et al., 1996; Leland et al., 1994; Leland et al., 1998). This study is the first to date bedrock fluvial terraces on a passive margin. With a sample population greater than all of its predecessors combined, and a carefully designed sampling strategy, my study tests many assumptions regarding exposure age variance on and between fluvially sculpted bedrock landforms.

5.0 Work Done So Far:

5.1 *Field Work:* Working with Eric Butler as my field assistant, I have conducted three separate field sessions at the Holtwood Gorge site over the past 12 months. I have extensively explored and mapped the gorge with the aid of aerial photographs and high-accuracy GPS data. Using a hammer and chisel, I have collected 71 bedrock samples from fluvially sculpted strath terraces (as well as 2 samples from boulders) within and above the Susquehanna River. I employed a nested sampling strategy in order to investigate nuclide variance at small (10-15 m), medium (cross-stream), and large (downstream) spatial scales (Figure 2).

5.2 *Map and Laboratory Work:* I have analyzed and graphically represented the spatial distribution of sample sites within Holtwood Gorge. I have purified quartz (Kohl and Nishiizumi, 1992), and Jennifer Larsen has isolated ^{10}Be and ^{26}Al from all of my sample collected to date in the cosmogenic laboratory at UVM. Working with Paul Bierman, I measured ^{10}Be nuclide activities in a preliminary batch of 41 samples in January of 2003 at the Lawrence Livermore National Laboratory (LLNL), in Livermore California.

5.3 *Data Analysis:* I have reduced all measured nuclide activities to exposure ages using the altitude-latitude scaling function presented in Lal (1991). I have utilized several methods of inferential statistics to investigate the spatial and temporal patterning of erosion recorded within the gorge. Using a two-independent sample t-test, I tested for a significant age difference between samples collected along the level 1 and level 2 terraces. In order to detect the presence of an age gradient along either of these terrace, I utilized regression analysis to test for significant relationships between model age and either distance downstream from Holtwood Dam or height above the modern river bed.

6.0 Preliminary Data and Analysis

Of the initial batch of 41 samples, all but one of the samples are from bedrock strath terraces within Holtwood Gorge along the lower reaches of the Susquehanna River. Eleven samples are from the level 1 strath (lowest), twenty five samples are from the level 2 strath, two samples are intermediates (collected along a continuous rounded surface separating the two levels in the middle gorge), one sample is from the level 3 strath, and one sample is from a heavily weathered and eroded high point (level 4; highest) along the western shore in the middle gorge (Figures 3 & 4, Table 1).

6.1 *Spatial Pattern of Erosion:*

Exposure age correlated with height above river: As predicted, nuclide activities and model exposure ages increase with elevation above the modern river bed (Figure 5 & Table 1). The lowest strath, level 1, yields a mean exposure age of 14.0 +/- 1.3 ky (1 σ;

n=11), while the level 2 strath yields a mean exposure age of 19.2 +/- 3.1 ky (1 σ; n=25). Results from a two-independent sample t-test verify that model exposure ages for levels 1 and 2 are statistically distinguishable ($t=-5.93$, $p<0.0005$). Single samples from the level 3 and 4 (highest) strath levels yield mean exposure ages of 31.1 +/- 0.81 and 79.1 +/- 2.07 ky respectively, indicating that these bedrock surfaces at higher elevations have indeed experienced longer periods of exposure within the gorge.

Small Scale Replication: Measured activities and modeled exposure ages for spatially replicated samples (clusters of three separated by no more than 10 to 15 meters) on both the level 1 and level 2 straths are in tight agreement; level 1 cluster: 13.5, 13.6, 15.9 ky (1 σ = 1.36 ky, 10% of mean); level 2 cluster: 17.0, 17.8, 17.9 ky (1 σ = 0.47 ky, 2.7% of mean). Although the +/- 10% variance associated with the level 1 cluster is low, it is approximately three times what one would expect from AMS instrument error alone (+/- ~3.5%), and suggests real variability in ^{10}Be activity. In contrast, the +/- 2.7% variability associated with the level 2 cluster is consistent with instrument error, suggesting that the three samples have indistinguishable ^{10}Be activities and model exposure ages. The results of this spatial test, especially for the level 2 cluster, support the assumption that a single sample represents the exposure history of a fluvially sculpted bedrock surface at the scale of meters to tens of meters. This is an important and previously untested assumption upon which the interpretation of the erosional histories of bedrock channels has been based.

Laboratory Replication: In order to ensure consistency and reproducibility of laboratory techniques, we measured two independently processed laboratory replicates. Both replications matched almost perfectly; level 1 replication: (LR-04C) 13.6 +/-0.49 ky & (LR-04CX) 13.8 +/-0.63 ky, 1.6% difference; level 2 replication: (LR-37) 16.9 +/-0.51 ky & (LR-37X) 17.3 +/-0.63 ky, 2.2% difference. In both cases, the relative percent difference (RPD) between sample and replicate is consistent with the expected error of AMS measurement.

Longitudinal Variance: Model exposure ages along the level 1 strath show a different longitudinal pattern than those along the level 2 strath (Figures 3 & 4). Regression analysis indicates that no significant relationship exists between model age and distance downstream from Holtwood Dam ($p=0.543$), or between model age and elevation (p=0.753) or model age and height (p=0.097) along the level 1 strath. Similarly, results from stepwise multiple regression indicates that no significant relationship is detectable between model age and any combination of distance, elevation, and height. Thus, I conclude that no spatial or temporal pattern of erosion can be detected along the level 1 strath from one end of the gorge to the other. Conversely, model ages varied by nearly ten ky over the approximately 5 km spanned by the level 2 strath. This relationship suggests a longitudinal age gradient of approximately 1.46 ky/km ($p<0.0005$, $R^2=0.48$). Bedrock surfaces, on the whole are substantially older at the downstream end of the terrace, and become progressively younger upstream.

6.2 Temporal Pattern of Erosion and Possible Erosional Processes:

Model exposure ages derived from measured nuclide activities of my first samples imply that the strath terraces preserved within Holtwood Gorge are Middle to Late Pleistocene in age. A mean model age of ~14 ky for the level 1 (lowest) strath suggests that this strath terrace was created following the Wisconsinan glacial maximum in Pennsylvania (~20 ky; Braun, 1988). The lack of a significant relationship between model age and distance downstream along the level 1 terrace is consistent with several important geomorphic observations. Most bedrock surface within the gorge preserve a fluvially rounded form. In contrast, the level 1 (lowest) strath, while planar at large spatial scales, is quite rough at smaller scales. Abundant bedrock knobs, raised by as much as one meter above the surrounding surface, and the largely unsculpted appearance of the surface as a whole suggest that this terrace is the result of a different erosional mechanism than surfaces higher above the river bed. It appears that this surface is the result of rapid downcutting achieved by block quarrying, the removal of large blocks of rock defined by several prominent joint sets and foliation within the Wissahickon Schist which comprises the gorge. Such erosion may have resulted from elevated stream power associated with extreme discharge events, such as glacial outburst floods (Baker and Kale, 1998; Kochel and Parris, 2000; Kockel and Parris, 2000). The lack of an age gradient along the strath and the 10% variance measured at small scales support the rapid removal of 'dosed' slabs of rock, thus revealing the relatively 'undosed' underlying bedrock which yields a younger model age. This process can explain the occurrence of large model age difference (>3500 yrs) between samples collected adjacent to each other from both the top and base of a bedrock knob (LR-54 and LR-55, Table 1).

In contrast, the range of model ages along the level 2 strath (14.9 ky to 24.3 ky) straddle the last glacial maximum (late Wisconsinan), suggesting that incision at the lower end of the gorge commenced during, or prior to the glacial advance. The data supports a model of steady upstream knickpoint propogation (Zen, 1997a, 1997b) through the gorge during maximum glaciation and ending in the upper gorge during Wisconsinan deglaciation. The model age/distance downstream regression model could reflect the upstream propogation of a knickpoint at a rate of ~1.5 ky/km for ~9 ky from the lower to the upper end of the gorge. Model ages for the level 2 strath correspond to oxygen isotope stage 2 (extremely cold glacial temperatures), and a eustatic sea level low stand approximately 130 meters below present (Figure 5). Level 2 bedrock surfaces, as mentioned earlier, preserve a fluvially rounded and polished form, which could reflect that either a different erosional mechanism, or that they were reworked subsequent to the initial abandonment of the level 2 paleo river level (during the beveling of the level 1 surface perhaps).

A potential problem arises from the difference in longitudinal distance over which I was able to correlate, and in turn sample each the level 1 (~2.5 km) and level 2 (~4.7 km) straths (Figure 2). The level 1 strath is accessible only at times of low discharge, and backup from the Conowingo reservoir inundates the level 2 km downstream from Holtwood Dam. The difference in the longitudinal pattern of age variation between the two levels could reflect the distance over which I was able to sample each. In order to address this problem, I will return to the gorge during late summer of 2003, a period when flows on average are extremely low, and attempt to extend the level 1 transect farther downstream.

The model age (~31 ky) for the level 3 strath is based on a single sample, so I will refrain overinterpretation and say only that it appears to coincide with the cutting/abandonment of a prominent strath terrace within Mather Gorge, along the Potomac River just outside of Washington, DC (Bierman et al., 2002). We have suggested that this major strath terrace reflects the initiation of the late Wisconsinan glaciation (~30-35 ky). Due to the degradation of the bedrock surface, the model age of

~80 ky for the level 4 high point should be viewed as a lower limiting age; the terrace level can be no younger than 80 ky. At this point in time, it is not possible to estimate how much bedrock, and cosmic ray dosing history has been removed from these topographic high points in the gorge.

7.0 Plans for data interpretation and remaining field work:

A number of theories have been proposed, and numerically modeled, in an attempt to explain the genesis of strath terraces, and identify exactly what these bedrock surfaces represent. On a passive margin, rivers can presumably be induced to incise by fluctuations in land level resulting from glacial loading and the forward propogation of a glacial forebulge. As well, land surface rebound during interglacials could force river incision. Conversely, changes in discharge and/or sediment load resulting from climate fluctuations during the Quaternary have been cited as conditions capable of lowering bedrock channels and forming bedrock terraces (Hancock and Anderson, 2002). Much of the remainder of my time at the University of Vermont will be spent working with those individuals who have developed models capable of estimating changes in land level, discharge, and sediment load. Ultimately, I aim to identify the most important agents, as well as their relative contributions, in creating the spatial and temporal pattern of erosion recorded in Holtwood Gorge. Some of my future plans for data analysis are as follows:

Discharge and Sediment Load: Many researches view strath-terrace sequences as records of discontinuous incision throughout the Quaternary. Valley widening, or planation presumably occurs when stream power equals critical power (the stream power necessary to transport enough sediment to maintain grade; Bull, 1990), while vertical incision occurs when stream power exceeds critical power. Changes in discharge (stream power) resulting from climate fluctuations, and/or critical power (sediment load or size; Bull, 1990) disturb this balance and cause rivers to episodically incise. I will attempt to apply a channel-evolution model developed by Hancock and Anderson to explore whether temporal variations in sediment load and discharge can explain the flights of bedrock terraces preserved within Holtwood Gorge (Hancock and Anderson, 2002).

Overlying Water Column: Due to the attenuation of cosmic rays through an overlying column of water before reaching bedrock of the 'active' river level (represented by the strath terraces), exposure ages modeled from nuclide activities are too young; they have 'lost' comic rays, and in turn, exposure time, to the water (Hancock et al., 1998). In order to address this complexity, I will correct the modeled ages by 'adding back' the fraction of nuclide activity lost to the water for a number of average water depths. Because I do not have flow records and stage heights for the entire Late Quaternary, I will base these calculations on flow distributions for the past ~100 years and estimates of the relative magnitudes of discharge levels during glacial and interglacial periods. Initial estimates suggest this correction will be very modest (<10%).

Inferential Statistics: Once I have nuclide activities for all of my samples in hand, I will apply several methods of inferential statistics, such as one-way ANOVA and multiple linear regression analysis, in order to further investigate the spatial and temporal patterning of erosion recorded within Holtwood Gorge.

Remaining Field Work: In May of this year, I will collect a string of samples along a prominent terrace remnant in the middle gorge with the help Jennifer Larsen. During the month of August, Eric Butler will again assist me for one final field session in the gorge. I will recheck all sample locations, construct several cross-sections through the gorge, collect samples from several boulders, and attempt to extend the sample coverage for the level 1 terrace farther downstream.

8.0 Time line

Work Completed To Date:

- Summer 2002: Mapping of Holtwood gorge. Sample collection and preparation.
- Fall 2002: Proposal defense and chemical isolation of ^{26}Al and ^{10}Be at the University of Vermont cosmogenic laboratory with Jen Larsen
- Oct.,2002: Present poster on the Potomac River project at the GSA Annual meeting in Denver, Colorado.
- Nov., 2002: Return to Holtwood Gorge for follow-up sampling and GPS work on sites previously under leaf cover.
- Jan. 2003: Initial Mass Spectrometer measurement of sample nuclide concentrations at the Lawrence Livermore National Laboratory.
- Continue research and background reading.

Spring, 2003:

- Applied for the GSA Quaternary Geology and Geomorphology Division Howard Award.

- Present progress report oral defense.
- Present poster at Graduate Research Day.
- Continue research and data analysis.
- Statistical analysis of first 41 measured samples.

Summer, 2003:

- May, 2003: Potomac sampling trip with Paul, Milan, and Jennifer Larsen.
- June, 2003: Trip to LLNL to measure nuclide abundances in another batch of samples
- July, 2003: Submit GSA annual meeting abstract.
- July or August, 2003: Return to Holtwood Gorge with Eric Butler. Field check all samples collected to date. Collect more samples as needed. Measure several cross sections in various parts of the gorge.
- August, 2003: Sample preparation.
- Begin working with Milan Pavich and Gregory Hancock on numerical modeling of terrace formation.
- Continue with data analysis and begin writing sections of my thesis.
- August, 2003: Possibly take another trip to LLNL.

Fall, 2003:

- TA Geomorphology with Paul Bierman.
- Continue with isostasy and stream power modeling.
- Finish any sample preparation as needed.
- Continue writing thesis.
- Present at GSA annual meeting in Seattle, Washington

Spring, 2004:

- RA supported.
- Continue with data analysis.
- Finish writing thesis.
- Spring, AGU.
- March, 2004: GSA Sectional Meeting, special session and field trip through Potomac River Gorge and Holtwood Gorge.
- April, 2004: Lead Friends of the Pleistocene field trip through the gorge with Dorothy Merritts (Franklin and Marshall college).

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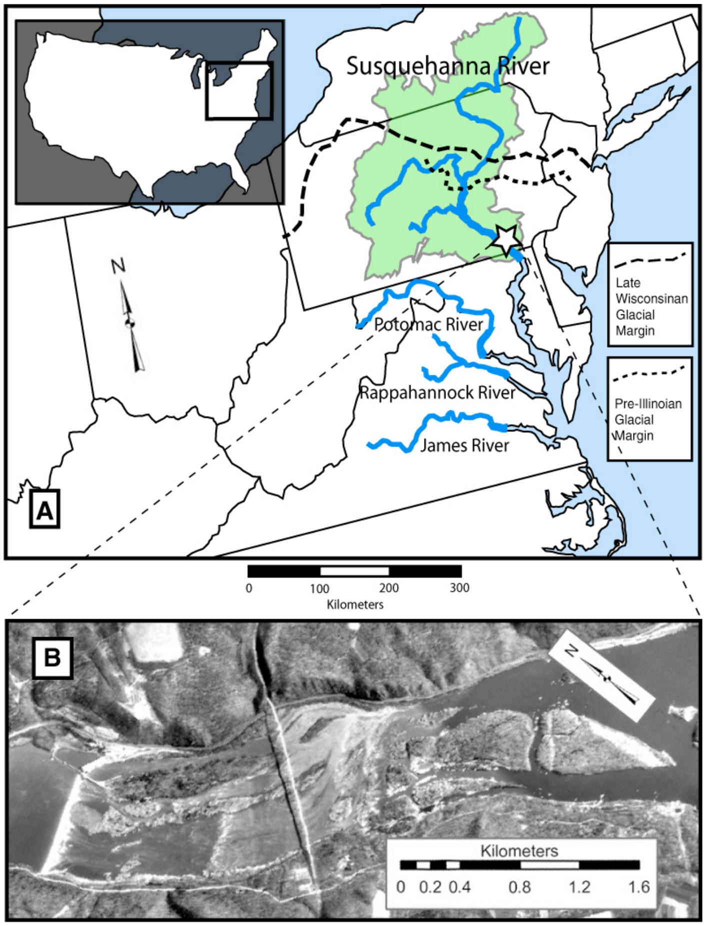
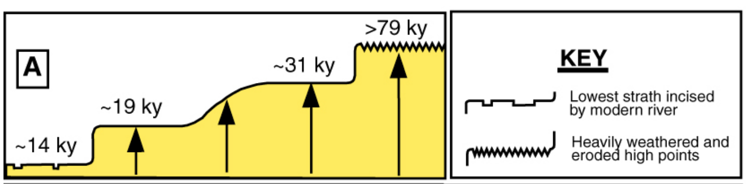
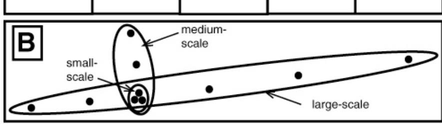


Figure 1. Location map of the Susquehanna River field area. **(A)** General layout of the US Atlantic passive margin with the locations of the James, Rappahannock, Potomac and Susquehanna Rivers. The Susquehanna River basin originates in central New York State and drains into Chesapeake Bay. Mapped glacial margins show that approximately 50 percent of the basin was glaciated during the Late Quaternary. **(B)** Section of the Holtwood Digital Orthoquad (DOQ) showing the extent of Holtwood Gorge below Holtwood Dam along the lower reaches of the Susquehanna River as it flows to the southeast.



1	2	Intermediate	3	4	Terrace Level
1.5 m km^{-1}	1.6 m km^{-1}	NA	1.8 m km^{-1}	NA	**Surface Gradient**
2.56	4.74	NA	4.51	NA	**Correlation Distance (km)**
8	18	NA	6	2	# of Longitudinal Samples (large-scale variance)
4	7	NA	5	0	# of Cross-Sectional Samples (medium-scale variance)
3	3	NA	5	0	# of Same Outcrop Samples (small-scale variance)
13	25	18	13	2	**Total Number of Samples**



Schematic Example of a Nested Sampling

Figure 2. Strategy used for sample collection within the Holtwood Gorge field area. **(A)** Schematic diagram of terrace levels seen within the gorge, number of samples collected at all variance scales, correlation distance, and surface gradient. Ages reflect 41 samples already measured. Because the level 4 high points are heavily eroded, >79 ky is given as a lower limit. **(B)** Schematic cartoon of nesting sampling strategy showing how individual samples can be used multiple times at different spatial scales.

Level 1 Summary

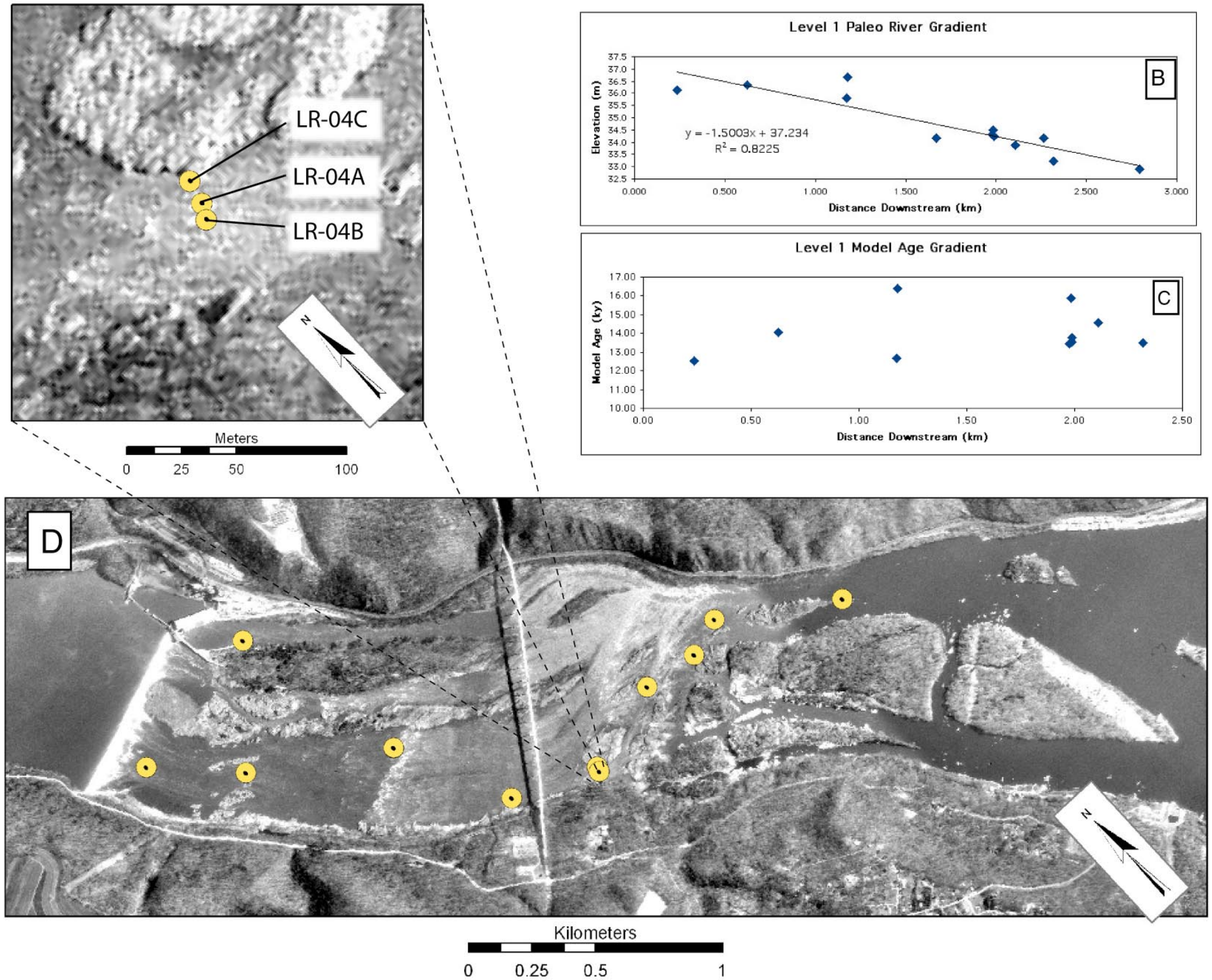


Figure 3: Sumary figure of sample coverage and spatial statistics for the Level 1 terrace. (A) shows the spatial layout of the the level 1 small scale variance study. (B) shows the downstream paleo river gradient inferred from the regression model of sample locations. (C) show the model age as a function of distance downstream. Note that there is no statistically significant relationship. (D) show the spatial coverage of samples colleceted along the level 1 strath.

Level 2 Summary

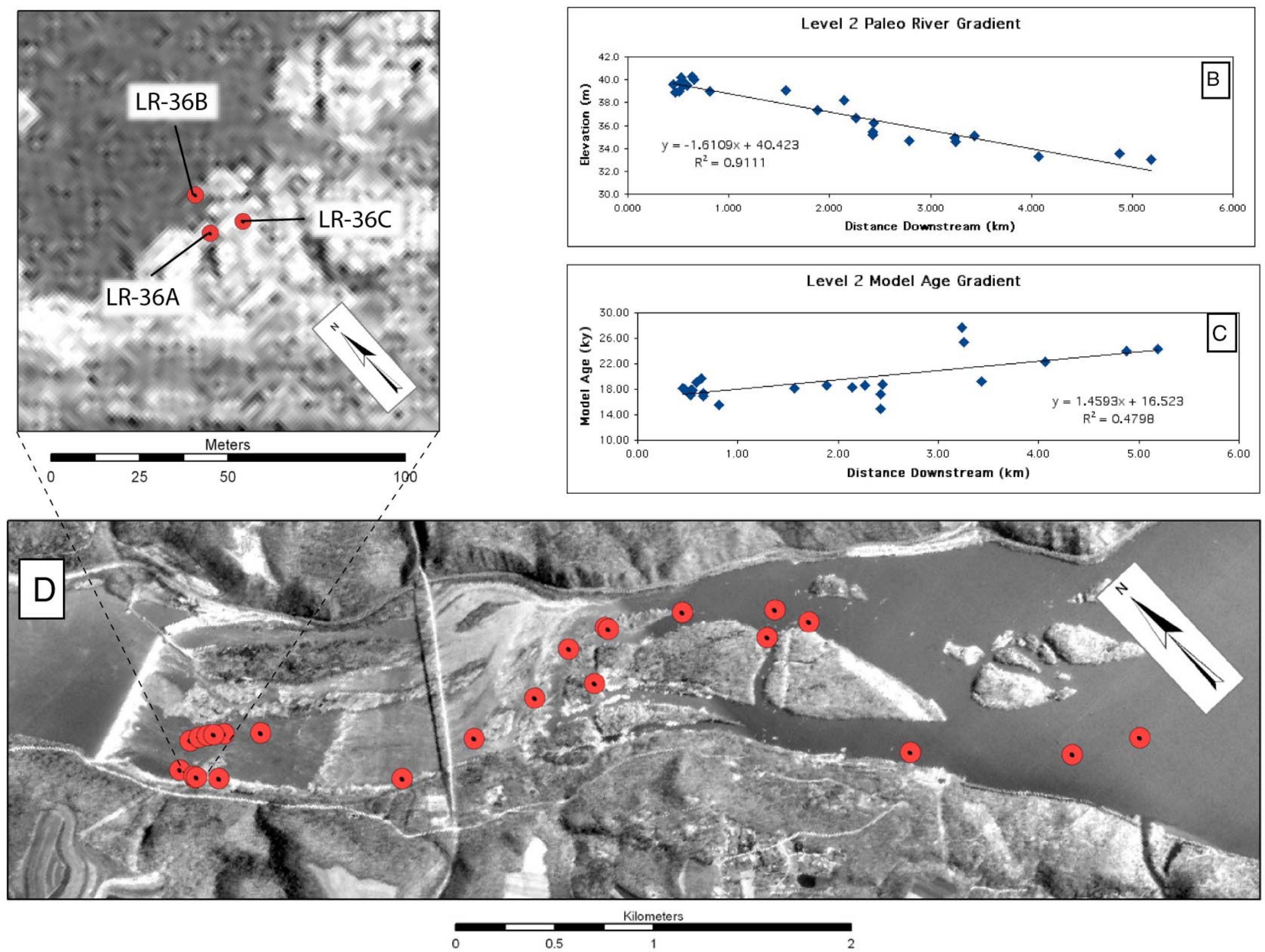


Figure 4: Sumary figure of sample coverage and spatial statistics for the Level 2 terrace. (A) shows the spatial layout of the the level 1 small scale variance study. (B) shows the downstream paleo river gradient inferred from the regression model of sample locations. (C) show the model age as a function of distance downstream. (D) show the spatial coverage of samples colleceted along the level 2 strath.

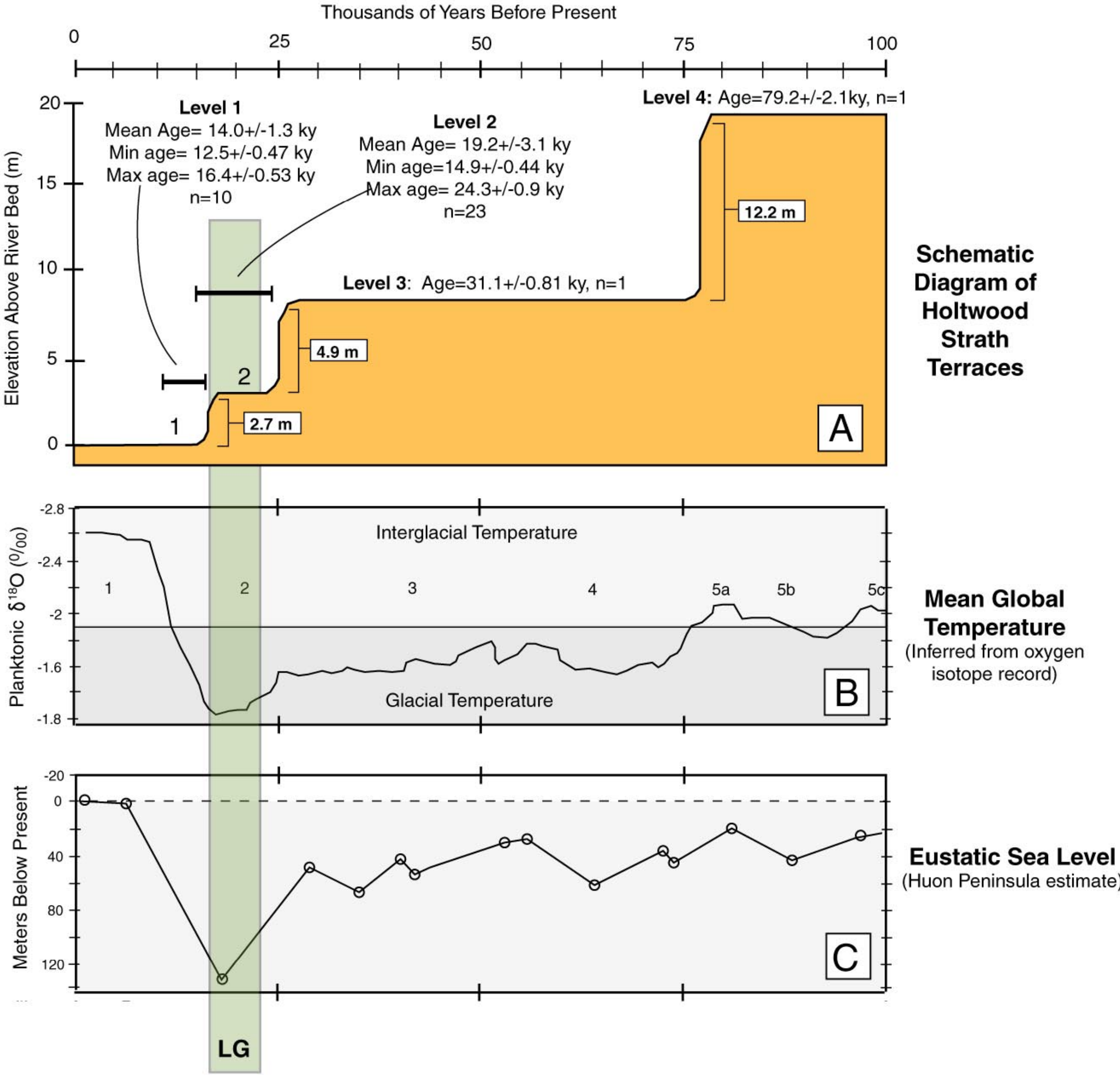


Figure 5: Summary of the spatial and temporal patterning of erosion within Holtwood Gorge. Parts A, B & C are displayed on the same axis of time in order to allow for correlation. (A) A graphical representation of the age range and meam elevation above the modern river bed for each of the strath terrace levels. (B) Mean global temperature inferred from the deap-sea oxygen isotope record (Linsley, 1996). Numbers indicate oxygen isotope stages. (C) Eustatic sea level curve for the Late Pleistocene. Curve constructed from estimates from the Huon Peninsula (Chappell, et.al., 1996). 'LG' indicates the time span of the last glacial max in Pennsylvania (17-22 ky: Braun, 1988).

Table 1: Summary table of spatial locations, nuclide activities, and model ages for each of the 41 samples measured at the Lawrence Livermore National Laboratory in January of 2003. "In" stands for samples colleted from intermediate surfaces between the level 2 & 3 terraces. All uncertainties are 1 sigma values.

Sample ID	Terrace Level	Distance Downstream (km)	Elevation (masl)	Height Above Modern River Bed (m)	10-Be activity (10^4 atoms/gram)	10-BeModel Age (ky)
LR-57*	1	1.67	34.15	0.31	3.74 ± 0.19	7.5 ± 0.39
LR-52	1	0.23	36.12	0.20	6.25 ± 0.24	12.5 ± 0.47
LR-55	1	1.18	35.80	0.69	6.32 ± 0.31	12.6 ± 0.61
LR-04B	1	1.98	34.30	0.24	6.73 ± 0.25	13.5 ± 0.51
LR-50	1	2.32	33.23	0.39	6.75 ± 0.25	13.5 ± 0.50
LR 04C	1	1.99	34.22	0.17	6.78 ± 0.24	13.6 ± 0.49
LR-04cX	1	1.99	34.22	0.17	6.88 ± 0.30	13.8 ± 0.60
LR56	1	0.63	36.34	0.52	7.03 ± 0.23	14.1 ± 0.47
LR-51	1	2.11	33.89	0.00	7.30 ± 0.27	14.6 ± 0.54
LR4A	1	1.98	34.51	0.46	7.93 ± 0.26	15.9 ± 0.52
LR-54	1	1.18	36.67	1.57	8.19 ± 0.27	16.4 ± 0.53
LR13	2	2.42	35.15	1.67	7.45 ± 0.22	14.9 ± 0.44
LR53	2	0.82	38.97	3.40	7.76 ± 0.21	15.5 ± 0.43
LR37	2	0.65	40.04	4.26	8.48 ± 0.25	17.0 ± 0.51
LR36B	2	0.53	39.83	3.88	8.51 ± 0.27	17.0 ± 0.53
LR42	2	2.43	35.40	1.92	8.65 ± 0.28	17.3 ± 0.57
LR37X	2	0.65	40.04	4.26	8.67 ± 0.31	17.3 ± 0.63
LR27	2	0.51	38.95	2.99	8.79 ± 0.23	17.6 ± 0.47
LR36a	2	0.53	40.22	4.28	8.89 ± 0.29	17.8 ± 0.58
LR36C	2	0.54	39.90	3.97	8.94 ± 0.29	17.9 ± 0.58
LR33	2	0.55	39.50	3.58	8.95 ± 0.26	17.9 ± 0.51
LR26	2	0.47	38.92	2.91	8.96 ± 0.24	17.9 ± 0.47
LR39	2	1.56	39.07	4.47	9.05 ± 0.29	18.1 ± 0.57
LR35	2	0.45	39.55	3.51	9.09 ± 0.29	18.2 ± 0.59
LR22	2	2.14	38.19	4.34	9.12 ± 0.22	18.2 ± 0.45
LR40	2	1.88	37.36	3.18	9.28 ± 0.46	18.6 ± 0.91
LR21	2	2.26	36.69	3.00	9.32 ± 0.30	18.6 ± 0.60
LR15	2	2.44	36.23	2.77	9.38 ± 0.27	18.8 ± 0.55
LR34	2	0.58	39.50	3.63	9.57 ± 0.27	19.1 ± 0.55
LR06	2	3.43	35.11	2.94	9.62 ± 0.36	19.2 ± 0.73
LR32	2	0.63	40.23	4.42	9.86 ± 0.29	19.7 ± 0.58
LR48	2	4.07	33.28	1.94	11.1 ± 0.28	22.3 ± 0.57
LR44	2	4.87	33.57	3.27	12.0 ± 0.42	24.0 ± 0.84
LR45	2	5.19	33.03	3.14	12.2 ± 0.45	24.3 ± 0.90
LR07	2	3.25	34.60	2.19	12.7 ± 0.33	25.4 ± 0.66
LR08	2	3.24	34.88	2.46	13.9 ± 0.36	27.8 ± 0.71
LR02a	3	2.12	42.38	8.51	15.5 ± 0.40	31.1 ± 0.81
LR1	4	2.30	54.58	20.94	39.6 ± 1.03	79.2 ± 2.07
LR10	In	2.46	39.05	5.61	8.97 ± 0.36	17.9 ± 0.71
LR11	In	2.49	42.02	8.62	9.52 ± 0.25	19.0 ± 0.50
LR-3A**	na	na	159	na	54.0 ± 1.62	108 ± 3.24

* LR-57 excluded from analysis because of suspected measurement error. It is currently being reprocessed and will be rerun on our next trip to LLNL.

**LR-3A is a quartz clast from a hilltop several km upstream from the gorge. It was not included in the analysis.