USING COSMOGENIC NUCLIDES TO DETERMINE THE TIMING, SPATIAL PATTERN, AND RATE OF FLUVIAL INCISION WITHIN BEDROCK CHANNELS OF THE SUSQUEHANNA RIVER, PENNSYLVANIA

A Thesis Proposal Presented

by

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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:

I will investigate the timing, spatial patterning and rate of bedrock fluvial incision in Holtwood Gorge along the Susquehanna River, Pennsylvania using cosmogenic nuclides. The Gorge, located approximately 50 km upstream from Chesapeake Bay into which the Susquehanna River empties, displays at least three levels of bedrock terraces (straths) ideal for the application of cosmogenic dating techniques. The overall aim of my research is to develop a new application of cosmogenic dating in order to investigate the relationship between ancient, passive margin river levels, represented by the strath terraces, and otherwise documented changes in climate, land level and sea level during the late Quaternary.

I have conducted a high level GPS survey of Holtwood Gorge and collected 64 samples from water-polished bedrock surfaces representing all three prominent strath levels. I have constructed a detailed field map correlating surfaces using field observations, GPS data, aerial photographs and topographic maps. Paleo-river gradients have been calculated and graphically represented. I have purified quartz from the majority of my samples.

Exposure ages will be modeled from measured nuclide activities using standard altitude and longitude correction factors. The spatial patterning of erosion and vertical rates of incision will be compared to Pleistocene sea-level fluctuations, global ice volume estimates, the oxygen deep-sea isotope record and models of North American isostatic adjustment in an attempt to decipher how passive margin rivers respond to such external forces.

2.0 Introduction:

Large rivers draining the North American Atlantic passive margin (the Susquehanna, Potomac, Rappahannock, and James) have incised deep channels into bedrock of the Piedmont Province over the past several million years (Pazzaglia et al., 1998). The Susquehanna River, as it flows from its headwaters in the central Appalachian Mountains to the Chesapeake Bay, has cut flights of bedrock terraces (straths) that are preserved within, and along the sides of gorges in its lower reaches (Thompson and Sevon, 2001; Figure 1). Most workers believe fluvial terraces represent adjustments made by a river in reaction to external changes including climate fluctuations or isostasy (Bull, 1990; Engel et al., 1996; Pazzaglia and Gardner, 1994b). Thus, strath terraces, if they can be dated, are potentially useful tools for investigating the interaction between glaciation, fluvial processes, glacial isostasy and eustasy in the eastern United Stated during the Quaternary (Engel et al., 1996).

The rate at which passive margin bedrock rivers erode rock, and the ultimate causes and timing of this incision are poorly understood (Tinkler and Wohl, 1998), because, until recently, direct dating of the bedrock terraces left behind has not been possible. Measurement of cosmogenic nuclide activities by accelerator mass spectrometry (Elmore and Phillips, 1987) now provides an opportunity to estimate exposure ages of bedrock surfaces exposed by fluvial erosion (Bierman, 1994). I will measure ^{10}Be and some ^{26}Al activities in quartz extracted from approximately 80 bedrock samples collected from terraces within the lower reaches of the Susquehanna River in order to understand terrace exposure history and thus infer behavior of the river over time.

The physical process by which these rivers carve through their bedrock channels, leaving behind flights of strath terraces is uncertain. A model proposed by E-an Zen (1997a; 1997b) for the formation of similar strath terraces along the Potomac River, near Washington, DC, involves the headward migration of knickpoints, forming a cataract-gorge system through Great Falls Park. Along the Susquehanna River, the formation of potholes, which exploit natural weaknesses in the bedrock, could have aided in the propagation of such knickpoints (Thompson and Sevon, 2001; Figure 2 & 3e).

3.0 Primary Objectives:

This study will utilize cosmogenic nuclide analysis and interpretive modeling of approximately 80 samples collected from within the Susquehanna River basin in order to:

- determine the nuclide activity and model the exposure age of at least three levels of river terraces within the lower reaches of the Susquehanna River,
- determine 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 Study Site:

4.1 Susquehanna River: The Susquehanna River extends for more than 500 km (Engel et al., 1996) as it drains approximately 62,000 km^2 (Pazzaglia et al., 1998) of the Appalachian plateau and Piedmont Province in New York State, eastern Pennsylvania and northeastern Maryland. With a mean annual discharge of 1053 m^3/s and peak annual discharge of 8610 m^3/s (USGS Stream Flow Data from Gauging Station at Marietta, PA (1932-2001)) into the Chesapeake Bay, the Susquehanna is the largest drainage system of the Appalachian Mountain chain (Thompson, 1990). In northeastern and northcentral Pennsylvania, the Susquehanna generally exhibits a dendritic drainage pattern (Scharnberger, 1990) with broad, shallow channels and an average stream gradient of 0.5 m km^{-1} (Pazzaglia and Gardner, 1993, 1994a). In its lower reaches, the Susquehanna narrows and deepens as it cuts through the Wissahickon Schist of the high Piedmont. Its gradient steepens to an average of 1 m km^{-1} and it exhibits a strongly convex-up longitudinal profile (Pazzaglia and Gardner, 1993, 1994b).

4.2 Holtwood Gorge: Holtwood Gorge, located approximately 50 km upstream of Chesapeake Bay and immediately downstream from Holtwood Dam, is carved approximately 120 m (Thompson and Sevon, 2001) into the Wissahickon Schist and harbors at least three distinct levels of striking bedrock terraces which are preserved along the sides of the gorge and as isolated bedrock islands (dissected straths) within the gorge (Figures 4 & 3a through 3d). The uppermost level, which is restricted primarily to the western bank of the Susquehanna River and to island tops in the lower gorge, consists of heavily weathered accordant summits. I am uncertain if these summits represent abandoned fluvial surfaces. Intermediate levels (2 & 3) still preserve a fluvially sculptured form and, in some cases, can be correlated nearly 5 km downstream. The lowest strath is visible and accessible only at times when Holtwood Dam is not releasing water. This level exists as an expansive and planar surface stretching from the dam almost 2 km downstream on the western two-thirds of the river. In general, this surface is more ‘ragged’ and less sculptured than the intermediate levels, suggesting that a period of time is required for surfaces to acquire a water worn appearance.

Enormous potholes, ranging in size from several cm in depth and diameter to nearly 9 m in depth and 4-6 m in diameter, are abundant within the gorge (Figure 3e). These potholes, which dip upstream and develop at the intersection of the NE-striking foliation and a NNW-striking joint set, suggest that erosion and removal of material from the gorge was efficiently accomplished by quarrying of large bedrock blocks (Thompson and Sevon, 2001). The Wissahickon Schist dips steeply downstream and contains abundant boudins of almost pure quartz. The well preserved bedrock terrace levels and ubiquitous quartz, well suited for sample collection and processing, make Holtwood Gorge an ideal location to utilize cosmogenic dating techniques.

5.0 Previous Work:

The Susquehanna River basin, the southern half of which has remained free of ice during all Pliocene and Pleistocene glaciations, offers the opportunity to study a variety of proximate and distal glaciofluvial features not present in unglaciated or fully glaciated basins. For this reason, sequences of glacial moraines in northeastern Pennsylvania, river terraces preserved south of the glacial margin, and coastal deposits have been extensively studied in an effort to decipher the effect of glaciation and/or other climate perturbations on passive margin river systems.

5.1 Glacial Chronology of Pennsylvania: Evidence for nine periods of glaciation, ranging in age from older than the Pliocene/ Pleistocene transition (1.65 mya) to the late Wisconsin glaciation (35-10 kya) can be found within the U.S. (Richmond and Fullerton, 1986). However, tills from only three of these glacial periods are preserved in northeastern Pennsylvania, through which the North and West Branches of the Susquehanna River flow. Radiocarbon dating has constrained the age of the Late Wisconsin glacial advance to 17 k to 22 k ^{14}C years in Pennsylvania, with a maximum extent at about 20 k years (Braun, 1988; Sevon and Fleeger, 1999). Two older moraines, not overrun by the late Wisconsin advance, have been identified and assigned general ages through comparison to the oxygen isotope record and the Matuyamma-Brunhes magnetic polarity reversal. A swath of unnamed till across northeastern Pennsylvania correlates to the Titusville Till in western Pennsylvania and has been assigned an age of late-Illinoian (132 ka-198 ka; Sevon and Fleeger, 1999). The oldest of the

Pennsylvanian tills extends approximately 50 km further south from the late-Illinoian moraine and is overlain by lake clays displaying a reversed polarity signature. The age of this till can only be constrained to sometime between the last two polarity reversals. It has been assigned a poorly constrained age of pre-Illinoian (788 ka-2400 ka; Richmond and Fullerton, 1986; Sevon and Fleeger, 1999).

5.2 Fluvial Terraces and the Susquehanna River: Fluvial terraces presumably represent changes in climate as well as periods of isostatic adjustment, and are therefore useful tools for investigating the interaction between glaciation, fluvial processes and eustasy in the Eastern U.S. during the Quaternary (Bull, 1990; Engel et al., 1996; Hancock et al., 1999). Many researchers have studied fluvial terraces of the Susquehanna River in order to investigate the geomorphic evolution of the U.S. Atlantic passive margin, beginning primarily with an extensive study conducted by Peltier (1949). Correlation between a series of upland terraces (80-140 m above the modern channel) and coastal plain and fall zone deposits was used to establish terrace ages throughout the Piedmont Province of Pennsylvania in an attempt to quantify late Cenozoic passive margin deformation (Pazzaglia and Gardner, 1993, 1994a, b). Flights of younger (Pleistocene) alluvial terraces were identified and studied for the purpose of establishing soil chronosequences in order to facilitate correlation to similar features found elsewhere in the middle Atlantic region (Engel et al., 1996). Based on soil development characteristics, several of the six identified alluvial terraces, located upstream from the Holtwood Gorge field area, were tentatively correlated to the late Wisconsin, Illinoian, and pre-Illinoian glacial advances in Pennsylvania. However, no definite age control was established for the alluvial terraces. No such correlation or dating has been rigorously attempted on the bedrock straths preserved in Holtwood Gorge.

5.3 Cosmogenic Nuclides: The continual bombardment of Earth's surface by secondary cosmic rays (primarily neutrons) results in the steady production and accumulation of cosmogenic nuclides within exposed rock and sediment (Lal and Peters, 1967). The in-situ production rate of these nuclides depends upon the strength of Earth's magnetic field and thickness of the overlying atmosphere at any given point on Earth's surface (Lal, 1991). As a result, latitude and altitude corrections must be made when transforming measured nuclide concentrations into exposure ages (Lal, 1991). This study will utilize two radioactive cosmogenic isotopes, ^{10}Be and ^{26}Al, which result from the spallation of O and Si respectively, in order the obtain exposure ages of bedrock surfaces.

Cosmogenic nuclides have been employed in a variety of geomorphic studies since the mid 1980's. Nuclide activities have been used to obtain exposure ages of glacial boulders (Evenson and Goose, 1993; Marsella et al., 2000; Nishiizumi et al., 1989), estimate landscape erosion rates (Bierman and Caffee, 2001, 2002; Granger et al., 1996, 1997), calculate rates of sediment transport (Bierman and Steig, 1996; Nichols et al., 2002), and suggest depostional histories (Anderson et al., 1996; Granger and Muzikar, 2001). Although ^{10}Be and ^{26}Al have been used in many studies to date alluvial terraces (e.g., Hancock et al., 1999; Repka et al., 1997), only 3 studies have been conducted on bedrock (strath) terraces (Burbank et al., 1996; Leland et al., 1994; Leland et al., 1998), all in the Himalaya on rapidly downcutting rivers in an active tectonic setting.

6.0 Work Plan:

My work thus far has, and will continue to focus on Holtwood Gorge because of the flights of well preserved and extensive strath terraces, relatively easy accessibility afforded by Holtwood Dam, and the abundance of extractable quartz.

6.1 Field Work: Working with Eric Butler as my field assistant, I spent approximately four weeks within Holtwood gorge scouting every available surface for the most representative and accessible sample sites and conducting a comprehensive Trimble 4400 differential GPS (offering cm resolution) survey for the purpose of lateral and longitudinal correlation of identified terrace levels. In order to ensure the accuracy of GPS data, I established a series of control points along the length of the gorge and measured them daily. I used a hammer and chisel to collect 64 samples composed of quartz boudins or schist groundmass from the selected water polished surfaces of the Wissahickon Schist. Altitude, latitude, sample thickness, and exposure geometry were recorded in order to make the appropriate production rate corrections (Lal, 1991). I employed a 'nested' sampling strategy in order to investigate isotopic activity variance on what I interpret to be single terrace levels, at small (5-10 m), medium (cross-stream, 500 m), and large (downstream, up to 5 km) spatial scales (Figures 4 & 5).

6.2 Map and Laboratory Work: I constructed a field map delineating all correlated dissected strath terraces and sample-site locations using aerial photographs and high accuracy elevation GPS data collected from Holtwood Gorge (Figure 4). I have calculated and constructed trend surface plots of each terrace level in order to depict the downstream gradient that occurs over the five kilometers spanned by the gorge (Figure 6).

Most samples have already undergone the first step in processing at the University of Vermont using standard techniques (Bierman and Caffee, 2001). I have purified 40 g of quartz through the use of acid etching and density separation (Kohl and Nishiizumi, 1992). I will assist Jennifer Larsen in the isolation of ^{26}Al & ^{10}Be in the cosmogenic laboratory as it is prepared for isotopic measurement by accelerator mass spectrometry at the Lawrence Livermore National Laboratory in Livermore, California. Two full laboratory replicates will be run to test for accuracy and reproducibility of sample preparation and nuclide concentration measurement. ^{10}Be will be measured for all samples while paired nuclide analysis (^{26}Al and ^{10}Be) will be conducted on several samples for quality control and to rule out extended (>100 ky) periods of burial, which appear geomorphically unlikely.

6.3 Data Analysis: Nuclide activities will be analyzed in an attempt to decipher the spatial patterning, timing, and rates of bedrock incision as well as to infer the erosional processes responsible for carving Holtwood Gorge. Measured nuclide activities for all samples will be reduced to exposure ages using the altitude-latitude scaling function presented in Lal (1991). Exposure ages will be plotted against distance downstream from the dam front for all terrace levels in order to determine rates of knickpoint propagation (if this is indeed the how the gorge incised). Terrace level exposure ages from samples collected in cross-section will be used to calculated rates of vertical incision between levels. The spatial pattern of erosion for each correlated strath will be investigated using small and medium scale nuclide activity variance. Statistical analysis will be applied to all small, medium, and large scale sampling strategies to determine the power with which conclusions can be drawn. Finally, the modeled erosional history of Holtwood Gorge will be compared to the Pleistocene glacial chronology of Pennsylvania (Braun, 1988, 1994) and the northern hemisphere (Richmond and Fullerton, 1986), the Pleistocene sea level record, and the glacial forebulge model in the hopes of understanding the timing and ultimate causes of episodic incision recorded as bedrock terraces within the gorge.

7.0 Time Line:

Work Completed To Date:

- May and June, 2002: Scout and map Holtwood gorge field area. Select potential sample sites. Conduct Pro XR GPS survey within the gorge.
- June, 2002: Field check sample sites with Paul Bierman and collect samples from all terrace levels except the lowest strath (underwater at this time of year).
- July, 2002: Visit with Paul Bierman and Milan Pavich of the USGS for mapping and sample collection at the Mather Gorge site on the Potomac River.
- July, 2002: Collect samples from the now exposed lower strath and collect high accuracy (cm) 4400 GPS data for all sample sites.
- August 2002: Quartz making at the University of Vermont. Continue background reading, construct air photo maps, construct Susquehanna Project webpage and, finish writing proposal and prepare defense presentation.

Fall 2002

- Sept. or Oct., 2002: Proposal Oral Defense.
- Sept. and Oct., 2002: Continue quartz making 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.
- Dec., 2002: Initial Mass Spectrometer measurement of sample nuclide concentrations at the Lawrence Livermore National Laboratory.
- Continue research and background reading.

Spring 2003

- AMS measurement of most samples.
- Submit written progress report in March.
- Present progress report oral defense.
- Begin writing thesis.
- Possible presentation at Spring AGU meeting
- Conduct follow-up sampling and/or GPS work as needed.

Summer 2003

- Return to Holtwood Gorge and field check all sample sites.
- Continue writing thesis.
- Salary supported by grant

Fall 2003
- RA supported.
- Complete thesis and begin edits.
- Present at GSA annual meeting.

8.0 Discussion of Preliminary Data:

Data collected during my first season of field work has been analyzed and used in a number of ways, both while at the Holtwood Gorge field area and at the University of Vermont. Field observations, GPS data, aerial photographs, and map interpretations have been used to determine the present river gradient and infer paleo-river gradients for the correlated strath terraces (Figures 4 & 5).

Present Water Level Gradient: A distinctive water level mark on the lowest strath was observed in the upper gorge (0-2 km downstream from the dam front) during a sustained period of no flow (on the order of weeks). Locally, it represented a pool elevation at a certain distance downstream from the dam. GPS coordinates for pool elevations were collected from the dam face to approximately 2 km downstream, which when plotted as distance downstream vs. elevation yielded what is interpreted to be the present river gradient (1.3 m/km, R^2=0.97; Figures 3f & 6).

Terrace Level 1: Level 1 is restricted to the western two thirds of the river and is exposed only in the upper gorge. This level can be correlated for 2.56 km downstream and yields an inferred paleo-river gradient of 1.5 m/km with an R^2 value of 0.82 (Figure 6).

Terrace Level 2: Level 2 can be correlated 4.74 km downstream and is the best preserved and most obvious level seen in most parts of the gorge. In general, level 2 exhibits well preserved, water sculpted surfaces and yields a paleo-river gradient of 1.6 m/km (R^2=0.91; Figure 6).

Terrace Level 3: Exposures of the level three terrace are restricted primarily to the middle gorge as the highest surfaces on the upstream nose of many mid-channel islands. It has been correlated 4.51 kilometers downstream with an inferred paleo-gradient of 1.8 m/km (R^2=0.69; Figure 6).

There appears to be an increase in terrace level gradient with elevation above the modern channel. I am uncertain whether this is a 'real' trend, or simply the result of natural variability along correlated terrace surfaces.

Level 4: Due to the heavily weathered condition of surfaces reaching an elevation high enough to be called greater than level 3, this level is not considered a terrace. Two samples were collected from level 4 high points to investigate the nuclide activity on these weathered surfaces, which are thought to be of considerable age (several 100's ky).

Control Points: Three control points were established, one in each the upper, middle and lower gorge and measured in the morning and evening over the course of five consecutive days. Standard deviations for point locations were +/- 0.009 m, +/- 0.016 m, and +/- 0.020 m respectively, offering extremely accurate terrace level elevations and paleo-river gradients.

Having no nuclide data at present, it is difficult to speculate about the timing and rate of incision, or the mechanisms responsible for carving the gorge. There are, however, several scenarios to consider. If knickpoints did, at times in the past, migrate headwards through Holtwood Gorge (Figure 2), we would expect to see nuclide concentrations (and corresponding model ages on each terrace) decreasing upstream as the river abandoned its channel for a lower one during the steady incision of the gorge. This scenario requires that the rate of knickpoint retreat is slow enough to allow for measurable longitudinal variance (accumulation of cosmogenic nuclides within exposed rocks). A potential driving force for terrace formation of this kind would be a eustatic drop in sea level caused by the onset of a glacial period.

On the other hand, if no longitudinal variance of nuclide concentration is detected on a terrace level, we must look for another mechanism capable of forcing a river to incise quickly through bedrock on a passive margin. The easiest explanation would be that the rate of retreat was faster than the resolution of the cosmogenic dating technique. Some researchers (Kockel and Parris, 2000; Sevon and Thompson, 1987) have proposed that catastrophic floods, caused by glacial outbursts during deglaciations, had the power to carve through Holtwood Gorge in this manner. Another possible mechanism would be regional isostatic adjustment which would slowly and uniformly raise the bed of the river, forcing the Susquehanna to incise its channel in order to maintain a steady gradient. A glacial forebulge or flexural upwarping of the fall-zone and high piedmont, caused by sediment loading into the Baltimore Trough (Pazzaglia and Gardner, 1994a, b) are other potential mechanisms capable of forcing the Susquehanna River to incise into the bedrock channel of Holtwood Gorge.

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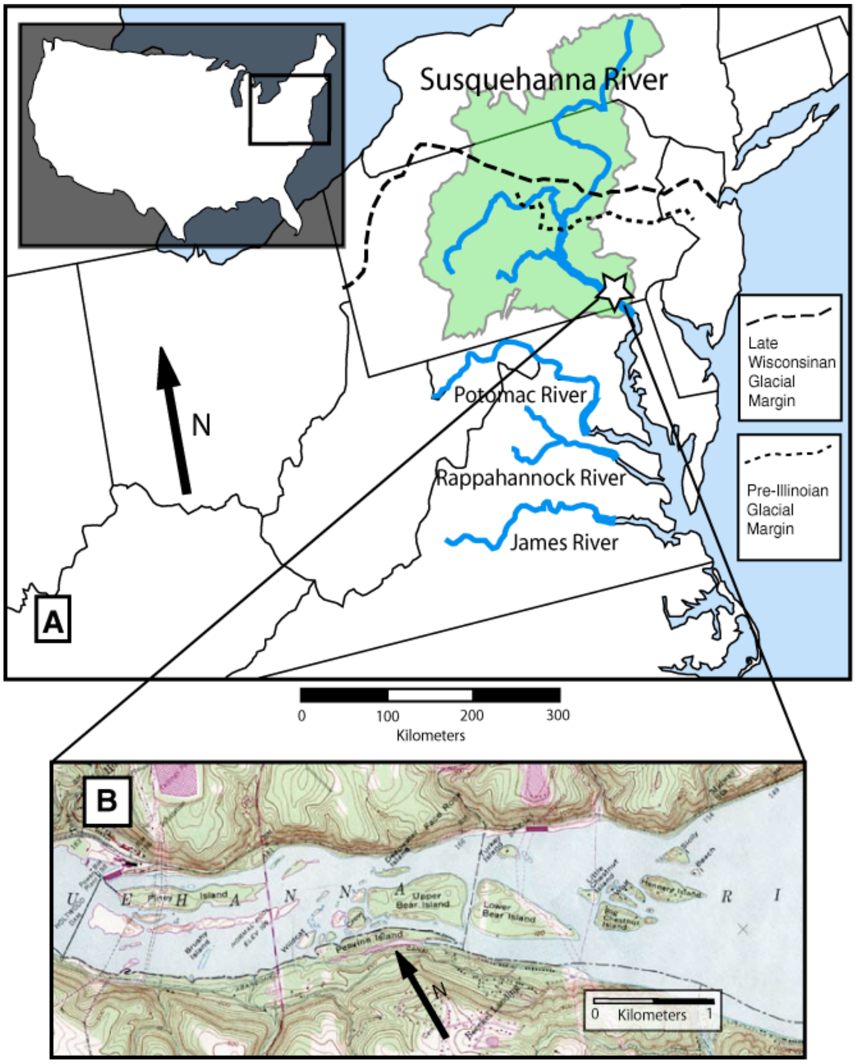


Figure 1. Location map of the Susquehanna River field area. **(A)** General layout of the US Atlantic passive margin with the locations of the James, Rappahannock, Potomac and Susquehanna Rivers. The Susquehanna River basin originates in central New York State and drains into Chesapeake Bay. Mapped glacial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

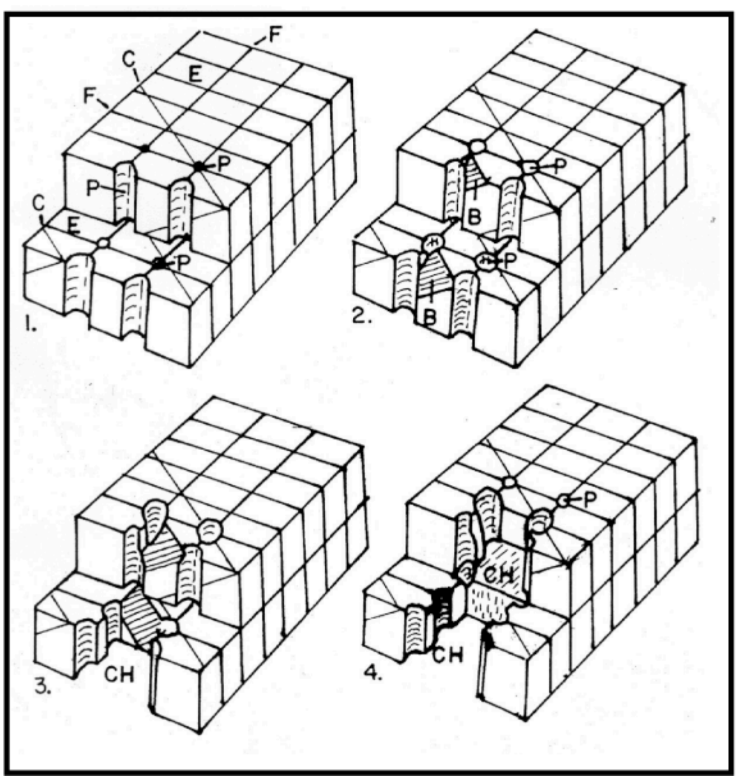
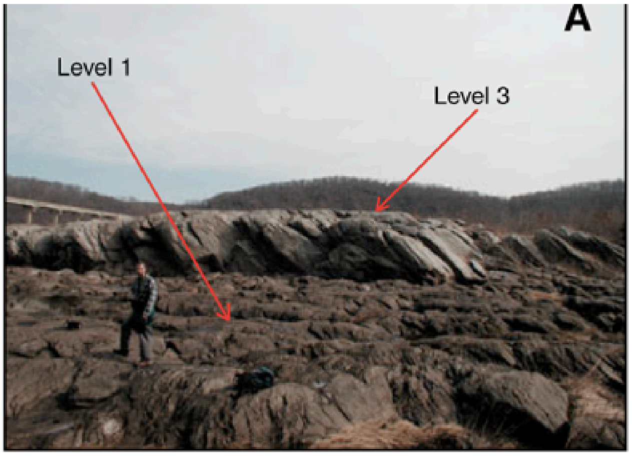
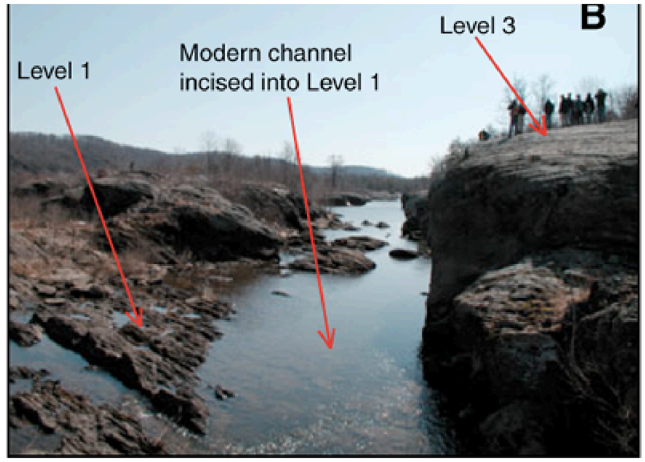


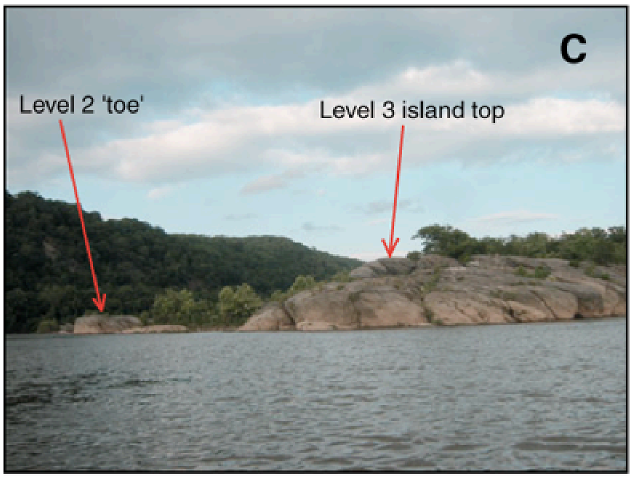
Figure 2. Schematic cartoon showing a possible mechanism of knickpoint retreat through Holtwood Gorge. A base level drop, such as a eustatic sea level drop at the onset of a glacial period could theoretically have initiated bedrock incision such as this. Key: B=space left by eroded block; C=cleavage orientation; CH=new channel; E=eroded surface; F=fracture; P=pothole. Water flow is from upper right to lower left. Figure shows periods of incision and terrace tread formation as several waves of knickpoints migrate toward the upper right (upstream). Figure taken from Thompson and Sevon, 2001.



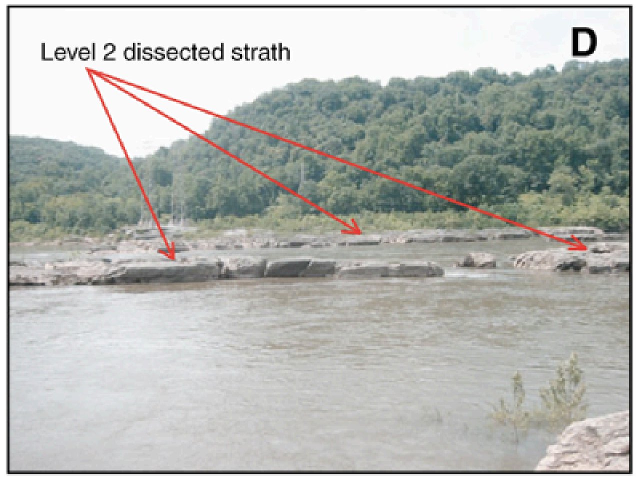
A: Picture from the middle gorge showing level 3 (upper surface) and level 1 (lower surface) at low water conditions. When water is releasing from Holtwood Dam, level 1 is under water.



B: Picture from the 'middle gorge' showing level 3 (upper surface upon which the people are standing) and level 1 (lower surface) at low water conditions.

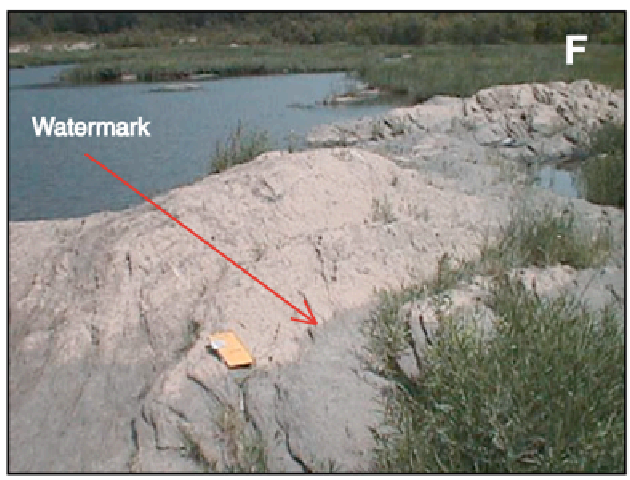


C: Picture of a 'rounded front' found in the middle gorge. The islet seen on the left side of picture is a level 2 'toe' which grades into a level 3 island top.



D: Picture displays isolated pieces of a dissected strath in the upper gorge which have been corrletated and assigned to the level 2 terrace level.

E: Example of an enormous pothole. Pothole is 4-6 meters in diameter and at least 8 meters in depth. It is unknown how far it extends under the water level.



F: Picture shows the distinctive watermark used to determine the present river gradient in the upper gorge (mark could be correlated for approximately 2 km downstream). Field book for scale.

Figure 3. Pictures from Holtwood Gorge, Pennsylvania, showing a variety of terrace levels, an example of an enormous pothole and a distinctive watermark seen in the upper gorge in July, 2002.

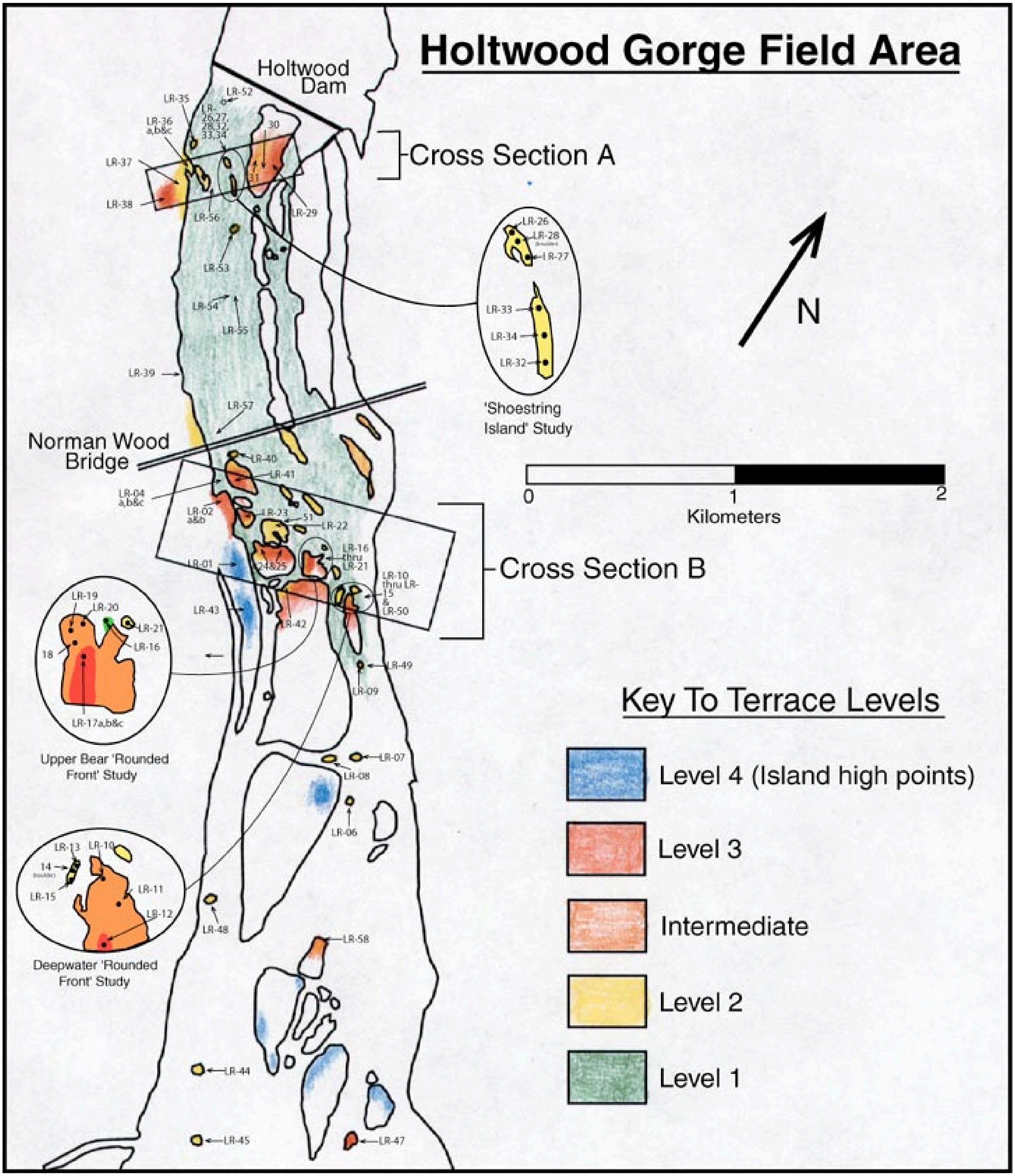
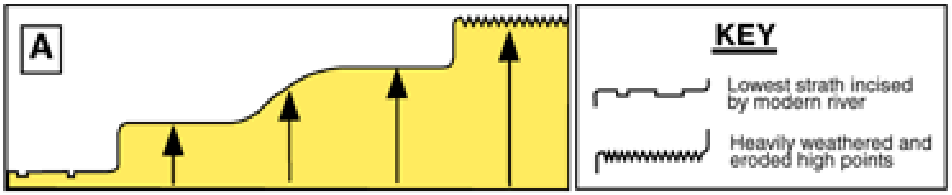
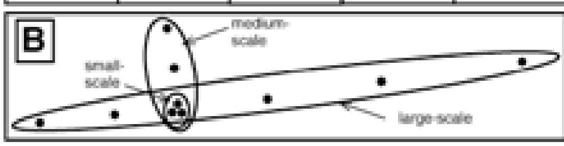


Figure 4. Field map of the Holtwood Gorge field area along the Susquehanna River in southeastern Pennsylvania. Map displays all sample sites, cross sections, small scale 'studies,' and correlated strath terrace levels.



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)
7	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)
12	25	10	12	2	Total Number of Samples



Schematic Example of Nested Sampling

Figure 5. 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. **(B)** Schematic cartoon of nested sampling strategy showing how individual samples can be used multiple times to investigate variance at different scales.

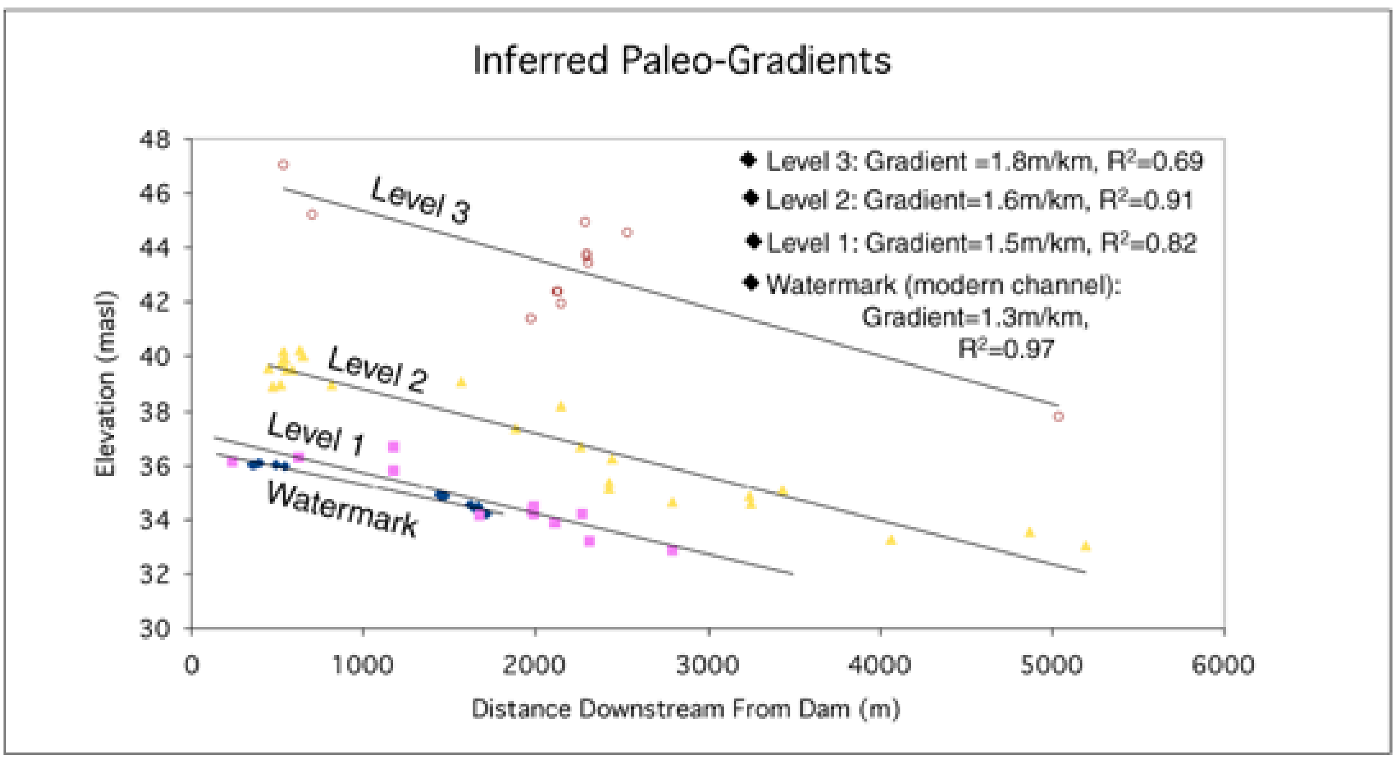


Figure 6. Inferred paleo-gradients for terraces levels 1, 2 & 3 derived from Trimble 4400 differential GPS data collected from all sample sites within the Holtwood Gorge field area in southeastern Pennsylvania. The Watermark trendline was constructed using GPS point of a distinctive watermark observed in the upper gorge (July, 2002). It is interpreted as being representative of the present river gradient.