LATE PLEISTOCENE BEDROCK CHANNEL INCISION ALONG THE U.S. ATLANTIC PASSIVE MARGIN MEASURED WITH ^{10}Be: HOLTWOOD GORGE, SUSQUEHANNA RIVER, PENNSYLVANIA

A Thesis Presented

by

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to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Masters of Science
Specializing in Geology

March, 2005

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ABSTRACT

^{10}Be measured in over 80 samples collected from fluvially eroded rock within Holtwood Gorge quantifies, for the first time, when, how fast, and why the Susquehanna River incised through bedrock along the east coast of North America, one of the most prominent and ancient passive margins. Although the rate at which large rivers incise rock is a fundamental control on the development of landscapes, very little is known about how quickly such incision occurs either in tectonically active environments or along passive margins.

Exposure ages of fluvial carved bedrock strath-terraces preserved within Holtwood Gorge demonstrate that even along the Atlantic passive margin, large rivers are capable of incising through rock for short periods of time at rates approaching those recorded in the tectonically active Himalaya. Beginning between ~45 ka and ~35 ka, rates of incision accelerated dramatically, and continued at a rapid rate until ~14 ka. This phase of rapid incision, also measured within Mather Gorge along the Potomac River located ~100 km to the south, correlates well with a period of cold and stormy climate recorded by the GISP2 ice core, central Greenland. Unstable climate during the late Pleistocene increased the frequency and magnitude of flood events capable of exceeding thresholds for bedrock erosion, thus enabling both the Susquehanna and Potomac Rivers to incise quickly into rock.

Rates of incision during the late Pleistocene, constrained with ^{10}Be, range from 0.8 to 0.4 m/ky between ~45 and ~14 ky, and are almost two orders of magnitude faster than long-term estimates of integrated bedrock incision rates (~12 m/My) since the middle Miocene along the Atlantic passive margin. Discordance between short- and long-term rates indicates that incision through bedrock on this passive margin occurs episodically. Driven by long-term flexure of the Atlantic passive margin by offshore deposition of sediment, the lower reaches of the river have remained oversteepened since the Miocene, increasing stream gradients and the potential for incision. The high rates of late Pleistocene incision inferred using data collected for this project represent a pulse of erosion during an ongoing period of river adjustment over geologic time scales.

This research provides a framework for future investigation into the style and tempo at which rivers elsewhere incise through bedrock. Results from a variety of spatial tests further our understanding of how and when large passive rivers incise rock and show that the age signal preserved in terrace rocks is consistent and interpretable. Cosmogenic isotopes allow us to measure rates of incision over millennial time scales, an appropriate time frame for considering the influences of changing boundary conditions during glacial-interglacial cycles. Similar studies conducted along additional rivers draining the east coast of North America, as well as passive margins around the globe, will help us to understand better how fluvial incision through these resistant channel reaches modifies ancient terrains.

CITATIONS

Material for this thesis has been published in *Science Magazine* on July 23, 2004 in the following Form:

Reusser, Luke J., Bierman, Paul R., Pavich, Milan J., Zen, E-an, Larsen, Jennifer, and Finkel, Robert, **2004**, Rapid late Pleistocene incision of Atlantic passive margin river gorges: Science Magazine, v. 305, no. 5683, p. 499-502.

AND

Material for this thesis will be submitted for publication in *The American Journal of Science* in the following form:

Reusser, Luke J., Bierman, Paul R., Pavich, Milan, Larsen, Jennifer, and Finkel, Robert. Late Pleistocene incision along the U.S. Atlantic passive margin, Holtwood Gorge, Susquehanna River, Pennsylvania: American Journal of Science.

ACKNOWLEDGMENTS

Many individuals and organizations deserve thanks for both their financial support, as well as their expertise and guidance during the coarse of this project. This thesis was supported primarily by National Science Foundation Grant # EAR0003447 awarded to Paul Robert Bierman.

Thoroughly enjoyable and productive field work for this project was made possible by several key individuals. A special thanks to Eric Butler for countless hours of help in the field and numerous trips down to the Susquehanna River over the past two and a half years in the glorious and faithful Green Beast. Many thanks also to Paul Bierman for great field assistance, sample collection, and a particularly exciting canoe trip in the middle gorge on a hot summers day. I would also like to extend my appreciation to Chris Porse and all the other engineers at Holtwood Dam who helped immensely with the logistics of this project (and thanks for letting us borrow your walkie-talkies). Similarly, I would like to thank George and Melody Strickler for provided us with a home at the Otter Creek Campground, and for much good conversation during field work.

This project would not have been possible without the expertise and hard work of Jennifer Larsen, who single handedly found and captured all of the ^{10}Be and ^{26}Al in my samples at the Cosmogenic Laboratory at the University of Vermont. I also thank Robert Finkel at the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory (LLNL) for providing us with the time and know-how to measure all 81 samples. A portion of this work was supported under the auspices of the U.S. D.O.E. to LLNL under contract number W-7405-Eng-48.

My sincere gratitude goes to my advisor, Paul Bierman, for all of his help and guidance along the way, his endless editing, and for developing the idea for this project in the first place. I look forward to continuing my work with him at the University of Vermont in the years ahead. Thank you to the geology graduate students and professors for all of your help during my time at UVM. I would like to thank Milan Pavich at the U.S. Geological Survey, and E-an Zen at the University of Maryland for their vast knowledge of the geology of the central Appalachian Mountains, and the rivers that drain them.

Finally, I would like to thank my parents, Jonathan and Christina Reusser, and my sister Meghan for their love and support, and for being the best family anyone could hope for. And so many thanks to Paula Mouser for everything you have brought into my life since I came to Vermont. Thank you for pushing me to be my best, and thank you for helping me to step back and look around.

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CHAPTER 1: Introduction

RIVER INCISION THROUGH BEDROCK

River incision through bedrock communicates the effects of changing boundary conditions, such as climate and tectonics, through hillslopes and drainage networks, and thus has important implications for understanding how landscapes evolve (Howard, 1994; Tinkler and Wohl, 1998; Whipple etal., 2000). Rivers flow over, and erode rock in tectonically active and passive settings around the world. Despite the importance of bedrock channel incision to the development of landscapes, study of erosional mechanisms and process rates active within these resistant river reaches has been largely ignored in the past (Tinkler and Wohl, 1998). Driven by broad interest in understanding how landscapes change, these complex geomorphic systems have been increasingly studied over the past several decades. However, we still know little about the timing, rate, and style of such incision in either actively rising terrains, or along ancient passive margins. My thesis uses measurements of ^{10}Be to quantify when, how fast, and to infer why the Susquehanna River incised into the rocks of the Appalachian Piedmont along one of the world's most prominent and ancient passive margins.

Rates of river incision into bedrock have been estimated or measured directly over a range of temporal and spatial scales, but may not accurately describe the processes responsible for erosion, or the time frame over which most incision occurs. Long-term consideration of landscape development and the evolution of mountain ranges, accomplished with numerical models (e.g. Baldwin and others, 2003; Snyder and others, 2003; Whipple, 2004) and proxies for rates of exhumation (e.g. Zimmermann, 1979; Doherty and others, 1980) offer intriguing results, but both temporal and spatial resolutions are often too coarse to understand the means by which river systems dissect landscapes. Similarly, direct measurements of erosion within bedrock channels at specific locations may not capture the dominant erosional mechanisms by which rivers shape landscapes because of the short duration of time and the small spatial scales over which such rates are measured (e.g. Wohl, 1993; Hancock and others, 1998; Hartshorn and others, 2002). Only a handful of studies have directly measured the rate, timing and style of fluvial bedrock over millennial time scales using cosmogenic nuclides (Burbank and others, 1996; Hancock, Anderson, and Whipple, 1998; Leland and others, 1998; Whipple, Hancock, and Anderson, 2000a; Whipple and others, 2000b; Hartshorn and others, 2002; Burbank and others, 2003); virtually all such studies have been conducted in tectonically active regions.

IN SITU-PRODUCED COSMOGENIC NUCLIDES AND EXPOSURE AGE MODELING

Cosmogenic nuclides, such as ^{10}Be, are produced and accumulated within exposed rocks and sediments by the continual cosmic-ray bombardment of Earth's surface (Lal and others, 1967). Extremely low concentrations of such nuclides can now be measured by accelerator mass spectrometry due to advances in nuclear physics (Elmore and others, 1987). Because cosmogenic nuclides are rare in deeply shielded terrestrial materials, they are useful monitors for near-surface exposure duration and thus provide quantitative constraints on rates of landscape change over millennial time scales (Gosse and others, 2001; Bierman and others, 2003; Bierman and others, 2004a).

Concentrations of cosmogenic nuclides have been utilized in a variety of geologic pursuits, ranging from quantifying rates of landscape denudation (e.g. Bierman and Steig, 1996; Granger and others, 1996) to estimating the age of depositional surfaces (e.g. Anderson and others, 1996). Because activities of cosmogenic nuclides monitor the duration of time earth materials have been exposed at or near the surface, they can be used to date when rock surfaces were exposed within bedrock channels during periods of fluvial incision. Over the past decade, several researchers have utilized ^{10}Be and ^{26}Al activities to model the exposure history of fluvially eroded bedrock surfaces in order to infer the timing and rate of river incision into rock (Burbank and others, 1996; Hancock, Anderson, and Whipple, 1998; Leland and others, 1998; Weissel and others, 1998; Pratt and others, 2002; Burbank and others, 2003).

Application of cosmogenic isotopes in tectonically active regions

Most cosmogenic dating of bedrock channel incision has focused on tectonically active regions. For example, dating of strath terrace surfaces bordering the Indus River indicates that, in the tectonically active Himalayas, river downcutting keeps pace with bedrock uplift by incising extremely rapidly through rock at 1 to 12 m/ka (Burbank and others, 1996; Leland and others, 1998). Cosmogenic exposure ages also provide evidence for climatically triggered cycles of aggradations within bedrock gorges, followed by re-excavation during ongoing tectonically-induced river incision (Pratt and others, 2002). Furthermore, coupling between rates of river incision and differential rates of bedrock uplift imply that bedrock erosion rates are very sensitive to changes in river gradient (Leland and others, 1998).

Application of cosmogenic isotopes in passive margin settings

Although the majority of Earth's surface is not tectonically active, very few studies consider river incision into bedrock on passive continental margins. Cosmogenic isotopes have been used to understand better slow and steady escarpment retreat in southeastern Australia (Wiessel and Seidl, 1997; Wiessel and Seidl, 1998). Although this application of cosmogenic dating does not address directly vertical rates of river incision through bedrock, the rate and style of escarpment retreat provides important information regarding the coupling of bedrock channel incision, hillslope processes, and the long-term development of the Australian passive margin.

FIELD AREA

Many large rivers (e.g. Susquehanna, Potomac, James, and Rappahannock) draining the central Appalachian Mountains flow through bedrock gorges as they drain the Atlantic passive margin. Holtwood Gorge, located along the lower reaches of the Susquehanna River harbors at least three prominent levels of well-preserved bedrock strath-terraces, which provide an ideal opportunity to investigate bedrock river incision on the Atlantic passive margin. The origin of these bedrock gorges, and their importance to understanding the long-term development and topographic persistence of the central Appalachian Mountains has been pondered for decades (e.g. Peltier, 1949; Reed, 1981; Thompson, 1990; Pazzaglia and others, 1993; Pazzaglia and others, 1994a and 1994b; Engel, 1996; Zen, 1997a and 1997b; Thompson and others, 2001), however, directly dating bedrock surfaces within them has not been possible. Holtwood Gorge is carved into the schist of the Appalachian Piedmont, which provides ample quartz, required for cosmogenic dating with ^{10}Be. A large sample population, and carefully designed sampling strategy allow me to constrain the timing, rate, and spatial patterning of passive margin bedrock channel incision along the Susquehanna River. While work for this thesis was underway, a similar study was conducted in Mather Gorge, along the Potomac River, located ~100 km to the south. While the northern half of the Susquehanna basin was glaciated during all Pleistocene glaciations, the Potomac basin remained ice-free (Braun, 1998) allowing us to investigate the potential effects of basin glaciation and associated meltwaters on the rate and timing of bedrock channel incision (Reusser and others, 2004).

RESEARCH OBJECTIVES

My research utilizes measurements of ^{10}Be produced by cosmic ray bombardment in >80 samples collected from fluvially-carved bedrock surface bordering the Susquehanna River to understand better the timing and nature of river incision through bedrock along one of the world's most prominent and ancient passive margins. The specific objectives of my work are as follows:

- quantify the ^{10}Be activity and model the exposure age of multiple bedrock samples collected along and between the three well-preserved levels of strath terraces within Holtwood Gorge along the lower reaches of the Susquehanna River,
- calculate both the vertical and longitudinal rate at which the Susquehanna River incised through bedrock during the carving of Holtwood Gorge,
- determine whether the timing and rate of this incision can be correlated to otherwise documented records of climate change, and its derivative effects during the late Pleistocene.
- refine this new application of cosmogenic dating by investigating the spatial pattern of nuclide activity at various scales on fluvially-carved bedrock landforms in order to understand better the style and tempo of bedrock channel incision along the Atlantic passive margin.

STRUCTURE OF THESIS

This thesis follows the guidelines of a "journal article thesis" as outline by the graduate college at the University of Vermont. Chapter 1 provides an overview of the study of river incision through bedrock, and its importance for understanding the development of landscapes in both tectonically active and passive settings. The specific goals of this project are laid out, and the utility of cosmogenically produced ^{10}Be to model the exposure history of fluvially eroded bedrock is introduced.

Chapter 2 is a journal article published on July 23, 2004 in *Science Magazine*. This article presents a sub-set of the data generated for my work on the Susquehanna River (this thesis), as well as a sub-set of the data generated from a similar study conducted on the Potomac River. Due to the brevity of reports published in *Science*, this chapter addresses only the "big picture" implication of the work conducted for this project.

Chapter 3 is a paper for submission to *The American Journal of Science*. This paper contains all cosmogenic data from the Susquehanna River, as well as a discussion of all methods and data analysis performed over the course of the project. Comprehensive review of literature pertaining to the long-term development of the Atlantic passive margin, the Susquehanna River, cosmogenic isotopes and their utility for constraining the timing and rate of bedrock incision, the study of bedrock channel incision over a range of time scales, and proxies for climate change during the late Pleistocene can be found in the Introduction, Background, Discussion, and Implications sections of this chapter.

Chapter 4 provides a summary of the overall findings of this research and their contribution to understanding the style of river incision into bedrock. Future avenues of research are also introduced and discussed in this chapter. A comprehensive bibliography, as well as two appendices, which provide a more in depth discussion of several methods employed in my work, follow the main text.

CHAPTER 2: Paper published in *Science Magazine*

Rapid late Pleistocene incision of Atlantic passive margin river gorges

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ABSTRACT:

The direct and secondary effects of rapidly changing climate caused large rivers draining the Atlantic passive margin to incise quickly into bedrock beginning about 35,000 years ago. 10-Beryllium, measured in samples from bedrock fluvial terraces, shows that both the Susquehanna and Potomac Rivers incised 10- to 20-meter deep gorges along steep, convex lower reaches during the last glacial cycle. This short-lived pulse of unusually rapid downcutting ended by 12,000 years ago. The timing and rate of downcutting are similar on the glaciated Susquehanna and unglaciated Potomac Rivers indicating that regional changes, not simply glacial meltwater, initiated incision.

ARTICLE TEXT:

A fundamental control on the development of landscapes is the rate at which rivers cut through rock. River incision into bedrock translates the effects of climate and tectonics through drainage networks, thus controlling rates of landscape evolution (*1, 2*). Despite broad interest in understanding the style and timing of landscape change, only a handful of studies have directly measured the rate and timing of fluvial bedrock incision. Most of these studies quantifying bedrock incision rates have been conducted in tectonically active regions (*3*-*5*); however, the majority of Earth's surface is tectonically quiescent including passive margins around the globe for which river incision rates are largely unknown. In this report, we use 59 measurements of cosmogenic ^{10}Be (Tables S1 and S2) to quantify the rate and timing of bedrock incision along two of the largest rivers draining the Atlantic passive margin, the Susquehanna (70,200 km^2) and the Potomac (29,900 km^2; Fig. 1).

Over millions of years, large rivers draining the Atlantic passive margin have carved broad valleys into rocks of the Appalachian Piedmont where river profiles are convex along their lower reaches (Fig. 2C&D; *6-8*). Long-term, gradual lowering of the Susquehanna and Potomac Valleys (~0.01 to 0.02 m/ka) into the Piedmont uplands reflects a combination of slow flexural uplift of the Atlantic margin from offshore sediment loading, isostatic response to denudation, and protracted late Cenozoic sea-level fall (*7-9*). Within these broad valleys are narrow gorges, bounded by bare-rock terraces.

The Susquehanna River narrows and deepens in its lower reaches passing through a series of bedrock gorges. Holtwood, the largest gorge, is approximately 5 km long, 1 km wide, and incised into a broad valley set nearly 150 m into the Piedmont uplands. This gorge contains three distinct levels of bedrock terraces (Fig. 2A), as well as weathered high points representing remnants of older, degraded levels. The northern half of the Susquehanna Basin has been glaciated repeatedly (*10*); thus, glacial meltwater and sediment passed down the Susquehanna channel and through Holtwood Gorge.

Similarly, the Potomac River lies more than 100 meters below the uplands within a broad outer valley. The river drops nearly 20 m as it passes over Great Falls and through 3-km-long Mather Gorge. The gorge is 75 to 125 m wide (*11*) and confined by a km-wide bedrock terrace (Fig. 2B). This terrace is studded with fluvially rounded outcrops standing decimeters to meters above the bedrock surface. The Potomac Basin remained glacier-free during the Pleistocene (*10*).

We sampled fluvially eroded bedrock surfaces exposed as these rivers incised toward younger and lower levels. Most outcrops preserved distinct fluvial forms, suggesting little erosion since abandonment and exposure (*12*). Modeling suggests that ^{10}Be ages are not substantially affected by floodwater absorption of cosmic rays (*13*) and no sediment covers the outcrops today. Rapid incision and the low ^{10}Be content of samples collected from the modern bank of the Potomac River (*14*) allow us to model ^{10}Be concentrations directly as terrace abandonment ages.

Rates of downcutting on both rivers dramatically increased after 35 ka as evidenced by abandonment and exposure of prominent bedrock terraces defining the gorges on both the Susquehanna and Potomac Rivers at 30 $\pm$ 6.9 ka (n=10) and 33 $\pm$ 5.4 ka (n=8), respectively (Fig. 3A&B). Four samples collected along an elevation transect in the middle of Holtwood Gorge indicate that from >100 to 32 ka, the Susquehanna River incised at <0.2 m/ka. From 32 to 16 ka, the rate of downcutting more than doubled to ~0.5 m/ka, closely matching a rate of ~0.6 m/ka (r^2=0.94; 31 to 15 ka) calculated using 14 samples along a cross-section in upper Holtwood Gorge. The mean exposure age of the lowest terrace suggests that rapid incision ceased on the Susquehanna by 14 ka (Fig. 3A).

Incision on the Potomac River below Great Falls began at a similar time, continued at a similar rate, and ended coincident with the end of incision on the Susquehanna. Samples collected down the wall of lower Mather Gorge to just above mean water level, yield an incision rate of ~0.8 m/ka (r^2=0.90, n=6) beginning at 37 ka and ending at 13 ka (Fig. 4B). Other outcrops, standing only meters above the terrace that bounds the gorge, have model ^{10}Be ages ranging from 53 to 86 ka, suggesting that although the Potomac was indeed incising prior to formation of the gorge (~33 ka), it was doing so at a much slower rate. Three samples, collected just downstream of Great Falls, suggest that the Potomac incised here later and longer but at a slower rate (0.5 m/ka; 27 ka to 8 ka; Fig. 4B).

These data demonstrate that rivers draining the Atlantic passive margin are capable of periodically incising through bedrock quickly. The bedrock incision rates we measured are slower than the 1 to 12 m/ka calculated from cosmogenic data for tectonically active regions such as the Himalayas (*3, 4*). Yet, the pulse of incision we measured was one to two orders of magnitude faster than long-term rates of river downcutting on the Atlantic passive margin (*7, 8, 15*). The question remains, what drove this episode of rapid Late Pleistocene incision?

While a simple explanation for the cutting of these bedrock gorges is not yet possible, it appears that climate change, acting through a variety of primary and secondary effects, initiated and maintained incision through the late Pleistocene (*16*). For example, the timing of terrace abandonment and the last major drop in sea-level are similar (FIG. 3A-C). Driven by rapid ice sheet growth, the most pronounced sea-level drop of the last glacial cycle occurred about 32 ka (*17-20*), coincident with initiation of rapid incision along both rivers. If this final sea-level drop was the proximal cause of rapid late Pleistocene gorge incision, then the effect must have translated instantaneously across the already-drained continental shelf and through the lower bedrock reaches of both rivers.

In addition, modeling suggests that the glacial forebulge may have raised the land surface near the gorges by tens of meters (*21*) increasing river gradients, stream power, and the potential for incision. However, the timing and lateral extent of this uplift, resulting from mantle displacement by the growing mass of Laurentide Ice (*22*), remain uncertain. When gorge incision began, ice volume was ~50% of maximum (*23*) suggesting that most forebulge-induced uplift in the vicinity of Holtwood and Mather Gorges probably post-dated measured incision rate increases; thus, it is unlikely that the forebulge initiated incision between 30 and 33 ka. However, forebulge-induced uplift likely helped maintain high rates of incision during and perhaps after the last glacial maximum.

Because most bedrock erosion occurs during floods (*24, 25*), increases in flood magnitude and/or frequency could have driven late Pleistocene incision. Although there are no paleo-discharge records for these rivers, other data can be used to infer changes in flood frequency and magnitude over time. Good correlation between the Greenland storminess record (Fig. 3D; *26*) and that from northeastern North America over the past 13 ka (*27*) suggests the Greenland record is a reasonable proxy for geomorphically-effective flood events on the Susquehanna and Potomac Rivers. In addition, cooling climate during the last glacial, as inferred from the GISP2 ice-core record (Fig. 3E; *28-31*), probably changed runoff dynamics within both basins increasing the number, severity, and duration of snowmelt floods. Over the past ~75 years, such floods represent ~75% and ~65% of the largest 25 discharge events on the Susquehanna and Potomac Rivers, respectively (*32*). The GISP2 records of increased storminess and falling temperatures in the North Atlantic are coincident with the onset of rapid gorge incision ~33 ka. Furthermore, storminess rapidly decreased and temperatures climbed ~15 ka, coincident with the end of rapid incision on both rivers (Fig. 3).

High rates of bedrock incision on the Susquehanna and Potomac Rivers were initiated and sustained during a period of cold, stormy, and unstable climate (Fig. 3). Incision ceased 13 to 14 ka, just prior to the transition into the warmer and more climatically stable Holocene. Since both the timing and rate of gorge incision on the glaciated Susquehanna and the unglaciated Potomac rivers are similar, regional forcings, not glacial meltwater, must have initiated downcutting. Our dating does not altogether discount the effects of meltwater; indeed, an increase in the rate of incision as well as the formation of a distinct terrace (Level 2; Fig. 3A) on the Susquehanna ~19 ka (an effect not seen on the unglaciated Potomac) is coincident with the beginning of glacial retreat and increased meltwater discharge (*33*).

Cosmogenic dating appears to implicate climate change as the driver of late Pleistocene passive margin river incision into rock; yet, modeling results suggest that sediment availability is also a critical variable controlling bedrock incision (*1, 34, 35*). Although we have no quantitative record of paleo-sediment load, there are discontinuous low gravel terraces along the Susquehanna River through Holtwood Gorge (*7*) suggesting a change in sediment dynamics during the Pleistocene. A change in the relationship between flow and sediment load could have removed bed armoring, allowing incision, or increased tool loading, promoting abrasion (*34, 35*). Rapid excavation of alluvial fills in response to falling sea-level could have exposed broad straths previously blanketed with sediment, thus allowing the initiation of rapid incision.

Extensive dating has now constrained the exposure age of bedrock terraces and the rate at which two major Atlantic passive margin rivers incised through rock; however, such dating alone does not explain why incision occurred. For the Susquehanna and Potomac Rivers, continued flexural upwarping of the Atlantic passive margin (*1*) steepens river gradients making these convex lower reaches predisposed to incision when boundary conditions, such as climate, change as they did in the Late Pleistocene. Exactly why this and other episodes of incision occurred when and where they did will only become clear when we better understand the complex interactions between land-level change, river hydraulics, sediment dynamics, and bedrock erosion.

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River, we used flow data from March, 1930 to present recorded at the Little Falls Pump Station, MD (USGS 01646500).

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37. This study was funded by NSF Grant EAR0003447 to P. Bierman, and D.O.E. contract no. W-7405-Eng-48. R. Alley, I. Winograd, F. Pazzaglia, H. Markewich, K. Whipple, A. Noren, and three anonymous referees reviewed the manuscript. E. Butler provided field assistance.

Supporting Online Material

www.sciencemag.org

Methods

Figure S1

Tables S1 & S2

FIGURE CAPTIONS:

Figure 2.1: Map of the Atlantic passive margin and the Susquehanna and Potomac River Basins. Both Holtwood (black star) and Mather Gorges (black circle) lie near the Appalachian Piedmont/ Coastal Plain transition. During the last glacial maximum, ice

covered ~40% of the Susquehanna Basin; the Potomac Basin remained free of glacial ice (*10*).

Figure 2.2: Bedrock terraces within Holtwood and Mather Gorges, and longitudinal profiles of the lower Susquehanna and Potomac Rivers. **A**: Terrace levels 1 and 3 in the middle of Holtwood Gorge along the Susquehanna River at low flow conditions. Level 2 is not preserved at this location. At higher discharges, lower strath is inundated. Person in foreground for scale. **B**: View across Mather Gorge along the Potomac River at high flow (1700 m^3/s). Well-defined strath terrace treads on both banks. Two meter black bar for scale. **C:** Long-profile of the lower Susquehanna River (*6*) showing the location of Holtwood Gorge. **D:** Long-profile of the lower Potomac River (*6*) showing the location of Great Falls and Mather Gorge. (m asl) is meters above sea-level.

Figure 2.3: Summary of the timing of incision and terrace abandonment within Holtwood and Mather Gorges in relation to otherwise documented changes in climate and sea-level. All panels are displayed on the same time axis (0 to 100 ka). Panels **A & B**: Schematic diagrams of Holtwood and Mather gorges conveying ^{10}Be model age data and important geomorphic characteristics of each gorge. LR-01 (Panel A, level 4) was collected from a heavily weathered surface and is given as a lower limiting age. Panel **C**: Late Pleistocene sea-level record derived from Huon Peninsula (*18*). Roman numerals are oxygen isotope stages. Panel **D**: GISP2 sea salt (s.s.) Na record (*26*) resampled to a 50 yr interval with Analyseries™, and smoothed with a 10 point (thin line) and 100 point

moving window (bold line). Panel **E**: Paleotemperature estimates inferred from the GISP2 ice core record (*28*) resampled to a 50 yr interval with Analyseries™, and smoothed with 10 point (thin line) and 100 point moving window (bold line). Heinrich events (H1 through H6) from dating of Deep Sea Drilling Project (DSDP) site 609 core (*36*). Hatched areas in **C**, **D**, and **E** show the episode of rapid incision we measured. (m asl) is meters above sea-level.

Figure 2.4: Plots of incision rates at discrete locations or along cross-sections within each gorge. The shift between upstream and downstream transects within both Holtwood (**A**) and Mather (**B**) Gorges is due largely to river gradients. Data points labeled as "minimum ages" are from weathered outcrops and thus provide lower limiting ages. In panel **A**, the minimum age sample was collected from a heavily eroded island peak standing >10 m above the prominent Level 3 terrace. In panel **B**, the minimum age samples (labeled with black diamonds) were collected from bedrock knobs standing decimeters to meters above the prominent strath surface. Dashed arrows indicate flow direction. (m asl) is meters above sea-level.

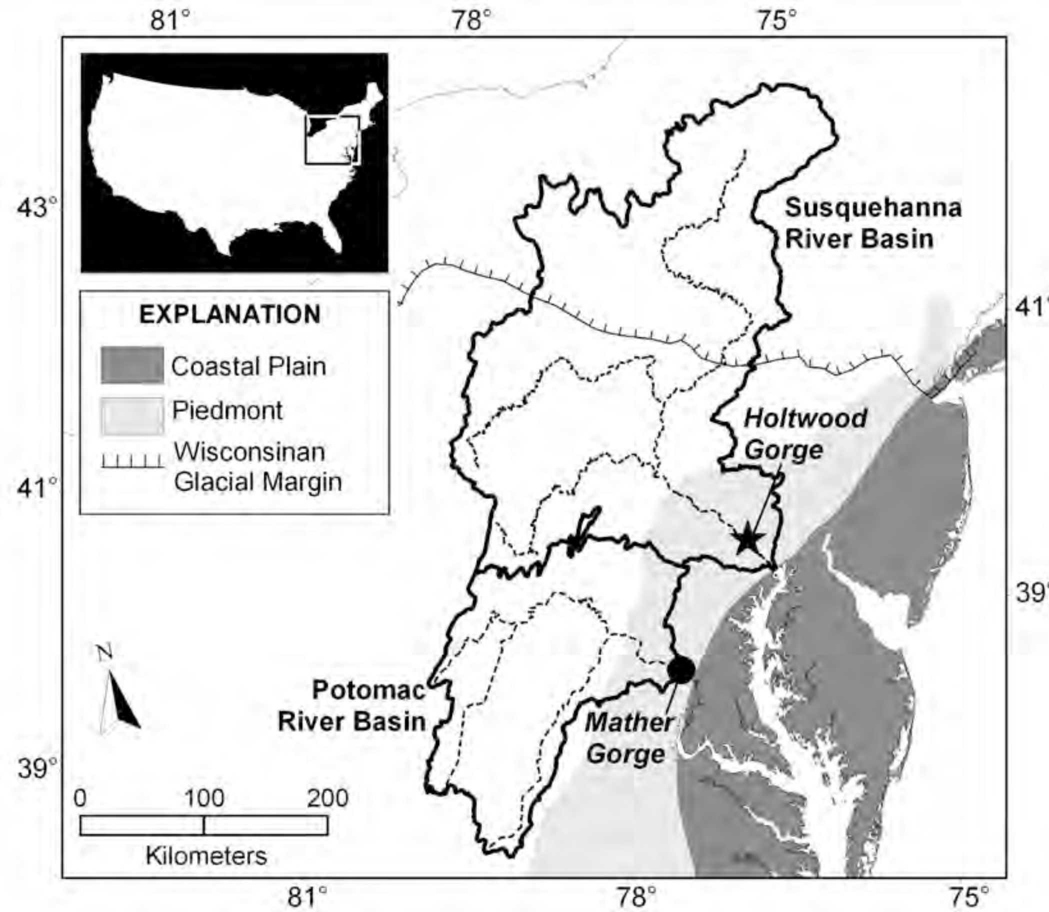

FIGURE 2. 1 Map of the Atlantic Passive Margin and the Susquehanna and Potomac Rivers. Both Holtwood (Black Star) and Mather Gorges (Black Circle) lie near the Appalachian Piedmont/ Coastal Plain transition.

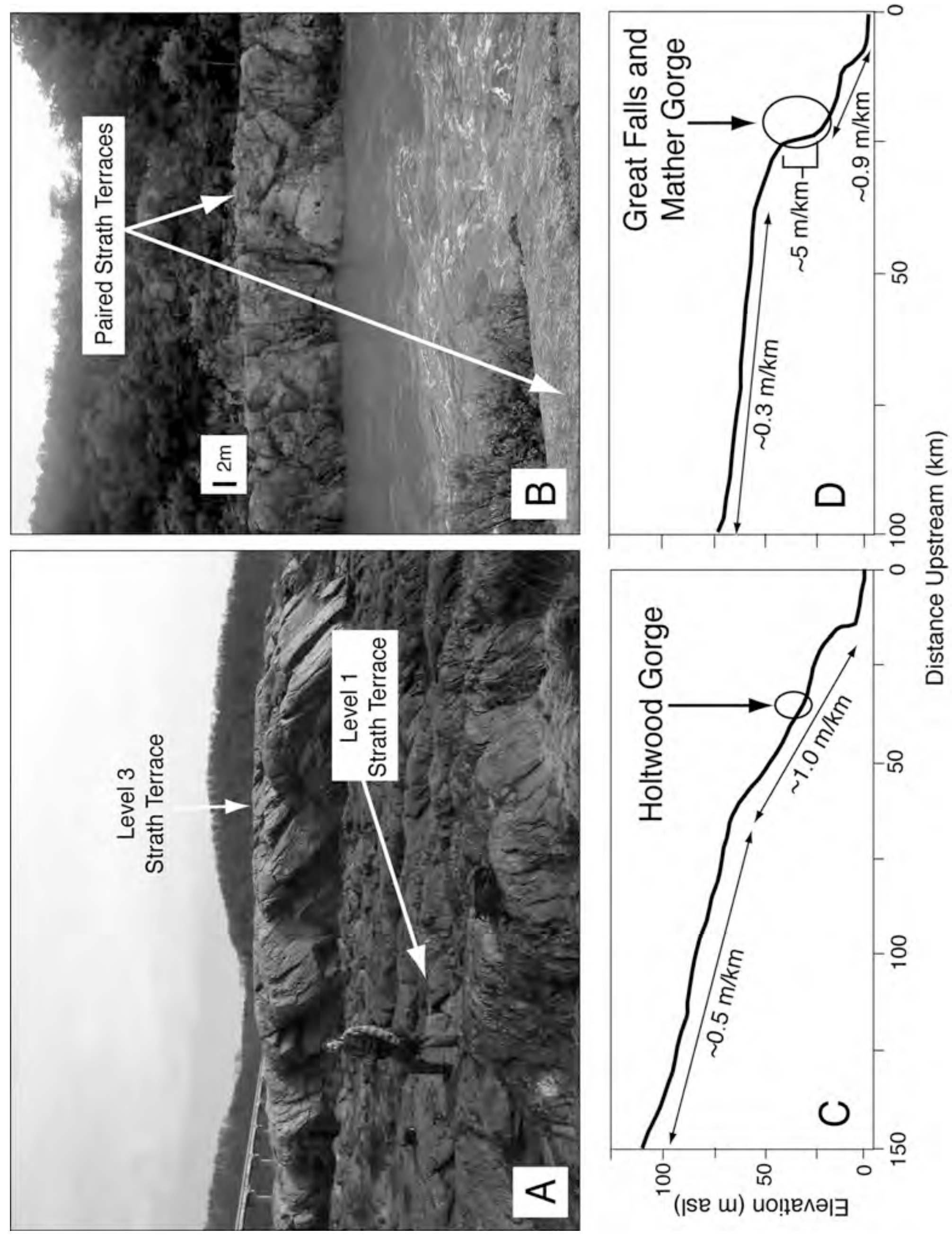

FIGURE 2. 2 Bedrock Terraces within Holtwood and Mather Gorges, and longitudinal profiles of the lower Susquehanna and Potomac Rivers.

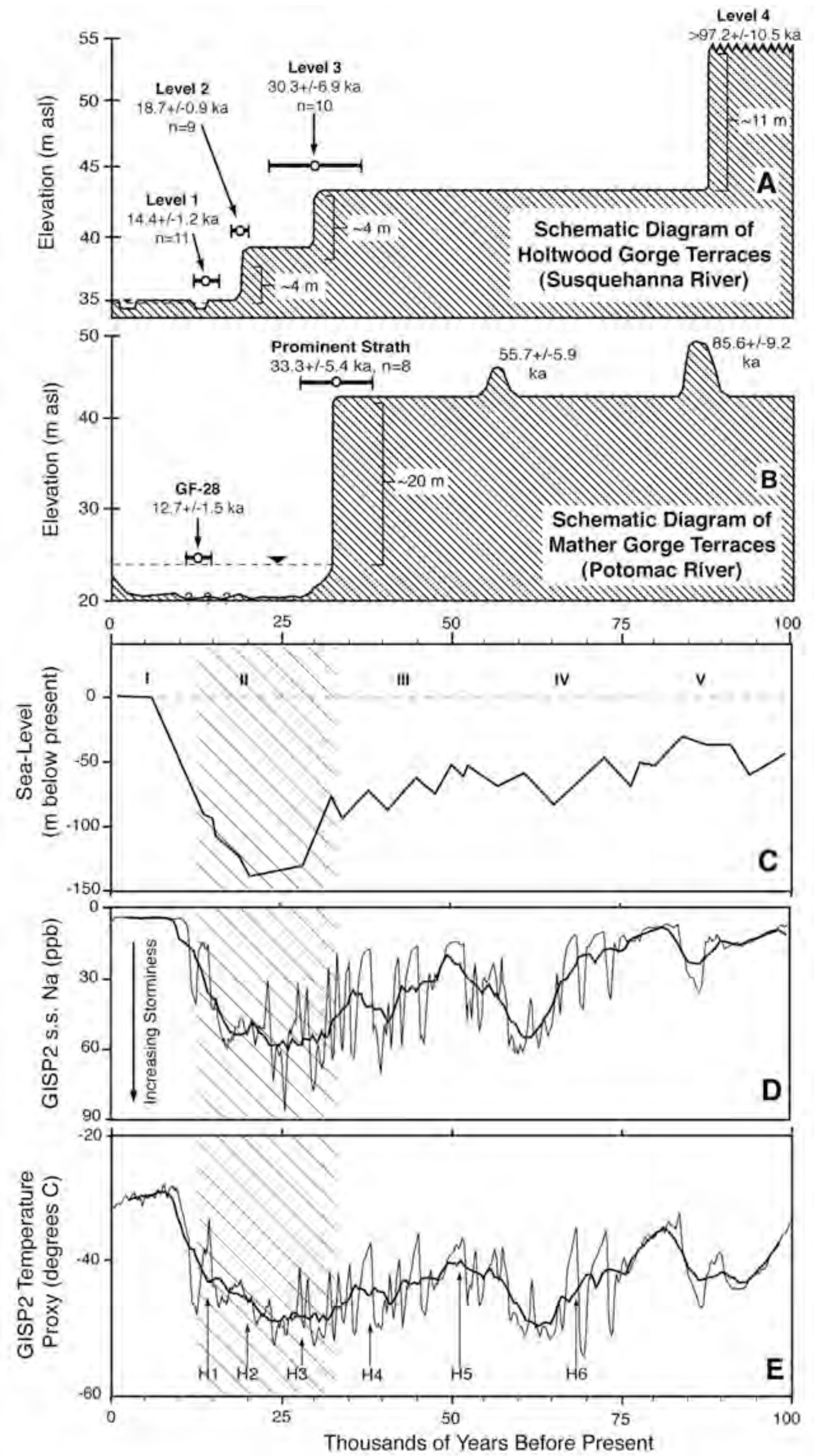

FIGURE 2. 3 Summary of the timing of incision and terrace abandonment within Holtwood and Mather Gorges in relation to otherwise documented changes in climate and sea-level.

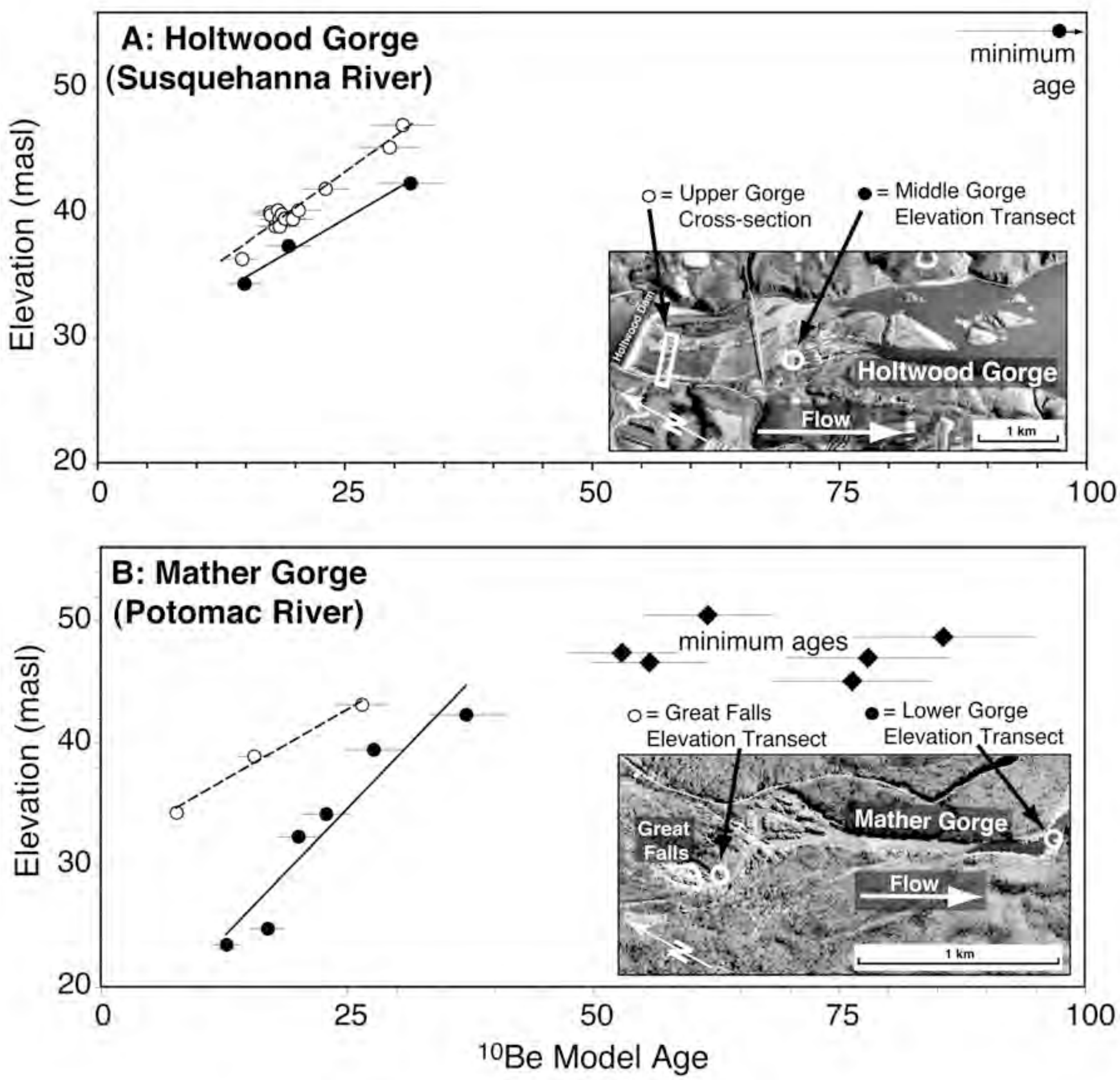

FIGURE 2. 4 Plots of incision rates at discrete locations or along cross-sections within Holtwood and Mather Gorges.

SUPPORTING ONLINE MATERIAL

MSID: 1097780

Title: Rapid Late Pleistocene Incision of Atlantic Passive Margin River Gorges

Authors: L. Reusser, P. Bierman, M. Pavich, E. Zen, J. Larsen, R. Finkel.

Methods:

Field Mapping and GPS Work:

We identified and mapped levels of strath terraces within Holtwood and Mather Gorges using air photos, topographic quadrangle maps, field observations, as well as results for previous mapping efforts (e.g. S1). All UTM coordinates for sampled sites within both gorges are reported in Horizontal Datum NAD27 CONUS (North American Datum, 1927, Continental United States). We collected GPS data in Holtwood Gorge using a differential unit (Trimble 4400™) offering decimeter scale precision. In Mather Gorge, we collected GPS data using a Coast Guard beacon-corrected unit (Trimble ProXR™) offering meter scale precision.

Sampling Strategies and Sample Collection:

Within both Holtwood Gorge and Mather Gorge, along the Susquehanna and Potomac Rivers respectively, we collected samples from fluvially eroded bedrock surfaces along and between levels of strath terraces. We collected clusters of samples at a number of spatial scales (small scale: two to three samples collected within meters of one another on contiguous terrace remnants, longitudinally: strings of samples collected along each terrace level from one end of the gorge to the other, and vertically: series' of samples collected in elevation transects at discrete locations, or along cross-sections within each gorge) in order to measure the spatial variance in ^{10}Be and model age along bedrock erosional surfaces, and to estimate rates of downcutting through the late Pleistocene. We used a hammer and chisel to collect ~1 kg of schist, or vein quartz where available, from each sampled outcrop.

Sample Preparation, Isotopic Analysis, and Exposure Age Modeling:

We processed samples using standard techniques (S2) at the University of Vermont Cosmogenic Laboratory. Using the accelerator mass spectrometer at the Lawrence Livermore Laboratory in Livermore California, we measured ratios of ^{10}Be/^{9}Be. We calculated exposure ages for each sampled surfaces using a sea-level high-latitude ^{10}Be production rate of 5.2 atoms g^{-1} yr^{-1} adjusted for elevation, latitude, and geometry of the sample site considering neutron-only corrections (S3, S4). Corrections made for site geometry include sample thickness, surface dip, and topographic shielding. Uncertainties assigned to ages represent propagated analytic errors (1 sigma) in carrier addition and AMS measurement, as well as a 10% (1 sigma) uncertainty in ^{10}Be production rates including calibration, normalization, and geometric corrections.

We used an interpretive model of rapid exposure followed by no erosion or burial subsequent to the initial exposure of sampled bedrock surfaces. The exposed bedrock is hard and fresh; quartz veins rarely protrude more than a cm from the surface. There is no evidence that outcrops were buried by a significant thickness of fluvial sediment, snow, or loess during or after the carving of both gorges.

^{10}Be activities and model ages for independently processed and measured laboratory replicates from both gorges (Holtwood Gorge: LR-04c and LR-04cX; Mather Gorge: GF-37 and GF-37X) agree within 2 percent. Similarly, nuclide and model age results for small-scale variance studies (clusters of three samples collected within 5 to 10 meters of one another) conducted on each of the three prominent levels of strath terraces with Holtwood Gorge agree within 10 percent (Level 1: LR-04a, b & c; Level 2: LR-36a, b &c; Level 3: LR-17a, b & c).

<u>Water Inundation Modeling:</u>

Incoming cosmic rays, responsible for the production of radionuclides such as ^{10}Be, are absorbed by material overlying a sampled surface. The effective production rate decreases exponentially with depth as a function of the density of the material through which cosmic rays pass (3). In the case of bedrock erosional surface within river channels, it is uncertain whether ^{10}Be model ages calculated directly from accelerator measurements reflect the entire exposure history of bedrock surfaces. If the integrated average depth of an overlying water column through time is substantial, model ages could appear too young.

We used HEC-RAS version 3.1 (www.hec.usace.army.mil) to estimate the amount of cosmic radiation absorbed by outcrop-covering floodwaters in Holtwood Gorge (Susquehanna River) through time. We modeled the gorge using 10 cross sections taken from detailed surveys drafted during the planning of Holtwood Dam. We modeled the water depth over the lowest strath (Level 1) using ~70 years of daily flow records from the Marietta gauging station located ~50 km upstream from the gorge. The effective production rate for each sample site for each day of record was calculated using the modeled water depth and integrated through time to estimate the percentage of radiation lost to overlying water under modern hydrologic conditions. We constrained the model using observed water depths at known discharges (Figure S1). Results suggest that ^{10}Be exposure ages for samples from the lowest strath represent on average 90% of their total possible exposure histories. The effect on each sample depends on its elevation above mean water level. Shielding for many outcrops is negligible under modern hydrologic conditions. Although there are no discharge estimates for the Susquehanna during the late Pleistocene, we speculate that water shielding had less effect on samples from higher terraces because the channel bed was actively and rapidly lowering during glacial times.

For acquisition of modeling spreadsheets, and/or to discuss the modeling strategy, please email Luke Reusser at the University of Vermont (lreusser@uvm.edu). Daily flow data can be obtained from the U.S. Geological Survey water website, Marietta, PA gauging station (USGS 01576000; http://waterdata.usgs.gov/nwis/rt).

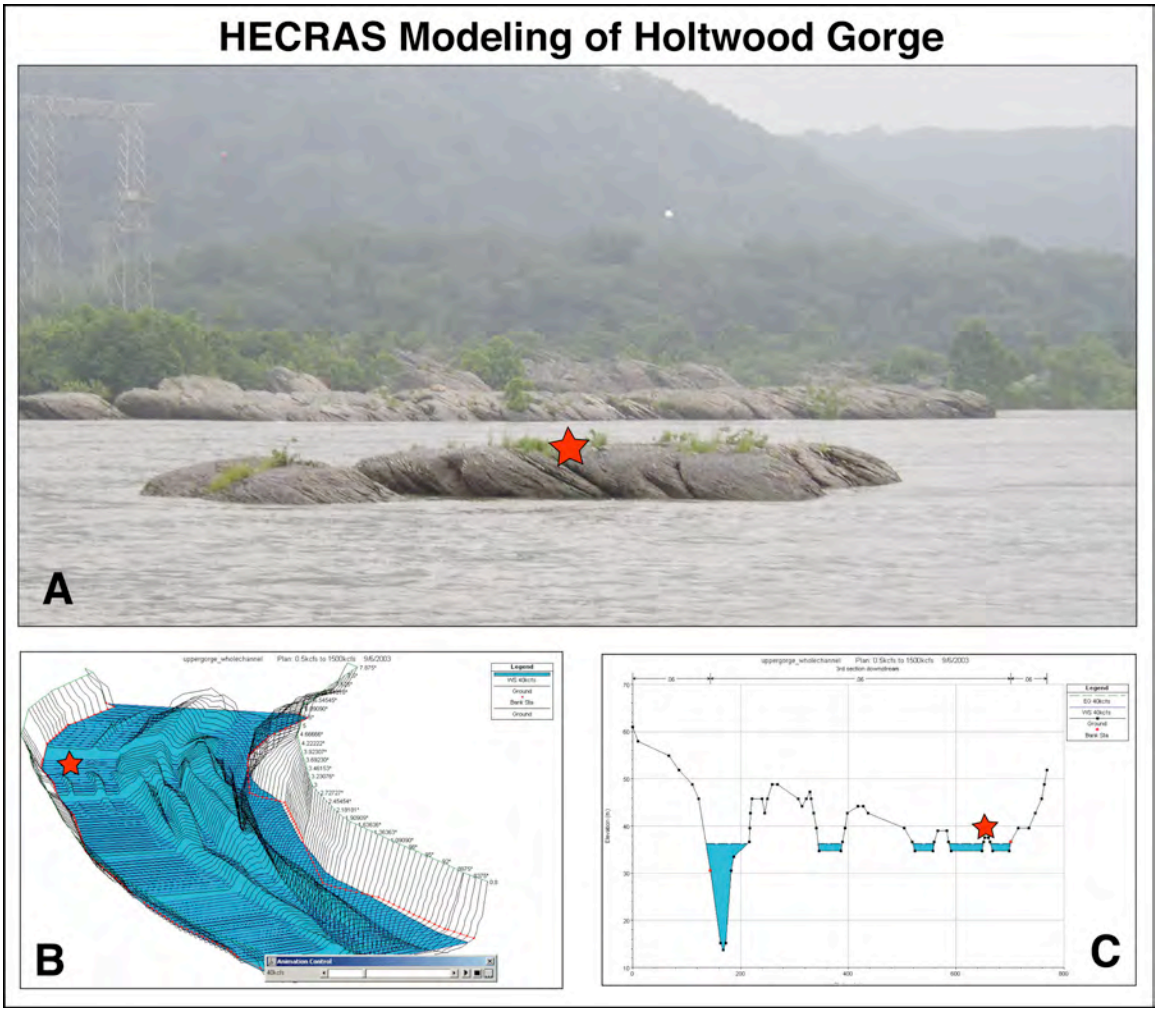

Figure 2.S1: Example of a calibration photo used to constrain water depths for the HECRAS model within Holtwood Gorge at known discharges. Photo (**A**) was taken from the western shore of the Susquehanna River in the upper gorge at a discharge of ~40 kcfs. River flow is from left to right (NW to SE). The X-Y-Z reconstruction (**B**), and a representative cross-section (**C**) of Holtwood Gorge show the modeled water depth at 40 kcfs. The red star in **A, B & C** is the same point within the gorge. Bank and bed roughness coefficients (Manning's *n* values) were adjusted so the model correctly reproduced stage elevation at known discharges.

TABLE 2. 1 GPS and isotopic data for bedrock samples collected within Holtwood Gorge along the Susquehanna River. Elevations are in meters above sea-level (masl).

Sample ID	Terrace Level	Elevation (masl)	Easting (m)	Northing (m)	^{10}Be Measured (10^4 atoms g^{-1})	Model Age (ky) ¶
LR-52	1	36.1	385435.2	4408936.8	6.29 ± 0.27	12.9 ± 1.4
LR-59	1	36.7	386058.1	4409019.7	7.40 ± 0.40	15.1 ± 1.7
LR-56	1	36.3	385697.8	4408642.9	7.08 ± 0.27	14.5 ± 1.6
LR-55	1	35.8	386179.7	4408302.7	6.44 ± 0.34	13.1 ± 1.5
LR-54	1	36.7	386178.3	4408299.6	8.28 ± 0.32	17.0 ± 1.8
LR-51	1	33.9	387055.9	4407765.8	7.34 ± 0.31	15.1 ± 1.6
LR-16	1	34.2	387275.9	4407723.9	6.92 ± 0.26	14.1 ± 1.5
LR-50	1	33.2	387431.1	4407765.7	6.79 ± 0.29	14.0 ± 1.5
LR-49	1	32.9	387846.1	4407466.7	6.43 ± 0.46	13.2 ± 1.6
LR-04ave*	1	34.3	386688.9	4407671.5	7.19 ± 0.29	14.8 ± 1.6
LR-04a	1	34.5	386688.9	4407670.0	7.98 ± 0.31	16.4 ± 1.8
LR-04b	1	34.3	386692.4	4407681.1	6.75 ± 0.29	13.9 ± 1.5
LR-04c	1	34.2	386685.2	4407663.3	6.82 ± 0.28	14.0 ± 1.5
LR-04cX †	1	34.2	386685.2	4407663.3	6.90 ± 0.33	14.2 ± 1.6
LR-35	2	39.6	385465.8	4408700.2	9.19 ± 0.35	18.9 ± 2.0
LR-26	2	38.9	385609.2	4408766.8	9.02 ± 0.30	18.3 ± 1.9
LR-27	2	39.0	385653.1	4408747.9	8.82 ± 0.29	17.9 ± 1.9
LR-33	2	39.5	385688.2	4408725.2	8.98 ± 0.31	18.3 ± 1.9
LR-34	2	39.5	385714.2	4408704.4	9.63 ± 0.34	19.7 ± 2.1
LR-32	2	40.2	385755.3	4408670.9	9.92 ± 0.35	20.2 ± 2.2
LR-37	2	40.0	385575.8	4408529.6	8.57 ± 0.31	17.4 ± 1.9
LR-40	2	37.4	386635.0	4407757.1	9.45 ± 0.50	19.2 ± 2.2
LR-36ave*	2	40.0	385496.0	4408619.0	8.86 ± 0.33	18.1 ± 1.9
LR-36b	2	39.8	385496.2	4408627.5	8.60 ± 0.32	17.4 ± 1.9
LR-36a	2	40.2	385491.4	4408616.8	8.92 ± 0.34	18.2 ± 2.0
LR-36c	2	39.9	385500.4	4408612.7	9.07 ± 0.35	18.6 ± 2.0
LR-31	in §	42.0	385724.8	4408806.3	11.3 ± 0.4	23.0 ± 2.4
LR-30	in §	43.7	385769.0	4408811.4	17.5 ± 0.6	35.7 ± 3.8
LR-29	3	47.0	385827.6	4408840.9	15.3 ± 0.5	30.8 ± 3.3
LR-29	3	47.0	385827.6	4408840.9	15.3 ± 0.5	30.8 ± 3.3
LR-38	3	45.2	385602.8	4408484.3	14.6 ± 0.6	29.4 ± 3.2
LR-41	3	41.4	386720.3	4407708.3	11.0 ± 0.4	22.3 ± 2.4
LR-02a	3	42.4	386788.5	4407571.0	15.5 ± 0.5	31.6 ± 3.3
LR-23	3	42.0	386904.8	4407614.7	9.90 ± 0.39	20.2 ± 2.2
LR-25	3	45.0	387161.8	4407622.8	17.0 ± 0.6	34.4 ± 3.7
LR-12	3	44.6	387600.3	4407614.9	15.8 ± 0.6	32.4 ± 3.5
LR-47	3	37.8	389447.6	4405836.4	22.1 ± 0.7	45.3 ± 4.8
LR-17ave*	3	43.6	387275.6	4407683.6	12.8 ± 0.5	25.9 ± 2.8
LR-17a	3	43.8	387273.3	4407683.6	13.3 ± 0.5	26.8 ± 2.9
LR-17b	3	43.7	387275.5	4407684.1	12.4 ± 0.4	25.0 ± 2.7
LR-17c	3	43.5	387278.0	4407682.9	12.7 ± 0.5	26.0 ± 2.8
LR-01	4	54.6	386953.0	4407462.2	47.4 ± 1.6	97.2 ± 10.5

* Samples labeled "ave" are the averages of all fields of data for spatial replicates a, b, and c for that particular sample site. Spatial replicates consist of three samples collected within 5 to 10 meters of one another. † LR-04cX is an independently processes and measured laboratory replicate of LR-04c. § "in" in the terrace level field indicates that samples were collected between the second and third terrace levels. ¶ Age uncertainties include propagated analytic errors (1 sigma) in carrier addition and AMS measurement, and +/-10% (1 sigma) uncertainty in 10-Be production rate.

TABLE 2. 2 GPS and isotopic data for bedrock samples collected within Mather Gorge along the Potomac River. Elevations are in meters above sea-level (masl).

Sample ID	Description *	Elevation (masl)	Easting (m)	Northing (m)	^{10}Be activity (10^4 atoms g^{-1})	Model Age (ky) §
GF-21	PS/CHT	42	305651	4316940	17.8 ± 0.6	37.1 ± 3.9
GF-29	PS	39	305478	4317077	17.8 ± 0.7	38.1 ± 4.1
GF-32	PS	44	305331	4317611	18.8 ± 0.7	38.8 ± 4.2
GF-33	PS	47	304998	4318280	15.6 ± 0.5	32.4 ± 3.4
GF-40	PS	46	305164	4318186	18.2 ± 0.6	37.5 ± 4.0
GF-65	PS/GFT	43	304964	4318557	12.9 ± 0.4	26.5 ± 2.8
GF-37	PS	44	304792	4318599	12.5 ± 0.5	25.5 ± 2.7
GF-37X †	PS	44	304792	4318599	12.7 ± 0.5	25.9 ± 2.8
GF-46	PS	47	304991	4318736	14.9 ± 0.5	30.2 ± 3.2
GF-42	High PS	47	305258	4317839	26.8 ± 0.9	55.7 ± 5.9
GF-43	High PS	47	305230	4317859	25.6 ± 0.8	52.9 ± 5.6
GF-31	High PS	47	305394	4317349	37.5 ± 1.1	77.9 ± 8.3
GF-35	High PS	45	305372	4317142	36.8 ± 1.2	76.3 ± 8.1
GF-38	High PS	49	304740	4318427	41.7 ± 1.3	85.6 ± 9.2
GF-39	High PS	51	304765	4318443	30.3 ± 0.9	61.7 ± 6.5
GF-22	CHT	39	305663	4316947	11.6 ± 0.4	27.7 ± 3.0
GF-23	CHT	34	305664	4316954	9.37 ± 0.3	22.8 ± 2.4
GF-25	CHT	32	305681	4316952	8.88 ± 0.4	20.0 ± 2.2
GF-27	CHT	25	305674	4316965	7.59 ± 0.3	16.9 ± 1.9
GF-28	CHT	24	305650	4316970	5.82 ± 0.3	12.7 ± 1.5
GF-66	GFT	39	304941	4318549	7.59 ± 0.3	15.5 ± 1.7
GF-67	GFT	34	304932	4318542	3.72 ± 0.2	7.6 ± 0.8

* Abrieviations in the description field indicate from what part of Mather Gorge the samples were collected and/or what kind of analysis they were used for. PS=prominent strath level, High PS=moderately weathered high points on the prominent strath level, CHT=lower gorge (Cowhoof Rock) vertical transect, and GFT=Great Falls vertical transect. † GF-37x is an independently processed and measured laboratory replicate of GF-37. § Age uncertainties include propagated analytic errors (1 sigma) in carrier addition and AMS measurement, and +/-10% (1 sigma) uncertainty in 10-Be production rate.

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S2. P. Bierman, M. Caffee, *Am. J. of Sci.* **301**, 326 (2001).

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S4. A. Dunne, C. Elmore, P. Muzikar, *Geomorphology* **27**, 3 (1999)

CHAPTER 3: Paper for submission to *The American Journal of Science*

Late Pleistocene bedrock channel incision along the U.S. Atlantic passive margin: Holtwood Gorge, Susquehanna River, Pennsylvania

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ABSTRACT

We use ^{10}Be to decipher when, how fast, and why the Susquehanna River incised through bedrock along the east coast of North America, one of the most prominent and ancient passive margins. Although the rate at which large rivers incise rock is a fundamental control on the development of landscapes, very little is known about how quickly such incision occurs either in tectonically active environments or along passive margins.

Exposure ages of fluvially-carved bedrock strath-terraces preserved within Holtwood Gorge demonstrate that even along the Atlantic passive margin, large rivers are capable of incising through rock for short periods of time at rates approaching those recorded in the tectonically active Himalaya. Eighty-one samples, collected along, between, and above the three prominent levels of terraces within the gorge, indicate that the Susquehanna incised more than 10 m into the Appalachian Piedmont during the late Pleistocene. Beginning between ~45 ka and ~35 ka, incision accelerated dramatically, and continued at a rapid rate until ~14 ka. This phase of rapid incision, also measured within Mather Gorge along the Potomac River located ~100 km to the south, correlates well with a period of cold and stormy climate recorded by the GISP2 ice core, central Greenland. Unstable climate during the late Pleistocene increased the frequency and magnitude of flood events capable of exceeding thresholds for bedrock erosion, thus enabling both the Susquehanna and Potomac Rivers to incise quickly into rock.

^{10}Be-constrained rates of incision range from 0.8 to 0.4 m/ky between ~45 and ~14 ky, almost two orders of magnitude faster than long-term estimates of integrated bedrock incision rates since the middle Miocene. Discordance between short- and long-term rates indicates that incision through bedrock on this passive margin occurs episodically. Driven by long-term flexure of the Atlantic passive margin as it responds to offshore deposition of sediment, the lower reaches of the river have remained oversteepened since the Miocene, increasing stream gradients and the potential for incision. The late Pleistocene incision we measured represents a pulse of erosion during an ongoing period of river adjustment operating over geologic time scales.

INTRODUCTION

The large-scale development of landscapes, in both passive and tectonically active settings, is governed largely by the timing and rate at which rivers cut through rock (Tinkler and others, 1998). River incision into bedrock communicates the effects of changing boundary conditions, such as climate and tectonics, through fluvial networks to hillslopes, and thus has important implications for rates of landscape evolution (Howard and others, 1994; Tinkler and Wohl, 1998; Whipple and others, 2000a). Yet, we know little about the timing, rate, and style of river incision through rock in either actively rising terrains, or along ancient passive margins.

Long-term consideration of landscape development and the evolution of mountain ranges, examined with numerical models (e.g. Baldwin and others, 2003; Snyder and others, 2003; Whipple, 2004) and proxies for rates of exhumation (e.g. Zimmermann, 1979; Doherty and others, 1980) offer intriguing results, but both temporal and spatial resolutions are often too coarse to understand the means and timing by which river systems dissect landscapes. Similarly, direct measurements of erosion within bedrock channels at specific locations may not capture the dominant erosional mechanisms by which rivers shape landscapes because of the short duration and the small spatial scales over which such rates are measured (e.g. Wohl, 1993; Hancock and others, 1998; Hartshorn and others, 2002). Indeed, despite broad interest in understanding the style and timing of landscape change, only a handful of studies have directly measured the rate and timing of fluvial bedrock incision (Burbank and others, 1996; Hancock, Anderson, and Whipple, 1998; Leland and others, 1998; Whipple, Hancock, and Anderson, 2000a; Whipple and others, 2000b; Hartshorn and others, 2002; Burbank and others, 2003).

Activities of cosmogenically produced nuclides, such as ^{10}Be, measured in fluvially eroded bedrock can be used to constrain the timing and rate of river incision over millennial time scales; an appropriate time frame over which to detect how rivers respond to changing boundary conditions during glacial-interglacial cycles. Although the majority of Earth's surface is tectonically quiescent, including passive margins around the globe, most studies utilizing cosmogenic dating techniques to quantify bedrock incision rates have been conducted in tectonically active regions (Leland and others, 1994; Burbank and others, 1996; Hancock, Anderson, and Whipple, 1998; Pratt and others, 2002; Burbank and others, 2003).

In this paper, we use concentrations of ^{10}Be measured in 81 samples collected from fluvially eroded bedrock surfaces on and between prominent levels of strath-terraces within Holtwood Gorge to determine when, why, and how quickly the Susquehanna incised through the Appalachian Piedmont (fig. 1). A nested sampling strategy, and the large population of samples allow us to investigate the spatial patterning in both measured ^{10}Be activities, and modeled exposure histories for bedrock surfaces within the gorge.

BACKGROUND

The Susquehanna River

The Susquehanna River drains more than 70,000 km^2 of the central Appalachian Mountains in New York State, central and eastern Pennsylvania, and northeastern Maryland into Chesapeake Bay (fig. 1). It is the largest drainage system on the east coast of North America (Thompson, 1990). More than a century of research on fluvial features bordering this passive margin river help us understand better its long- and short-term development (Davis, 1889; Peltier, 1949; Hack, 1960; Morisawa, 1989; Sevon and others, 1989; Scharnberger, 1990; Thompson, 1990; Pazzaglia and others, 1993; Merritts and others, 1994; Pazzaglia and others, 1994a; Pazzaglia and others, 1994b; Pazzaglia and others, 1994c; Engel and others, 1996; Pazzaglia and others, 1998; Kochel and others, 2000; Thompson and others, 2001). For example, flights of alluvial terraces along the lower reaches of the Susquehanna have been used to investigate the interaction between glaciation, fluvial processes, and eustasy in the Eastern United States (Engel, Gardner, and Ciolkosz, 1996). Correlation of upland gravel terraces to coastal plain deposits allows for calculation of long-term average incision rates (~12 m/My) for the Susquehanna River, and an estimate of flexural deformation of the Atlantic passive margin since the middle Miocene (Pazzaglia and Gardner, 1993; Pazzaglia and Gardner, 1994a; Pazzaglia and Gardner, 1994b).

The northern half of the Susquehanna Basin was ice-covered during all major Pleistocene glaciations (Richmond, 1986; Braun, 1988; Braun, 1994; Gardner and others, 1994); the southern half of the basin remained ice-free. Maximal Wisconsinan glaciation was ~20 ka (Braun, 1988; Mix and others, 2001; Winograd, 2001), at which time approximately 45% of the Susquehanna Basin contained glacial ice. During and after Wisconsinan glaciation, glacial meltwaters flowed down the Susquehanna channel. The effect of elevated water and sediment discharge during glaciation on rates of bedrock channel incision along the lower reaches of the Susquehanna River have been considered (Mathews, 1917; Thompson and others, 1999; Kochel and Parris, 2000; Thompson and Sevon, 2001), but remain unresolved.

The drainage pattern of the Susquehanna channel changes downstream as the river leaves its upstream reaches and crosses into the Appalachian Piedmont. In the

Appalachian Plateaus, and in Ridge and Valley provinces of northeastern and northcentral Pennsylvania, the Susquehanna generally exhibits dendritic and rectilinear drainage patternswith broad, shallow channel reaches and an average stream gradient of 0.5 m km^{-1} (Scharnberger, 1990). 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 the river's longitudinal profile is strongly convex-up (fig. 2) (Pazzaglia and Gardner, 1993; Pazzaglia and Gardner, 1994a; Pazzaglia and Gardner, 1994b). The present study considers river incision along this oversteepened lower reach of the Susquehanna River.

Over millions of years, the Susquehanna River has carved a deep, steep-walled bedrock valley into the Piedmont along its lower reaches (Pazzaglia and Gardner, 1993; Pazzaglia and Gardner, 1994a; Pazzaglia and Gardner, 1994b). Within this outer valley, the river flows through bedrock gorges bordered by flights of strath-terraces. Access to the rock-floored channel is limited because a series of hydroelectric dam reservoirs inundate most of the lower reaches of the Susquehanna River. The river flows freely for ~5 km between the base of Holtwood Dam and the northern end of Conowingo Reservoir (fig. 2). While many have speculated about the origin of well-preserved bedrock terraces and other fluvial features within Holtwood Gorge (Mathews, 1917; Thompson, 1987; Thompson, 1988; Thompson and Sevon, 1999; Kochel and Parris, 2000; Thompson and Sevon, 2001), the timing and cause of their formation have remained enigmatic.

Holtwoood Gorge

Well-preserved, fluvially eroded bedrock surfaces make Holtwood Gorge an ideal site to investigate the timing and nature of river incision into bedrock on one of the world's most prominent and ancient passive margins. The gorge is located approximately 50 km upstream of Chesapeake Bay and preserves three distinct levels of bedrock strath-terraces. Holtwood Gorge is incised into the Wissahickon Schist, which exhibits a strong NE-striking foliation and is cut by a number of joint sets both parallel to, and cross-cutting the orientation of flow (Thompson and Sevon, 2001). Just below Holtwood Dam, the gorge is approximately 0.8 km wide. About 2.5 km downstream from the dam, a cluster of islands dissects river flow and the gorge narrows to ~0.5 km. Backup from Conowingo reservoir begins at this point in the gorge, restricting access to the channel floor. Farther downstream, the gorge widens again, reaching a width of nearly 1.5 km at the mouth of the incoming tributary, Muddy Creek, ~5 km downstream from the dam. Below this point, most bedrock surfaces standing above the channel are inundated (fig. 3).

Today, fluvially sculpted landforms, reflecting both present and past hydrologic conditions, dominate the gorge (Sevon and others, 1987; Kochel and Parris, 2000; Thompson and Sevon, 2001). Upstream dipping potholes are common, ranging from several cm to nearly 9 m in depth and 4 to 6 m in diameter. In addition, several discontinuous spoon-shaped mega-scour features exist along the eastern side of the gorge and below water level. These depression are ~1 km long, ~100 m wide, and extend below present day sea-level (Mathews, 1917; Pazzaglia and Gardner, 1993). Although some have suggested that these scours could be the result of paleo-floods during Wisconsinan deglaciation (Thompson, 1990; Kochel and Parris, 2000), the existence of similar ‘deeps’ on the unglaciated Potomac River (Reed, 1981) located ~100 km to the south and outside the glacial limit suggests that large passive margin rivers are capable of generating such features with or without glacial meltwaters.

Bare-rock terraces at Holtwood are preserved along the sides of the gorge and as isolated bedrock islands (dissected straths) within the gorge (fig. 4). Standing well above the three strath-terrace levels, heavily weathered and eroded topographic high points, restricted primarily to the western bank of the Susquehanna River and to island tops in the lower gorge, are remnants of now-degraded, ancient river beds. The uppermost terrace (Level 3) stands, on average ~10 m above the modern channel floor and extends discontinuously for nearly 5 km downstream from the dam at a gradient of ~2.0 m/km (fig. 5). A lower terrace, Level 2, stands approximately 3 m above the channel floor and also can also be traced over nearly 5 km. The paleo river gradient of the Level 2 terrace decreases to ~1.5 m/km. Dissected strands on both levels 3 and 2 preserve fluvially sculpted and streamline forms. Level 1, the lowest level within the gorge, has been incised in some places by numerous small channels. It can be traced approximately 2.5 km downstream from the dam front at a gradient of ~1.5 m/km, after which backup from the Conowingo Reservoir prevents access to the level 1 surface.

Using cosmogenic nuclides to constrain the timing and rate of bedrock river incision

Cosmogenic nuclides, such as ^{10}Be, are produced and accumulated within exposed rocks and sediments by the continual cosmic-ray bombardment of Earth's surface (Lal and others, 1967). Advances in nuclear physics now allow for the measurement of extremely low concentrations of such nuclides by accelerator mass spectrometry (Elmore and others, 1987). Because cosmogenic nuclides are rare in deeply shielded terrestrial materials, they are useful monitors for near-surface exposure duration and thus provide quantitative constraints on rates of landscape change over millennial time scales (Gosse and others, 2001; Bierman and others, 2003; Bierman and others, 2004a).

Over the past decade, several researchers have utilized ^{10}Be and ^{26}Al activities to model the exposure history of fluvially eroded bedrock surfaces in order to infer the timing and rate of river incision into rock (Burbank and others, 1996; Hancock, Anderson, and Whipple, 1998; Leland and others, 1998; Weissel and others, 1998; Pratt and others, 2002; Burbank and others, 2003). Although these studies provide constraints on previously unknown rates of bedrock incision around the globe, sample populations have been small (<30 analyses), and in most cases, the field areas of interest quite large (>100 km of river length).

Most cosmogenic dating of bedrock channel incision has focused on tectonically active regions. For example, dating of strath terrace surfaces bordering the Indus River indicates that, in the tectonically active Himalayas, river downcutting keeps pace with bedrock uplift by incising extremely rapidly through rock at 1 to 12 m/ka (Burbank and others, 1996; Leland and others, 1998). Cosmogenic exposure ages also provide evidence for climatically triggered cycles of aggradation within bedrock gorges, followed by re-excavation during ongoing tectonically-induced river incision (Pratt and others, 2002). Furthermore, coupling between rates of river incision and differential rates of bedrock uplift implies that bedrock erosion rates are very sensitive to changes in river gradient (Leland and others, 1998).

Although the majority of Earth's surface is not tectonically active, few studies consider river incision into bedrock on passive continental margins. For example, although numerous studies have inferred long-term rates of incision into the Atlantic passive margin (Engel, Gardner, and Ciolkosz, 1996; Granger and others, 1997; Zen, 1997b; Pazzaglia, Gardner, and Merritts, 1998; Granger and others, 2001), dates of bedrock fluvial surfaces and/or direct calculations for rates of incision through rock do not exist.

METHODS

Field mapping and GPS measurements

We mapped bedrock surfaces over the ~5 km length of Holtwood Gorge in order to identify and correlate prominent strath-terrace levels downstream. Access to the gorge begins immediately downstream of Holtwood Dam where the main channel of the Susquehanna flows 'freely' for several km. Under low-flow conditions (<30,000 cfs), many parts of the channel bottom are accessible by foot, whereas during higher flows (>30,000 cfs) access to mid-channel islands is possible only by boat. Because the lower ~3 km of the gorge is subject to changes in daily pool elevations of the Conowingo

Reservoir located downstream, many bedrock surfaces and islands are visible and/or accessible only during periods of reservoir drawdown.

We collected bedrock samples above, along, and between each of the three main terrace levels. The position of each sample site was measured real-time differential GPS (Trimble 4400™). The base station was set up at benchmark BM 6W USGS 1937, located near the front entrance of the Holtwood Dam Hydrostation on the eastern shore of the river. We used these data to determine paleo-river gradients over the relatively short distance spanned by the gorge, to calculate incision rates between adjacent bedrock surfaces, and to model the depth of water overlying sampled sites through time (HEC-RAS modeling).

Sample collection and sampling strategies

We used a sledge hammer and chisel to collect 81 samples from the tops of fluvially sculpted bedrock surfaces within Holtwood Gorge. Where possible, we sampled vein quartz; otherwise we collected the quartz-bearing schist groundmass. We also sampled two boulders sitting on bedrock terraces and one cobble exposed on the uplands gravel terraces above Holtwood gorge.

We devised a 'nested' sampling strategy in order to efficiently investigate nuclide activity and ^{10}Be model age variance at a number of spatial scales on and between each of the three prominent terrace levels within the gorge (fig. 6). At one location on each of the three terrace levels, we conducted small-scale variance studies (three samples collected 5 to 10 meters from one another) to test whether one sample from a bedrock surface is representative of the entire surface at small scales.

To detect age variance from one end of the gorge to the other, we collected between 10 and 25 samples longitudinally along each of the terrace levels. The lateral extent spanned by these samples depends upon how far downstream each level is preserved and/or could be accessed. We examined longitudinal variance at small scales by sampling along several continuous fluvially-rounded bedrock benches on mid-channel islands. We collected 5 samples along an isolated and narrow (<20 m wide) level 2 island, called the "Shoestring," in the upper gorge over a downstream distance of approximately 250 m (LR-26 and 27, and LR-32 through 34; fig. 3). Similarly, we collected three samples along a segment of a level 3 terrace on the western side of Upper Bear Island over approximately 500 m (LR-70, 71, and 74; fig. 3).

We collected samples in cross-section to compare rates of vertical incision at two different locations within Holtwood Gorge. The upper gorge transect (Cross-section A), located approximately 200 m downstream of Holtwood Dam, consists of 14 samples on and between the first, second, and third terrace levels across the western two-thirds of the river. A second cross-section (Cross-section B) in the middle gorge (approximately 2 km downstream from the dam) is comprised of 21 samples covering the lower three terraces levels as well as several heavily eroded island tops standing more than 20 m above the river bed along the western shore of the river (fig. 3). To further investigate and compare rates of vertical incision at different locations within the gorge, we collected transects of samples down the rounded fronts of several large mid-channel islands. The upstream noses of many of these islands are either gradually sloping, or stepped bedrock surfaces that extend from the lowest (level 1) to the highest prominent terrace level (level 3).

Large, fluvially-rounded boulders of varying lithologies can be found perched upon bedrock surfaces, principally the level 2 terrace, within Holtwood Gorge. We collected samples from the tops of two such boulders. One rests upon the level 2 terrace in the upper gorge along cross-section A; the second rests upon a small remnant of the level 2 terrace in front of Deepwater Island in the middle gorge. Both boulders are quartz-pebble-conglomerate and have numerous potential points of origin upstream.

Remnants of gravel terraces, believed to be middle Miocene in age (Pazzaglia and Gardner, 1993; Pazzaglia and Gardner, 1994a; Pazzaglia and Gardner, 1994b), can be found today far above the lower reaches of the Susquehanna channel across the Appalachian Piedmont. Although heavily weathered, quartz cobbles, often referred to as "potato stones" can be found within the soil matrix of these terrace remnants. We collected one such cobble, and measured its ^{10}Be content.

Sample processing, isotopic measurement and exposure age modeling

Quartz was purified at the University of Vermont using a combination of mechanical and chemical separation techniques (Kohl and others, 1992). Beryllium was chemically isolated, precipitated as a hydroxide, and burned to produce Beryllium oxide (Bierman and others, 2002). The BeO was mixed with Nb powder and packed into targets for measurement on the Lawrence Livermore National Laboratory (LLNL) accelerator mass spectrometer (AMS).

All measured ^{10}Be activities are considered to reflect the production and accumulation of nuclides by cosmic ray bombardment at earth's surface only. A sea-level high-latitude ^{10}Be production rate of 5.17 atoms g^{-1}quartz yr^{-1} (Bierman and others, 1996; Gosse and Phillips, 2001) was adjusted for latitude and altitude using standard scaling functions for neutrons only (Lal, 1991; Dunne and others, 1999). Geometric corrections for sample thickness, surface dip, and topographic shielding were made. Uncertainties assigned to ages represent propagated analytic errors (1 sigma) in carrier addition and AMS measurement, as well as a 10% (1 sigma) uncertainty in ^{10}Be production rate including calibration, normalization, and geometric corrections.

This model assumes rapid erosion prior to exposure, continual exposure since that time, and no erosion of the bedrock surface following its initial exposure. The exposed bedrock is hard and fresh; quartz veins rarely protrude more than a cm from the sampled surface. There is no evidence that outcrops were buried by a significant thickness of sediment, snow or loess during or after the carving of the gorge.

Water inundation modeling

During and after periods of incision, river water covered bedrock surface within and above the active channel for varying periods of time. Incoming cosmic rays, responsible for the production of ^{10}Be, were absorbed by this water when it covered surfaces we later sampled. Since nuclide production rates decrease exponentially with depth as a function of the density of the material through which cosmic rays pass (Lal, 1991), we needed to consider the effect of water shielding on our model exposure ages. If the integrated water depth that covered sampled outcrops through time is substantial, our model ages will be too young.

We used HEC-RAS (3.1) developed by the US Army Corps of Engineers (www.hec.usace.army.mil) to estimate the amount of cosmic radiation absorbed by outcrop-covering floodwaters in Holtwood Gorge through time. We created a working model of the upstream half of Holtwood Gorge using 10 cross-sections taken from detailed surveys drafted during the planning of Holtwood Dam (Bennett File No. F-3-4; Pennsylvania Water & Power Co.). Using HEC-RAS, we modeled the depth of water covering the lowest strath (level 1) for an appropriate range of discharges. Rating curves for each of the ten cross-sections were generated from the model and used to estimate the daily water depth covering each level 1 sample in the upper gorge based on ~75 years of daily flow records from the Marietta gauging station (USGS 01576000) located ~30 km upstream from the gorge. We constrained the model using observed water depths along a cross section at known discharges (fig. 7). The effective ^{10}Be production rate for each sample site for each day of record was calculated using the modeled water depth and the production rate function presented in Lal (1991):

$$P_x = P_o e^{-(x\rho/\Lambda)} \tag{1}$$

Where P_o = the surface production rate, P_x = the effective production rate at water depth x over the sampled surface, ρ= is the density of water (1.0 g/cm^3), and Λ= the attenuation length for fast neutrons (~165 g/cm^2). For each sample site, the effective daily production rates were summed and divided by the total possible production rate (100% exposure for everyday of record). The resulting ratio is an expression of how much exposure history is recorded by the model age for each sample under modern hydrologic conditions; a sample site yielding a ratio of 0.93 for example, indicates that approximately 7% of the total exposure history has been lost to absorption of cosmic rays by an overlying column of water.

This approach assumes that the last 75 years of discharge records can be extrapolated through time. Although there are no discharge estimates for the Susquehanna during the late Pleistocene, we speculate that water shielding had an equal or lesser effect on samples from higher terraces. During the last glacial period, the channel bed was actively and rapidly lowering; thus exposed rock surfaces were quickly removed from inundating flood waters. For a more detailed discussion of HEC-RAS modeling of Holtwood Gorge, refer to Reusser (2004b; my thesis).

Statistical methods

We used a number of statistical methods to analyze model ages for samples collected within Holtwood Gorge. We calculated mean ages for each terrace by averaging the ages of all samples collected from that level. Reported errors represent one standard deviation around the mean ages. We used Bivariate Regression Analysis to estimate rates of both longitudinal and vertical incision. When significant, best-fit lines as well as their associated regression models and r-square values are presented with the data plots and discussed in the text. In order to determine whether multiple samples collected along each of the three prominent bedrock terraces reflect distinguishable periods of incision, we performed one-way Analysis of Variance (ANOVA). Statistical significance was assessed at the $\alpha=0.05$ level, and p values are provided in the text.

In addition to these methods, we also consider the model age probability resulting from multiple samples collected along each of the three prominent terrace levels. When discussing the timing of incision and/or timing of abandonment for each terrace, this method allows us to detect multiple modes or "phases" of incision represented by a sub population of samples collected from a distinct level within the gorge. These multiple modes are not necessarily reflected by mean ages calculated for each level.

We constructed summed probability curves by combining the Gaussian distributions (based on sample age and analytical uncertainty including carrier addition and AMS) for multiple samples collected along each prominent terrace level, following the method of Balco *et al.*, (2002). The model age probability for all samples was summed over 0.5 ka increments to produce summed probability distributions for each terrace level. These summed probability distributions were normalized by dividing each age increment by the number of samples collected from a given terrace, in order to allow us to compare the relative magnitude of probability peaks between levels.

DATA

Measurement of cosmogenically produced ^{10}Be in 81 samples show that most exposed rock surfaces in Holtwood Gorge are late Pleistocene features, that boulders sitting on bedrock terraces have late Pleistocene ages, and that "potato stones" preserved no useful age information (table 1). The ^{10}Be activity measured in each bedrock sample, coupled with its location within the gorge provide us with a context within which to investigate not only the timing and rate of incision, but also the patterning of erosion at a number of spatial scales. These data demonstrate that even in the absence of tectonic forcing, large passive margin rivers are capable of incising quickly through bedrock at rates approaching 1 m/ky. These rates are comparable to lower estimates for rates of river incision in the Himalayas measured with similar techniques (Burbank and others, 1996, Leland and others, 1998).

Variance at small spatial scales

Measured ^{10}Be activities for spatially replicated samples (clusters of three samples separated by 5 to 10 m) on each of the three prominent strath-terraces are in good agreement (table 1, fig. 8), consistent with independently prepared, processed and measured laboratory replicates. ^{10}Be activities measured within two pairs of replicate samples (LR-04c & LR-04cX; LR-37 & LR-37X) agree within $\pm$ 2% (table 1), within measurement error. Results from small-scale variance studies on the highest (Level 3; samples LR-17a, b, and c) and middle (Level 2; samples LR-36a, b, and c) terraces demonstrate that ^{10}Be activities reproduce within $\pm$ 2.7% and $\pm$ 3.7% (1 sigma), respectively (Level 3 mean: 12.8 $\pm$ 0.47 10^4 atoms ^{10}Be/ gram quartz; Level 2 mean: 8.86

$\pm$ 0.24 10^4 atoms ^{10}Be/ gram quartz). The similarity in nuclide activity between samples collected meters apart, verifies the assumption that single samples, collected from terrace levels 2 and 3, are representative of the history of cosmic-ray dosing at the scale of meter to tens of meters.

Replicates collected from the lowest terrace within Holtwood Gorge (level 1) suggest that cosmogenic nuclide activity on this surface is more variable at small spatial scales than on the higher terraces (samples include LR-04a, b, and c; mean: 7.20 $\pm$ 0.68 10^4 atoms ^{10}Be/ gram quartz). The variability between these three samples is almost 10%, nearly three times that measured for the two higher surfaces. This discrepancy could reflect the stage of development of this surface relative to higher terraces, or indicate that a different erosional process was responsible for its creation. For example, the level 1 terrace, although remarkably planar at large spatial scales, appears rough at smaller scales in comparison to more rounded outcrops comprising higher levels. This observation suggests that once elevated above the bed, older and higher bedrock outcrops are subject to abrasion and smoothing from entrained sediment over time. Nevertheless, agreement of three samples within 10% indicates that a single sample from the level 1 surface represents well the exposure history of the area from which it was collected.

Mean exposure ages of terrace surfaces

Exposure ages modeled from ^{10}Be activities indicate that fluvially eroded bedrock surfaces within Holtwood Gorge increase predictably in age with height above the channel floor, and that all are late Pleistocene features (table 1). The highest well-preserved terrace (level 3) yields a mean exposure age of 36.1 ± 7.3 ka (n=14). The middle and lowest terraces, levels 2 and 1, yield mean exposure ages of 19.8 ± 2.7 ka (n=20) and 14.4 ± 1.2 ka (n=10), respectively (fig. 9A). One-way Analysis of Variance (ANOVA) demonstrates that the terrace ages are distinguishable ($P<0.0005$), confirming that the three levels do indeed represent separable periods of strath formation, and terrace abandonment.

Two samples collected from heavily weathered and eroded topographic high points (LR-01 & LR-43), standing >20 m above the channel floor, yield model ages of 97.1 ± 10.5 ka and 84.5 ± 9.1 ka respectively. Because the bedrock sampled at these two locations was shattered and no longer preserved water-polished surfaces, we report these ages as lower limiting estimates only; the removal of rock and the associated cosmogenic nuclides by weathering and erosion means that these surfaces could be far older than their model exposure ages suggest. Model ages for samples collected from bedrock surfaces between the prominent terraces (n=22) range from 45.8 ± 4.9 ka to 15.3 ± 1.6 ka and, in general, increase in age with height above the channel floor.

Boulder ages

Exposure ages for two rounded boulders are late Pleistocene in age, like the terrace surfaces they rest upon. One boulder (LR-14) yields an exposure age of 24.0 ± 2.6 ka, and presently rests upon a remnant of the level 2 terrace in the middle gorge with an exposure age of 15.3 ± 1.6 ka (LR-13). This age discrepancy suggests that the boulder already contained some nuclides when it was deposited on the terrace. The second boulder (LR-28) also rests upon a remnant of the level 2 terrace in the upper gorge, and yields an exposure age of 15.5 ± 1.7 ka. In contrast to the first boulder, two bedrock samples collected near by on either side of the boulder indicate that this boulder is younger, if only slightly, than the surface upon which it sits (LR-26: 18.3 ± 1.9 ka; LR-27: 17.9 ± 1.9 ka).

Even though the exposure histories of such boulders may incorporate prior periods of exposure and burial prior to their emplacement in Holtwood Gorge, their young exposure ages are consistent with the late Pleistocene incision of the gorge. The age of LR-28, which is consistent with the age of the level 1 terrace, suggests that flows capable of moving a 1.5 by 2.5 m boulder, could have overwhelmed the gorge as the Susquehanna River abandoned the level 2 terrace while incising toward the level 1 surface visible today. However, without samples from more boulders, these initial results can not be used to differentiate between theories concerning when and how they were deposited, i.e., whether glacial outburst floods were responsible for boulder transport and deposition in the gorge (Thompson, 1988; Kochel and Parris, 2000; Thompson and Sevon, 2001).

Exposure age of Miocene gravel terrace cobble

A single quartz cobble (LR-03a) collected from a remnant of an upland, middle Miocene age gravel terrace yields an exposure age of 100 ± 11 ka. This age represents the cumulative history of cosmic ray dosing through time. Discordance between the exposure age of this cobble and the suspected middle Miocene origin of the gravel terrace

(Pazzaglia and Gardner, 1993) probably reflects erosion of the terrace and exposure of the clast long after the terrace was abandoned in the Miocene. The clast carries no useful information for constraining the age of the gravel terrace.

DISCUSSION

Our model ages record an episode of rapid river incision through bedrock during the last major Pleistocene glaciation. We use results from Holtwood Gorge, as well as from Mather Gorge along the Potomac River, located ~100 km to the south, to consider what the exposure histories of fluvially carved bedrock outcrops tell us about the timing, rate and nature of bedrock channel incision along the Atlantic seaboard. We conclude that in this passive margin setting, fluctuations in climate-related boundary conditions initiated and maintained rapid rates of fluvial incision during a period of climate instability.

The timing and rate of rapid incision within Holtwood Gorge:

Rates of vertical incision dramatically increased within Holtwood Gorge between ~35 ka and ~14 ka (fig. 9B). Lower limiting ages for samples collected from eroded high points (LR-01 and LR-43; mean= 90.0 $\pm$ 9.0 ka) imply that prior to ~35 ka, the Susquehanna was incising at a maximum rate of 0.2 m/ka. Average model age data suggest that from ~35 ka to ~20 ka, incision accelerated to a rate of 0.45 m/ka. Incision between the level 2 and level 1 strath-terraces appears to have increased again to ~0.52

m/ka between ~20 ka and ~14 ka. A mean age of ~14 ka for the lowest terrace (level 1) suggests that significant incision ceased around that time.

The initiation (~35 ka) and cessation (~14 ka) of rapid incision inferred from average terrace ages are supported by incision rates calculated at specific locations and along cross-sections within the gorge. Four samples, representing each terrace level as well as an eroded island top, collected along a vertical transect in the middle gorge, show a very similar temporal pattern of incision (fig. 10A & B). Similarly, samples collected in cross-sections in the upper and middle gorge yield incision rates between the highest and lowest terrace levels that are comparable to each other as well as gorge-wide averages (Upper Gorge: 0.60 m/ka, R^2=0.96, n=13; Middle Gorge: 0.52 m/ka, R^2=0.72, n=22; figs. 11 & 3).

Along each cross-section, we collected samples from prominent terrace levels, as well as from bedrock surfaces between each level. Trendlines through these data suggest that the Susquehanna incised quickly and steadily beginning approximately 35 ka, without detectable lags between the abandonment of one terrace level and the formation of a lower strath (fig. 11). Accordingly, we interpret the mean ages for the Holtwood terraces as reasonable approximations for the timing of their abandonment.

Twenty-five samples collected down the rounded fronts of three separate mid-channel islands suggest that the Susquehanna incised at rates ranging from 0.75 m/ka to 0.30 m/ka between ~45 ka and ~14 ka at these specific locations. The higher degree of variability reflected in this approach, relative to previously discussed methods of calculating incision rates (average terrace ages and cross-sections), is probably a reflection of erosional mechanisms and paleo-hydraulics specific to each island's location. All three island fronts are located at the entrance of regions of Holtwood Gorge where flow is dissected and diverted through multiple smaller channels. The complex channel geometries could have resulted in vastly different hydraulic conditions at different stages of the development of the gorge as a whole. Despite these differences, all samples plotted together show an increase in incision rate from 0.1 m/ka to 0.7 m/ka around 27 ka (fig. 12), consistent with the timing and rate calculated using average terraces ages and along cross-sections.

An alternative approach to interpreting the timing of rapid incision

Considering the probability distribution of model ages for multiple samples collected along each terrace level affords us the opportunity to detect more complex patterns in our model age data. For example, the summed probability plot for samples collected along the level 3 terrace reveals two prominent modes, ~32 ka and ~45 ka, and a lesser mode at ~26 ka, indicating that the mean age of ~36 ka does not accurately represent the timing of abandonment for the entire surface (fig. 13). In contrast, prominent probability peaks for both the level 2 and 1 terraces are in relatively good agreement with their respective means (level 2 mean 19.8 ka, peak = ~18 ka; level 1 mean = 14.4 ka, peak = ~14 ka) further supporting the notion that each surface represents a unique period of formation and/or abandonment (fig. 13).

To further investigate the importance of, and cause for the complexity in the timing of abandonment inferred by model age probability peaks along the level 3 terrace, we consider each individual sample's position with respect to the level 3 paleo riverbed (fig. 5). If bedrock surfaces standing slightly proud of the overall surface trend were exposed earlier, their model ages should be older. However, only a weak relationship exists between each sample's age, and its height above or below the paleo channel floor (R^2= 0.21; fig. 14); suggesting that topography alone does not control model exposure ages on the level 3 surface

Many level 3 samples were collected from the tops of rounded mid-channel islands confined to the middle gorge where the channel narrows considerably, and river flow is divided and diverted through a maze of small channels (fig. 3). Although it is not possible to quantify paleo hydraulics within the gorge, the complex channel geometry between the mid-channel islands likely focused erosion in different places at different times resulting in more variability in the timing of abandonment for individual bedrock surfaces above the lowest terrace. Indeed, in the middle gorge, an even weaker relationship (R^2= 0.17) exists between each sample's age and position above or below the ancient riverbed. In contrast, in the upper gorge, where the rock-floored channel is broad and terrace levels are easily identifiable, there is a much stronger relationship between sample elevation and age (R^2= 0.71; fig. 14). Because ages for multiple samples cluster around ~45 ka and ~32 ka in both the middle and upper gorge, these two prominent modes of model age probability likely represent two separable phases of incision into the highest, well preserved paleo riverbed.

Understanding exposure ages of fluvially eroded bedrock

Depending on the style of erosion and/or the burial history since terrace abandonment, exposure ages of fluvially carved bedrock surfaces may not describe accurately their exposure histories. If the overlying meter or so of rock was eroded slowly prior to the final exposure of a bedrock surface, its model age will appear too old as ^{10}Be accumulates during erosion. Conversely, if sampled surfaces were covered by cosmic ray-absorbing water or sediment for substantial periods of time after abandonment, or if surfaces were substantially eroded after initial exposure, exposure ages will appear too young. Below, we consider, in the specific context of Holtwood Gorge, several scenarios germane to interpreting exposure ages of bedrock surfaces within river channels.

Two lines of evidence suggest that the model ages we report do not incorporate ^{10}Be accumulated during slow erosion of the overlying meter or so of bedrock prior to terrace abandonment. First, bedrock samples collected from the modern bank of the Potomac River near Great Falls have very low ^{10}Be activities, cooresponding to young model ages (≤ 4 ka; Bierman and others, 2004b). Such low activity suggests rapid erosion and exposure of rock (Bierman and others, 2003; Bierman and others, 2004b) and indicates that model ages from strath terraces reflect predominately the duration of time that bedrock surfaces have been fully exposed at the surface. Second, field observations suggest that quarrying of meter-scale joint blocks is responsible for the majority of incision into the heavily jointed Wissahickon Schist within Holtwood Gorge. Rapid removal of large bedrock blocks during periods of incision and terrace abandonment quickly exposes undosed, underlying bedrock.

We see little evidence for substantial fluvial erosion of bedrock surfaces subsequent to their initial abandonment and exposure above the channel floor.
In both Holtwood Gorge along the Susquehanna River, and Mather Gorge along the Potomac River, bedrock interfluves standing proud of the active channel bottom show some degree of rounding, suggesting that surfaces were abraded after plucking, perhaps after they were no longer on the channel floor. However, in most instances the approximate dimensions of large plucked joint blocks are still evident, indicating that model ages have not been substantially affected by wear of bedrock surfaces following their initial exposure by plucking.

Today, virtually no sediment can be found on or between the three prominent terrace levels within Holtwood Gorge, suggesting that model ages probably were not affected by sediment burial during the carving of the gorge. While most cosmogenic studies of river incision in the tectonically active Himalayas found no evidence for periods of sediment burial (Burbank and others, 1996; Leland and others, 1998), dating of bedrock surfaces suggests that a >80 m thick blanket of sediment choked the Marsyandi River gorge in central Nepal during the early Holocene (Pratt and others, 2002). The subsequent excavation of sediment re-eroded the gorge walls resulting in similar model ages over an 80 meter span in elevation. In contrast, dating of bedrock surfaces within Holtwood Gorge yields a steady decrease in model age with decreasing height above the channel floor (spanning ~20 m elevation, fig. 11), further suggesting that sediment did not shield surfaces from cosmic ray dosing or substantially re-erode them during the carving of the gorge.

Water inundation through time, modeled with HEC-RAS River Analysis System, did not substantially affected cosmic ray dosing and exposure ages of bedrock surface within Holtwood Gorge. Model results suggest that exposure ages represent between ~95% and ~75% (mean = 88%) of the total unshielded exposure history of samples along the level 1 strath in the upper gorge (fig. 15). The relatively small magnitude of this correction reflects the infrequency of discharge events capable of inundating even the lowest bedrock surfaces. Although flood waters can rise tens of meters above sampled outcrops during exceptional events such as Hurricane Agnes in 1972, rare, high-magnitude events have little effect on model ages due to the short duration of flooding (Hancock, Anderson, and Whipple, 1998). Model ages for samples sites higher above the riverbed in Holtwood Gorge (terrace levels 2 and 3) reflect between 99% and 100% of their total unshielded exposure history, indicting that their exposure ages are unaffected by modern flooding.

Evidence for and against knickpoint retreat

Base level drops are believed to propagate upstream through bedrock channels via the headward migrations of knickpoints (e.g. Gardner, 1983; Zen, 1997a; Hancock, Anderson, and Whipple, 1998; Whipple, Hancock, and Anderson, 2000a; Zaprowski and others, 2001). In such a scenario, one would expect to see an upstream younging trend along dated terraces because individual bedrock surfaces would be abandoned sequentially as knickpoints migrate headward. If, however, the rate of knickpoint retreat were fast enough or the longitudinal distance over which samples are collected were short, the age resolution of cosmogenic dating might not be sufficient to detect age gradients.

Model ages for multiple samples collected longitudinally along some terraces within Holtwood Gorge argue for the headward migration of knickpoints, while along others, they do not. No significant relationship exists between model age and distance downstream along both the highest (Level 3) and lowest (Level 1) terraces (fig. 16), implying that these surfaces were abandoned quickly and within the method's resolution, simultaneously along the entire length of Holtwood Gorge. In contrast, the Level 2 terrace data display an age gradient (~1.4 ka/km, R^2=0.63) consistent with knickpoint retreat, implying that the surface is time transgressive. In general, bedrock outcrops located farther downstream were exposed before surfaces closer to Holtwood Dam. Together, these results suggest that the spatial pattern of erosion varied in the gorge at different times, or that correlation of terraces over longer distance is required in order to detect rapid rates of knickpoint retreat along the upper and lower terraces.

Episodic fluvial incision through bedrock

Short- vs. long-term rates of incision on the Atlantic passive margin

Rates of late Pleistocene incision implied by our data (<0.2 m/ka to 0.8 m/ka) are at least an order of magnitude greater than long-term estimates of fluvial incision into the Piedmont since the middle Miocene (~12 m/My) (Pazzaglia and Gardner, 1993; Zen, 1997b; Pazzaglia, Gardner, and Merritts, 1998). Short- and long-term estimates are clearly discordant. Short-lived, rapid incision must be complimented by periods of little to no vertical channel-bed lowering. Even during this pulse of late Pleistocene incision, there were periods of little or no incision when extensive straths were cut by the Susquehanna River within Holtwood Gorge and subsequently abandoned to form flights of bedrock terraces. Beginning between ~45 ka and ~35 ka, and ending around 14 ka, a shift in some combination of boundary conditions modulating river incision along the lower reaches of the Susquehanna compelled this river, and others near the glacial margin (Bierman and others, 2004b; Reusser and others, 2004) to cut quickly into bedrock.

Potential drivers of rapid late Pleistocene incision on the Susquehanna River

While a simple process-response model capable of explaining fully the period of rapid erosion recorded in Holtwood Gorge is not yet possible, it appears that climate change, acting through a variety of primary and secondary effects, initiated and maintained rapid incision through bedrock during the late Pleistocene (Reusser and others, 2004). Furthermore, similarities in the beginning and ending times of rapid incision within bedrock channels along both the lower Susquehanna River and the lower

Potomac River near Great Falls, located ~100 km to the south of Holtwood, suggest that regional forcing, and not simply the presence of glacial ice and associated meltwaters, were responsible for this pulse of incision (Bierman and others, 2004b; Reusser and others, 2004). Several important derivative effects of changing climate during the last glacial cycle include fluctuations in sea-level to which both rivers drained, growth of the Laurentide ice sheet, and passage of the resulting glacial forebulge. Climate itself, by altering the hydrology of both basins, also could have caused incision along these passive margin rivers.

Derivative effects of changing climate

In many instances, river incision through bedrock appears to be accomplished by headcutting in response to base-level drops (e.g. Bull, 1990; Zaprowski and others, 2001). However, several lines of evidence suggest that falling sea-level during the last glacial cycle did not on its own instigate incision on the Atlantic passive margin. For example, driven by rapid ice sheet growth, the most dramatic sea-level drop of the Wisconsinan Glaciation occurred between ~27 and ~32 ka (fig. 17C) (Shackleton and others, 1983; Shackleton, 1987; Chappell and others, 1996; Lambeck and others, 2001). The initiation of rapid incision within Holtwood Gorge, as indicated by both the abandonment of the level 3 terrace at ~35 ka (fig. 17A), as well as prominent model age probability peaks at ~45 ka and ~32 ka (fig. 17B), appears to pre-date this pronounced sea-level drop. Furthermore, it is uncertain by what process, and at what rate, base-level drops would translate across the already-drained continental shelf and through 10's of kilometers of bedrock channel to Holtwood Gorge. Although impossible to prove or disprove, the pulse of incision we measured could have resulted from the slow, up-channel propagation of sea-level drops occurring earlier in the Pleistocene. Because our data do not constrain the rate at which sea-level drops are transmitted upstream over long distances (tens of km) through solid rock, the role of sea-level fall in triggering and maintaining episodic but rapid late Pleistocene vertical incision rates remains uncertain.

Although poorly constrained both temporally and spatially, the glacial forebulge, reflecting mantle response to the growing Laurentide ice sheet, likely raised the land surface in the vicinity of Holtwood Gorge along the Susquehanna River (Douglas and others, 2002). Recent modeling efforts suggest that the forebulge extended approximately 200 km in front of the ice-sheet at its maximal extent and raised the land surface near Holtwood Gorge by as much as tens of meters (Pelltier, 2003). This component of uplift could have increased river gradients, stream power, and the potential for incision. However, when incision within Holtwood Gorge commenced, ice volume was probably less than 50% of maximum (Winograd, 2001) suggesting that most forebulge-induced uplift in the vicinity of the gorge likely post-dated the initiation of incision. Although the forebulge probably did not instigate incision, it likely contributed to high rates of incision during and perhaps after the last glacial maximum by increasing river gradients and available stream power.

Climate change during the late Pleistocene

Rates of bedrock incision increased dramatically ~45 ka, and were sustained during a prolonged period of climate instability, after which incision appears to have ceased near the transition into the warmer and more climatically stable Holocene (~14 ka). Increases in the frequency and magnitude of flood events capable of exceeding thresholds for rock detachment and induced by changing climate at the onset of and during the last glacial cycle, likely increased rates of bedrock channel incision within Atlantic passive margin rivers near the glacial margin. Recent efforts in numerical modeling of fluvial incision into bedrock demonstrate the importance of incorporating erosion-threshold terms and stochastic flood distributions (Willgoose and others, 1991b; Willgoose and others, 1991a; Hancock, Anderson, and Whipple, 1998; Whipple and others, 1999; Tucker and others, 2000; Tucker and others, 2002; Snyder and others, 2003; Tucker, 2004; Whipple, 2004). If these models portray natural systems well, then increases in the frequency, magnitude, and duration of flood events would have increased the rate of bedrock incision along the lower Susquehanna River as more flows exceeded critical erosion thresholds for longer periods of time.

Because paleo-discharge records do not exist, we look to other data to infer the frequency and magnitude of floods in the past. For example, the Greenland Ice Sheet Project Core 2 Sea-Salt Sodium record (GISP2 s.s. Na) is believed to reflect aerosol sea salt inputs and is thus interpreted as a gauge of wind speeds and paleo-storminess at high latitudes through the late Pleistocene (Mayewski and others, 1994). A marked increase in storminess, beginning at ~50 ka and lasting until ~10 ka, correlates well with the initiation and cessation of incision within Holtwood Gorge (fig. 17D), as indicated by the oldest surfaces on the Level 3 terrace (~45 ka) and the mean age of the youngest terrace (~14 ka). Recent analysis of a 600-year-long Greenland ice core record identifies the eastern and northeastern Pacific regions as the most significant contributors to variations in sea-salt aerosol concentrations in Greenland ice (Fischer, 2001). Although the North Atlantic is noted as only a secondary contributor, increases in North Atlantic storm activity during historical times lead to higher sea-salt concentrations in the Greenland record (Fischer, 2001), indicating that the Atlantic climate signal is documented in Greenland cores. Moreover, good correlation between the GISP2 s.s. Na record and a paleostorminess record from northeastern North America over the past 13 ka (Noren and others, 2002) suggest that the Greenland record is a reasonable proxy for geomorphically effective flood events on the Susquehanna, and other middle-Atlantic river systems.

In addition to storminess, cooling climate during the last glacial, as inferred from the GISP2 $\delta^{18}O$ record (fig. 17E) (Cuffey and others, 1997), presumably altered runoff dynamics within the Susquehanna basin. Oscillations in pollen spectra from Florida and the southern Appalachians (Grimm and others, 1993; Grimm and others, 2003; Litwin and others, 2004) correlate well with GISP2 paleotemperatures, indicating that high-latitude temperature changes similarly affected the Susquehanna Basin.

Cooling climate would effectively concentrate annual discharge into a fewer number of larger events in a several ways. A stormier climate, coupled with greater snow packs caused by below freezing temperatures for a larger proportion of the year, would likely increase the number, severity, and duration of snowmelt floods. Indeed, over the past ~75 years of record, nearly 75% of the largest 25 discharge events on the

Susquehanna River occurred as snowmelt floods or rain on snow events (Discharge records downloaded from http://waterdata.usgs.gov/nwis/rt for the Marietta, PA gauging station USGS 01576000, located ~30 km upstream from Holtwood).

The possibility that a cold, stormy, and unstable climate during the last glacial cycle was capable of instigating and maintaining the pulse of rapid incision we measured along the Susquehanna River is plausible. Numerous studies considering erosional efficiency and the exceedance of erosional thresholds within fluvial systems suggest that most geomorphic work in bedrock channels is likely done during rare high magnitude flood events (Baker, 1974; Wohl, 1993; Wohl and others, 1994; Baker and others, 1998; Kochel and Parris, 2000; Tucker, 2004). While it is not possible to deconvolve the relative importance of each of these climate-related boundary conditions, the timing and rates of incision recorded with ^{10}Be on both the Susquehanna and Potomac Rivers argue for changing climate itself as the first-order driver of incision during the late Pleistocene.

Potential roles of sediment in erosion of bedrock channels

Changing sediment dynamics during glacial-interglacial cycles, and its effect on bedrock incision along the Susquehanna River remains one of the most perplexing and difficult to constrain variables. Numerical and experimental modeling suggests that variations in the relationship between discharge and sediment load likely play an important role in determining when, where, and how fast rivers incise (Gardner, 1983; Sklar and others, 1998; Sklar and others, 2001; Hancock and others, 2002). Increases in sediment load could have choked the gorge, thus protecting the bed from erosion.

Alternatively, an increase in water discharge could have removed bed armoring, allowing incision, or increased tool loading could have promoted abrasion (Hancock and Anderson, 2002).

Although there is no record of paleo-sediment load, discontinuous low gravel terraces along the Susquehanna River (Pazzaglia and Gardner, 1993; Engel, Gardner, and Ciolkosz, 1996) suggest that sediment dynamics changed in the past. However, within Holtwood Gorge, significant alluvial deposits are found only along the banks of the gorge and well above the Level 3 terrace, implying that sediment likely did not choke the gorge for significant periods of time during the formation of the three prominent levels of strath-terraces we dated. Another possibility, at this time untestable, is that around 45 ka, alluvial fills were rapidly excavated in response to falling sea level and/or changes in sediment supply and transport capacity (Hancock and Anderson, 2002; Pratt and others, 2002), thus exposing a broad strath previously blanketed with sediment and allowing the initiation of the period of incision we measured. In this scenario, the broad level 3 terrace is cut by a meandering, sediment-choked Susquehanna and then uniformly exposed to cosmic radiation when the sediment blanket is removed rapidly.

Effects of drainage basin glaciation

Our dating does not altogether discount the effects of drainage basin glaciation. Following the initial acceleration in incision rate between ~45 ka and ~36 ka, incision rates increased again at ~20 ka, as evidenced by the average abandonment age of the Level 2 terrace. This mean age is coincident with the beginning of glacial retreat and increased meltwater discharge flowing down the Susquehanna Channel (Braun, 1988; Mix, Bard, and Schneider, 2001; Dyke and others, 2002). Interestingly, evidence for increased rates of incision around 20 ka does not exist within the Potomac River gorge (Bierman and others, 2004b; Reusser and others, 2004). The Potomac Basin lies >100 km south of the Wisconsinan glacial margin (fig. 1), suggesting that while changing climate during the last glacial cycle appears to have been the first-order driver of incision for both rivers, glaciation and increased meltwater during deglaciation within the Susquehanna Basin were also capable of affecting rates of bedrock incision.

IMPLICATIONS

Prolonged incision of the lower Susquehanna River commenced in the middle Miocene (15 to 20 My). Since that time, downstream reaches of the Susquehanna, and other rivers draining the Atlantic margin, have remained oversteepened, allowing ongoing incision into bedrock and generating the broad and deep bedrock valleys we see today (Reed, 1981). Steep gradients on the lower Susquehanna are driven, in the long-term, by continual base-level lowering resulting from both flexural upwarping of the Appalachian Piedmont (Pazzaglia and Gardner, 1994a) as well as protracted eustatic sea-level fall beginning in the middle Miocene (Haq and others, 1987; Pazzaglia, Gardner, and Merritts, 1998). Paleo river gradients for each of the three prominent bedrock terrace levels within Holtwood Gorge, constructed using GPS data, show a marked increase with height above the channel floor (fig. 5). This finding is consistent with other evidence for isostatically driven upwarping of the middle Atlantic passive margin by offshore sediment deposition over the past ~20 million years (Poag and others, 1989; Pazzaglia and Gardner, 1994a; Pazzaglia and Gardner, 1994b; Pazzaglia and others, 1996).

The persistence of steep river gradients along the lower reaches of the Susquehanna primes the river for incision by providing increased stream power needed to incise and remove rock, and the vertical accommodation space needed to preserve terraces during periods of downcutting. The Susquehanna has incised up to 150 m into the high piedmont since the middle Miocene in the vicinity of Holtwood Gorge, which is located along the oversteepened lower reaches of the river. Such incision has continued at a long-term average rate of 12 m/My (Pazzaglia and Gardner, 1993; Pazzaglia, Gardner, and Merritts, 1998) (fig. 2).

Short-term late Pleistocene incision rates derived from ^{10}Be exposure ages, are more than an order of magnitude faster than long-term rates of downcutting. Our data record an episode of incision during an ongoing period of river adjustment operating over geologic time scales. While we can not speak directly to the timing and nature of incision prior to the late Pleistocene, our data suggest that long-term adjustment of the lower Susquehanna and other rivers draining the Atlantic passive margin occurs episodically when the right combination of boundary conditions compels these rivers to cut rapidly into bedrock.

Many large rivers draining passive margins around the globe flow over, and incise rock (Mathews, 1917; Reed, 1981; Wohl, 1993; Merritts, Vincent, and Wohl, 1994; Weissel and others, 1997; Pazzaglia, Gardner, and Merritts, 1998; Weissel and A., 1998). Because river incision into bedrock is a fundamental control on the tempo and style of landscape development, understanding the timing, rate, and cause for such incision is an important geologic pursuit (Judson, 1975; Gilchrist and others, 1994; Tucker and others, 1994; Weissel and A., 1998; Cockburn and others, 2000; Matmon and others, 2002). Yet, very little quantitative bedrock incision rate data exist, especially for major passive margin drainage networks.

Although extensive cosmogenic dating has now constrained the timing, rate and spatial patterning of bedrock channel incision along one of the world's largest passive margin river systems, such dating alone does not explain fully why, and by what processes, incision occurred. Indeed, even in passive margin settings, river incision through bedrock, is a dynamic process. Comprehending when and where rivers incise will only become clear when we better understand the complex interactions between fluctuating boundary conditions, and the long-term context within which incision occurs.

Concentrations of cosmogenic isotopes, such as ^{10}Be, have proven to be a useful tool for measure the timing and rate of river incision through bedrock during glacial-interglacial cycles; an appropriate time frame to detect how a variety of climate-induced boundary conditions affect such incision. Furthermore, the large population of samples we collected, coupled with a nested sampling strategy, reveal how one passive margin rivers incised during the late Pleistocene. Future studies of bedrock channel incision along the Atlantic margin, as well as other passive margins around the globe, will further our understanding of when and why rivers incise through rock, and what role such incision plays in the development of present day, and ancient landscapes.

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ACKNOWLEDGEMENTS

We thank R. Alley, I. Winograd, F. Pazzaglia, H. Markewich, K. Wipple, E. Zen, and A. Noren for thoughtful comments during this project. We also thank E. Butler for field assistance, and C. Porse and the other engineers at the Holtwood Dam hydropower station for logistical assistance. This project was funded by the National Science Foundation, EAR0003447, awarded to P. Bierman. A portion of this work was supported under the auspices of the U.S. D.O.E. to Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.

FIGURE CAPTIONS

Figure 3.1: Map of the Atlantic passive margin and the Susquehanna and Potomac River Basins. Both Holtwood (black star) and Mather Gorges (black circle) lie near the Appalachian Piedmont/ Coastal Plain transition. During the last glacial maximum, ice covered ~40% of the Susquehanna Basin; the Potomac Basin remained free of glacial ice (Braun, 1988).

Figure 3.2: Long-profile of the downstream 200 km of the Susquehanna River. Oversteepening of the lower reaches begins ~70 km upstream from the river's outlet into Chesapeake Bay. Note that Holtwood Gorge is the longest length of river not currently inundated by hydroelectric dam reservoirs. Figure modified from Pazzaglia and Gardner (1993).

Figure 3.3: Field map of the Holtwood Gorge field area. Map displays all sample site locations, prominent cross-sections, and the terrace levels assigned to bedrock surfaces in the gorge.

Figure 3.4: Photographs of fluvially carved bedrock terraces within Holtwood Gorge. **A**: Terrace levels 1 and 3 in the middle of Holtwood Gorge along the Susquehanna River at

low flow conditions. Level 2 is not preserved at this location. At higher discharges, lower strath is inundated. Person in foreground for scale. **B**: A remnant of the Level 2 terrace preserved as a mid-channel island in the upper gorge. At the time the photograph was taken, water was spilling over Holtwood Dam and covering the Level 1 terrace (Flow from right to left). **C**: Terrace levels 1 and 3 in the middle of Holtwood Gorge. Note the rough texture of the lower surface relative to the upper-most terrace remnant. **D**: The upper-most surface (level 3) of Upper Bear Island in the middle of Holtwood Gorge. Sample site LR-17 (at the feet of people in photo) is also the location of the level 3 small scale variance study.

Figure 3.5: 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. The watermark trendline was constructed using GPS points collected along a distinctive watermark observed in the upper gorge (July, 2002). It is interpreted as representing the modern river gradient.

Figure 3.6: 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, and the distance over which each level could be correlated. **B**: Schematic cartoon of nesting sampling strategy showing how we used individual samples multiple times at different spatial scales.

Figure 3.7: Example of a calibration photo used to constrain water depths for the HEC-RAS model of Holtwood Gorge at known discharges. Photo (**A**) was taken from the western shore of the Susquehanna River in the upper gorge at a discharge of ~40 kcfs. River flow is from left to right (NW to SE). The X-Y-Z reconstruction (**B**), and a representative cross-section (**C**) of Holtwood Gorge show the modeled water depth at 40 kcfs. The black arrow in **A, B & C** is the same point within the gorge. Bank and bed roughness coefficients (Manning's *n* values) were adjusted so the model correctly reproduced stage elevation at known discharges.

Figure 3.8: Photograph depicts an example of a small scale variance study conducted on the level 2 terrace in upper Holtwood Gorge. On the level 2 terrace, model ages for samples collected within 5 to 10 m of one another agree within $\pm$ 2.7%, confirming that a single sample represents the exposure history of a bedrock surface well at small spatial scales. Similar studies were also conducted on the lowest (level 1) and highest (level 3) well-preserved terrace levels in the gorge.

Figure 3.9: **A**: Average ages for terraces within Holtwood Gorge were calculated from multiple samples collected longitudinally along each terrace level. Error bars represent a 1 sigma standard deviation. The mean age for 2 samples collected from heavily weathered and eroded high points standing well above the three well-preserved terrace levels are reported as lower limiting ages. Because we cannot determine how much rock has been removed from these surfaces, we do not know how much exposure history is

missing. **B**: Average incision rates calculated with average terraces ages and average heights above the river bed. Due to the poor surface preservation of the highest samples, the incision rate (<0.2 m/ka) prior to 36 ka is give as an upper estimate.

Figure 3.10: **A**: Model ages from four samples collected from each of the prominent terrace levels along an elevation transect in the middle gorge agree well with gorge-wide average ages (Figure 9). **B**: Similarly, incision rates between terrace levels calculated with the four samples are very similar to gorge wide average rates (Figure 9).

Figure 3.11: Plots of incision rates along cross-sections at specified locations within Holtwood Gorge. Data points labeled as black diamonds represent 13 samples collected in the upper gorge and data points labeled as shaded circles represent 22 samples collected in the middle gorge. Solid and dashed trendlines indicate incision rates along the cross-sections in the upper and middle gorge respectively. The oldest sample along the middle gorge section is reported as a minimum age.

Figure 3.12: Incision rates determined from 25 samples collected down the fronts of three separate mid-channel islands; Piney Island in the upper gorge, and Deepwater and Upper Bear Islands in the middle gorge. Combined, these samples suggest that incision rates increased ~30 ka to ~0.7 m/ka.

Figure 3.13: Summed model age probability plots for multiple samples collected along each of the three well-preserved terrace levels within Holtwood Gorge. Probability distributions were constructed by summing the Gaussian distributions of all samples from each terrace. 1 sigma errors associated with each model age reflect uncertainties including carrier addition and AMS measurement only. Probability plots in the main plot were normalized (each age increment was divided by the number of sampled collected from the terrace) to allow for comparison of the relative magnitude of each peak.

Figure 3.14: Using the level 3 paleo-river gradient constructed with GPS data for all sample sites, we consider the age of each sample vs. its height above or below the ancient riverbed (residual). **A:** Model age vs. residual for all samples collected along the level 3 terrace. **B:** Model age vs. residual for samples collected in the upper gorge only, and **C:** for samples collected in the middle gorge only. Note that most between sample variance in **A** is due to the samples collected in the middle gorge where the channel narrows and is flow is diverted and dissected by numerous mid-channel island.

Figure 3.15: To estimate the amount of exposure history lost to an overlying column of water through time, we modeled water depth for 75 years of daily flow data with HECRAS. Using the integrated depth of water, we estimate the percentage of exposure history missing from each level 1 sample site located in the upper gorge. Note that, in general, sample sites lower in elevation have been shielded from cosmic-ray bombardment to a great degree because they were inundated more frequently through

time. The between sample variance for the modeled samples is reduced from ± 23% to ± 16% with this method suggesting that, at least under modern hydrologic conditions, a substantial portion of the variability in the exposure histories of individual bedrock surfaces is due to their position above the bed.

Figure 3.16: Distance downstream vs. model age for multiple samples collected along each of the prominent terraces in Holtwood Gorge. No significant age gradient is detectable along the highest (level 3) or lowest (level 1) terrace. However, an age gradient of ~1.4 ka/km exists for samples along the middle (level 2) terrace supporting a model of knickpoint propagation through the gorge during the abandonment of this level.

Figure 3.17: Summary of the timing of incision and terrace abandonment within Holtwood Gorge in relation to otherwise documented changes in climate and sea-level. All panels are displayed on the same time axis (0 to 100 ka). **A**: Schematic diagrams of Holtwood Gorge conveying ^{10}Be model age data and important geomorphic characteristics of the gorge. LR-01 (level 4) was collected from a heavily weathered surface and is given as a lower limiting age. **B**: Normalized cumulative probability curves for each of the three prominent terrace levels. These curves allow us to detect multiple phases of terrace abandonment, particularly along the level 3 terrace. **C**: Late Pleistocene sea-level record derived from Huon Peninsula (Lambeck and Chappell, 2001). Roman numerals are oxygen isotope stages. Panel **D**: GISP2 sea salt (s.s.) Na record (Mayewski and others, 1997) resampled to a 50 yr interval with Analyseries™,

and smoothed with a 10 point (thin line) and 100 point moving window (bold line). Panel **E**: Paleotemperature estimates inferred from the GISP2 ice core record (Cuffey and Clow, 1997) resampled to a 50 yr interval with Analyseries™, and smoothed with 10 point (thin line) and 100 point moving window (bold line). Heinrich events (H1 through H6) from dating of Deep Sea Drilling Project (DSDP) site 609 core (Bond and others, 1992). Hatched areas in **C**, **D**, and **E** show the episode of rapid incision we measured. (*masl*) is meters above sea-level.

TABLE CAPTIONS

Table 3.1: GPS and isotopic data for bedrock samples collected within Holtwood Gorge. Elevations are in meters above sea-level (*masl*).

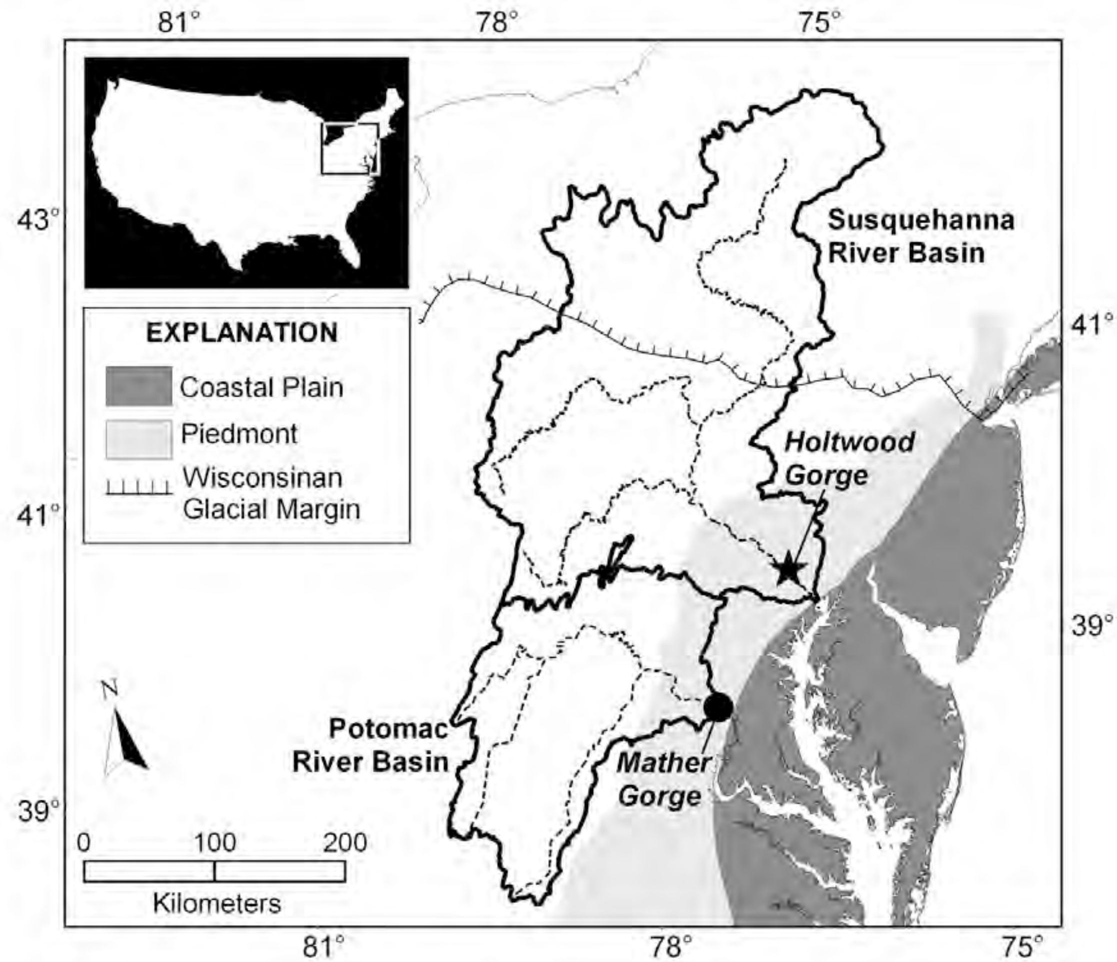


FIGURE 3. 1 Map of the Atlantic passive margin and the Susquehanna and Potomac River basins.

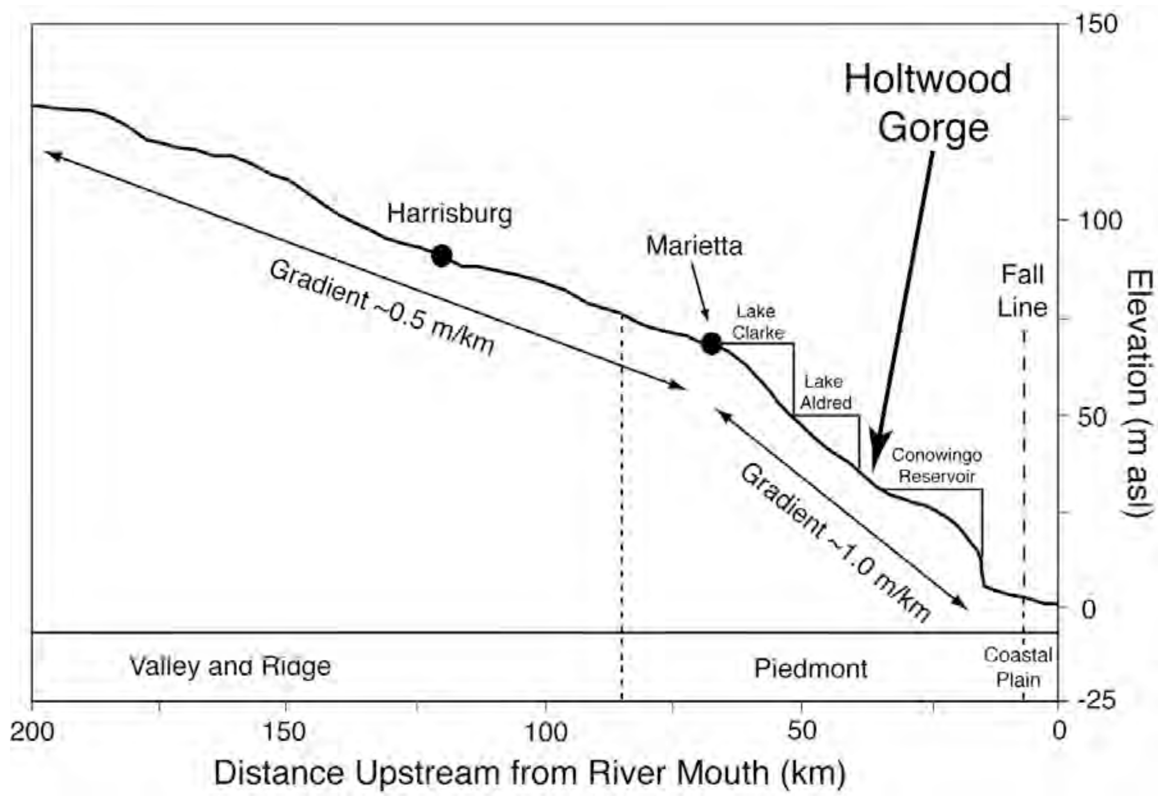


FIGURE 3. 2 Long-profile of the downstream 200 km of the Susquehanna River.

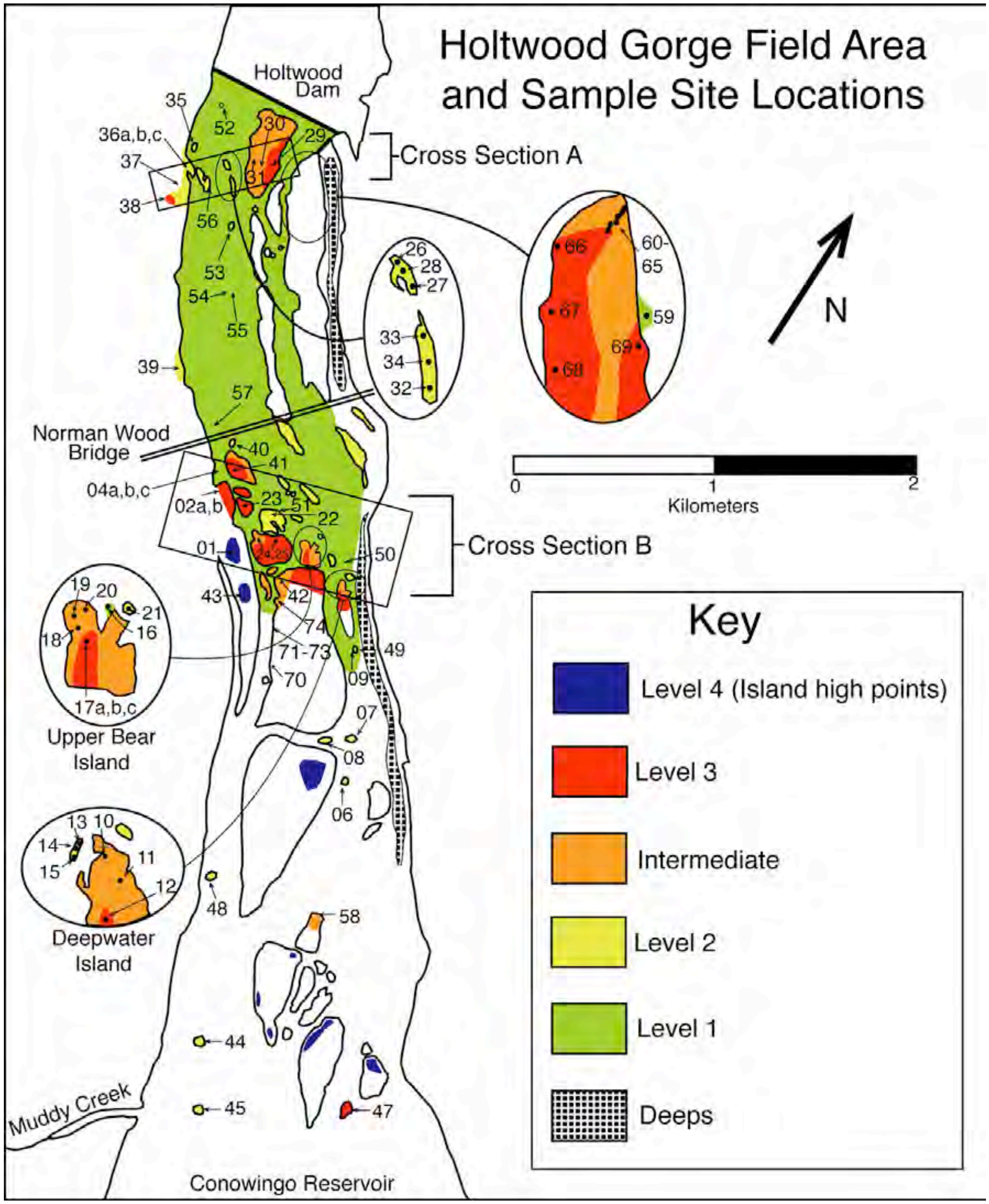


FIGURE 3. 3 Field map of the Holtwood Gorge field area.

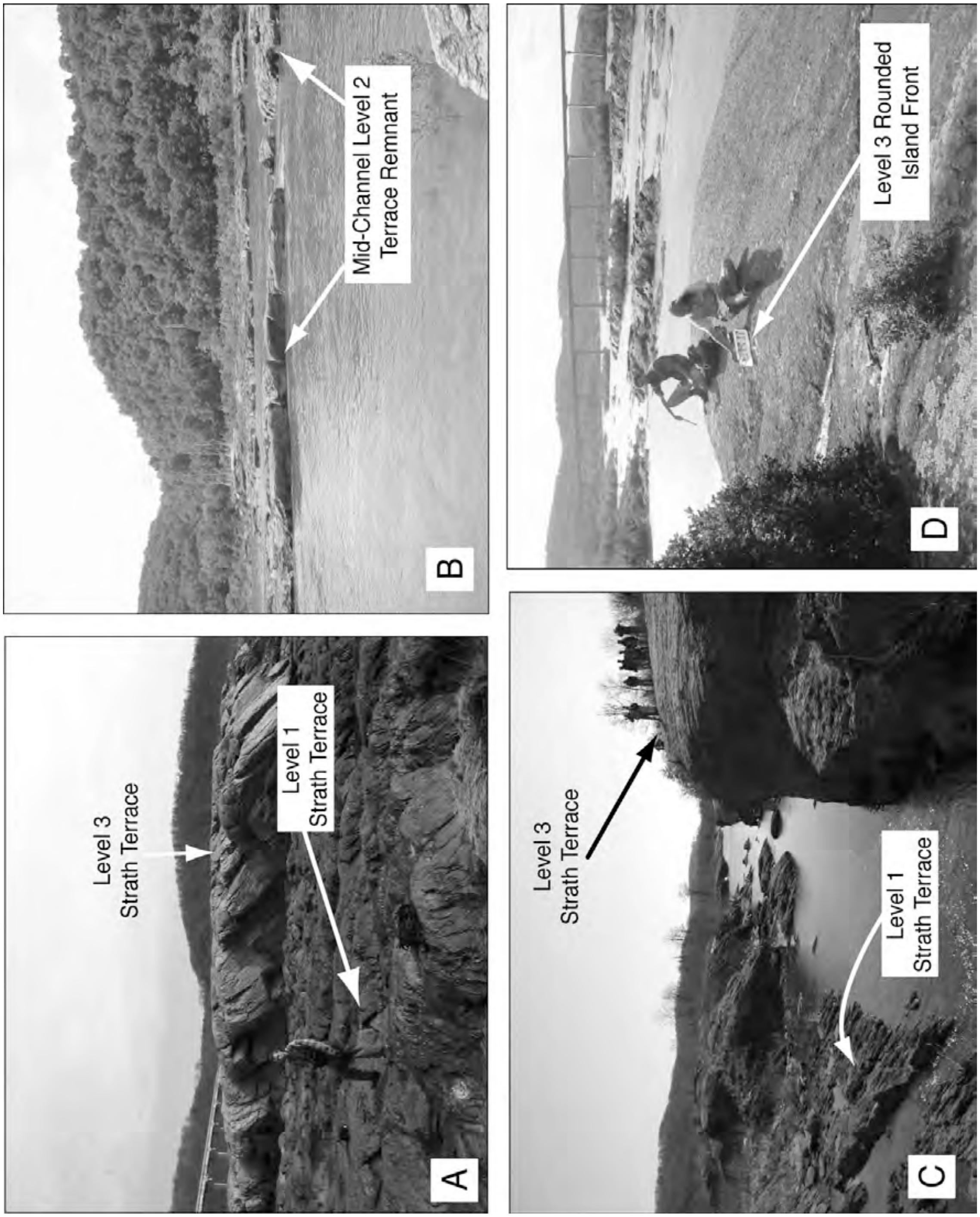


FIGURE 3. 4   Photographs of fluvially-carved bedrock terraces within Holtwood Gorge.

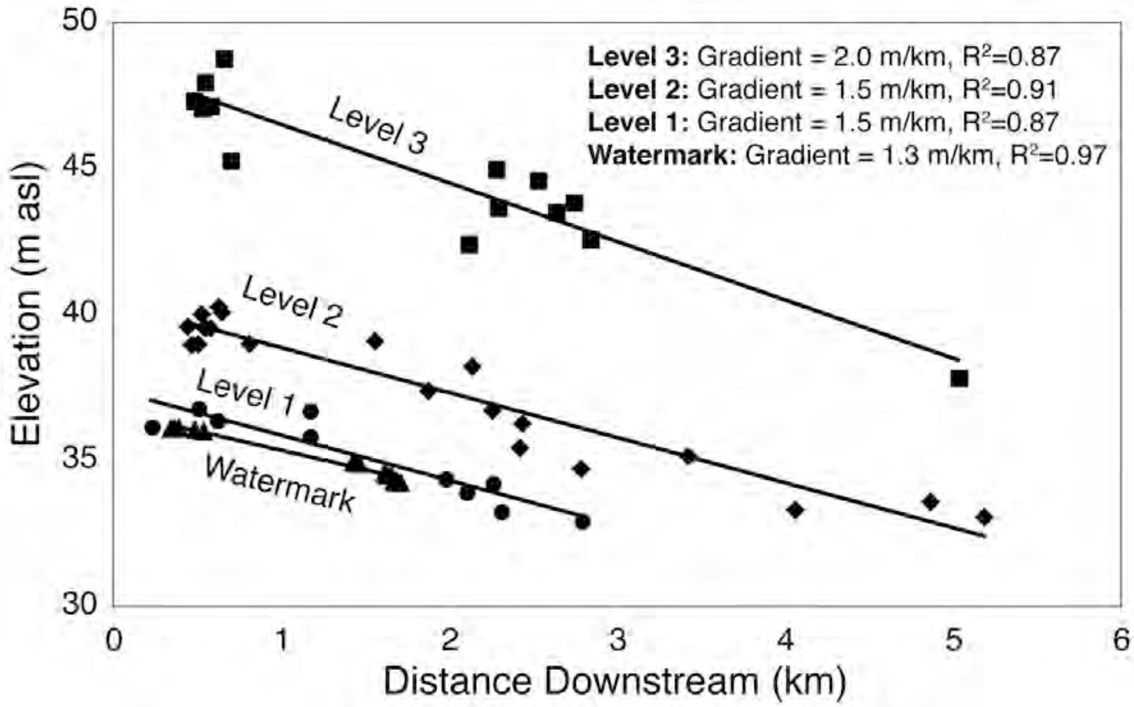
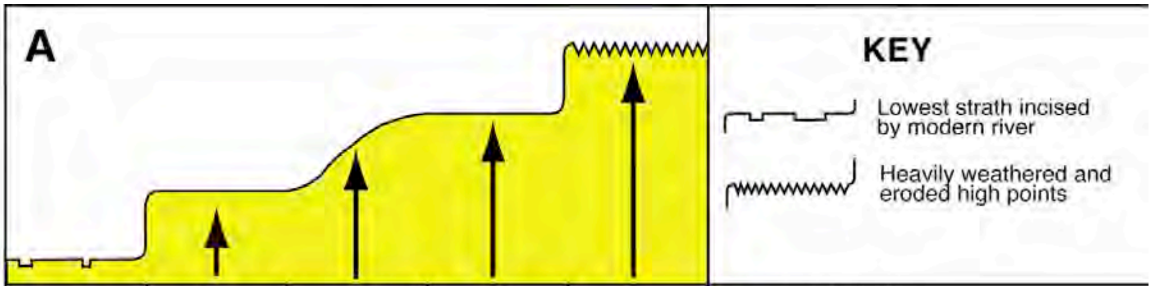
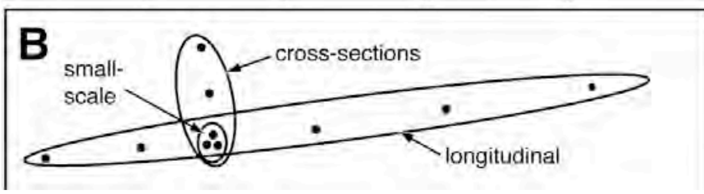


FIGURE 3. 5 Paleo-gradients for terrace levels 1, 2 & 3 derived from Trimble 4400 differential GPS data collected from sample sites within Holtwood Gorge.



1	2	Intermediate	3	4	Terrace Level
1.5 m/km	1.5 m/km	na	2.0 m/km	na	Paleo River Gradient
10	20	22	14	2	# Longitudinal Samples
3	3	0	3	0	# Small Scale Variance Samples
5	13	9	6	1	# Cross-Section Samples
13	**23**	**22**	**16**	**2**	**Total Number of Samples Collected**



Schematic Example of a Nested Sampling Strategy

FIGURE 3. 6   Strategy used for sample collection with the Holtwood Gorge field area.

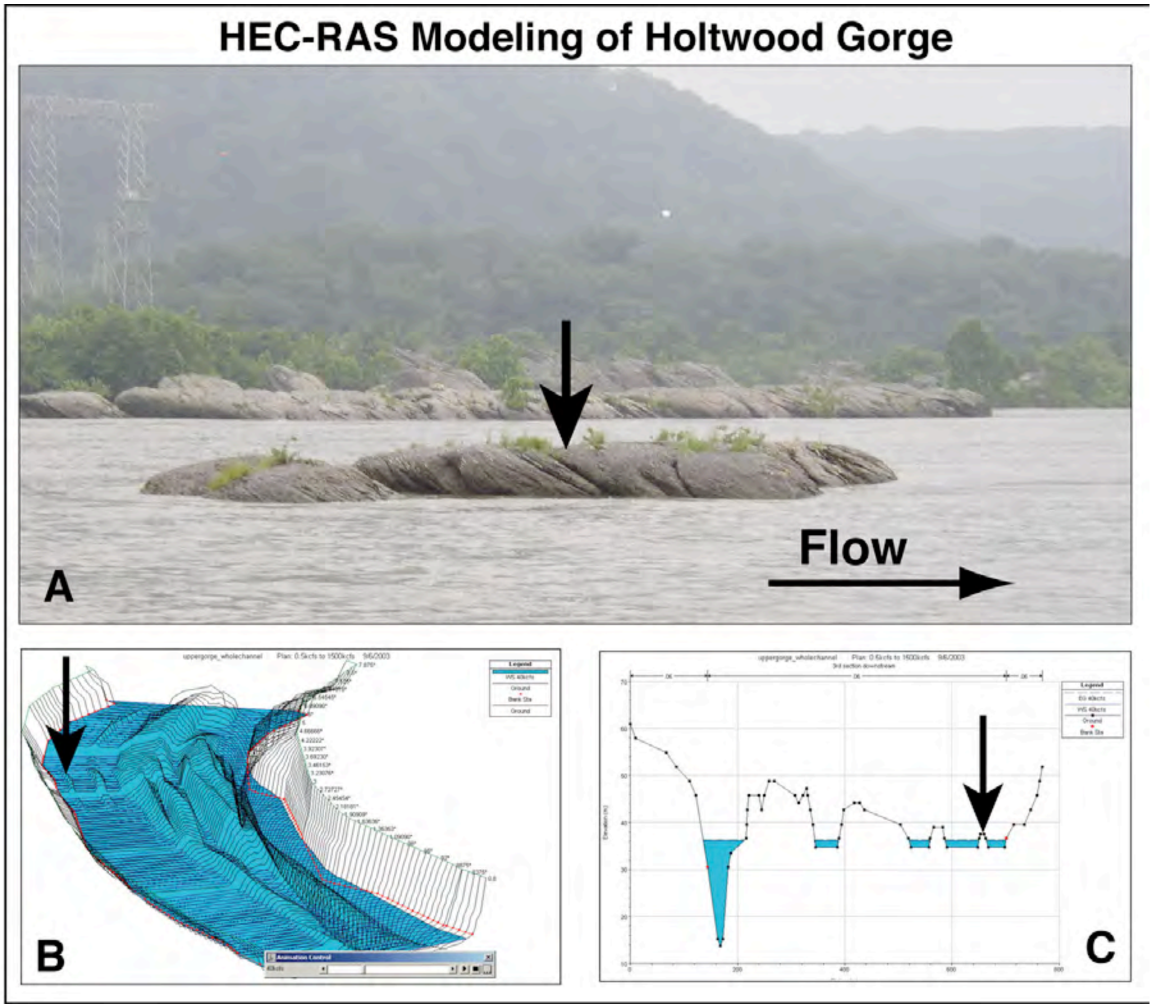


FIGURE 3. 7   Example of a calibration photo used to constrain water depths for the HEC-RAS model of Holtwood Gore at known discharges.

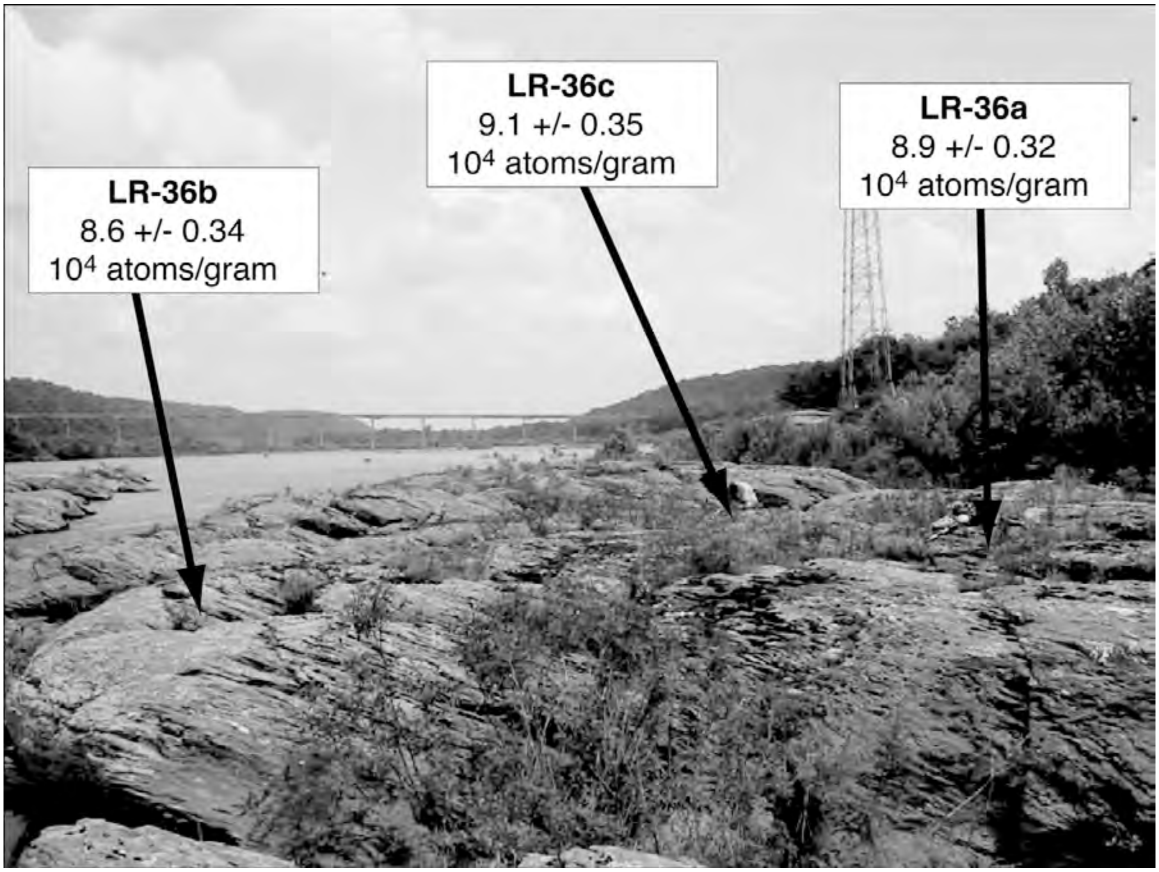


FIGURE 3. 8 Photograph depicts an example of a small-scale variance study conducted on the Level 2 terrace in upper Holtwood Gorge.

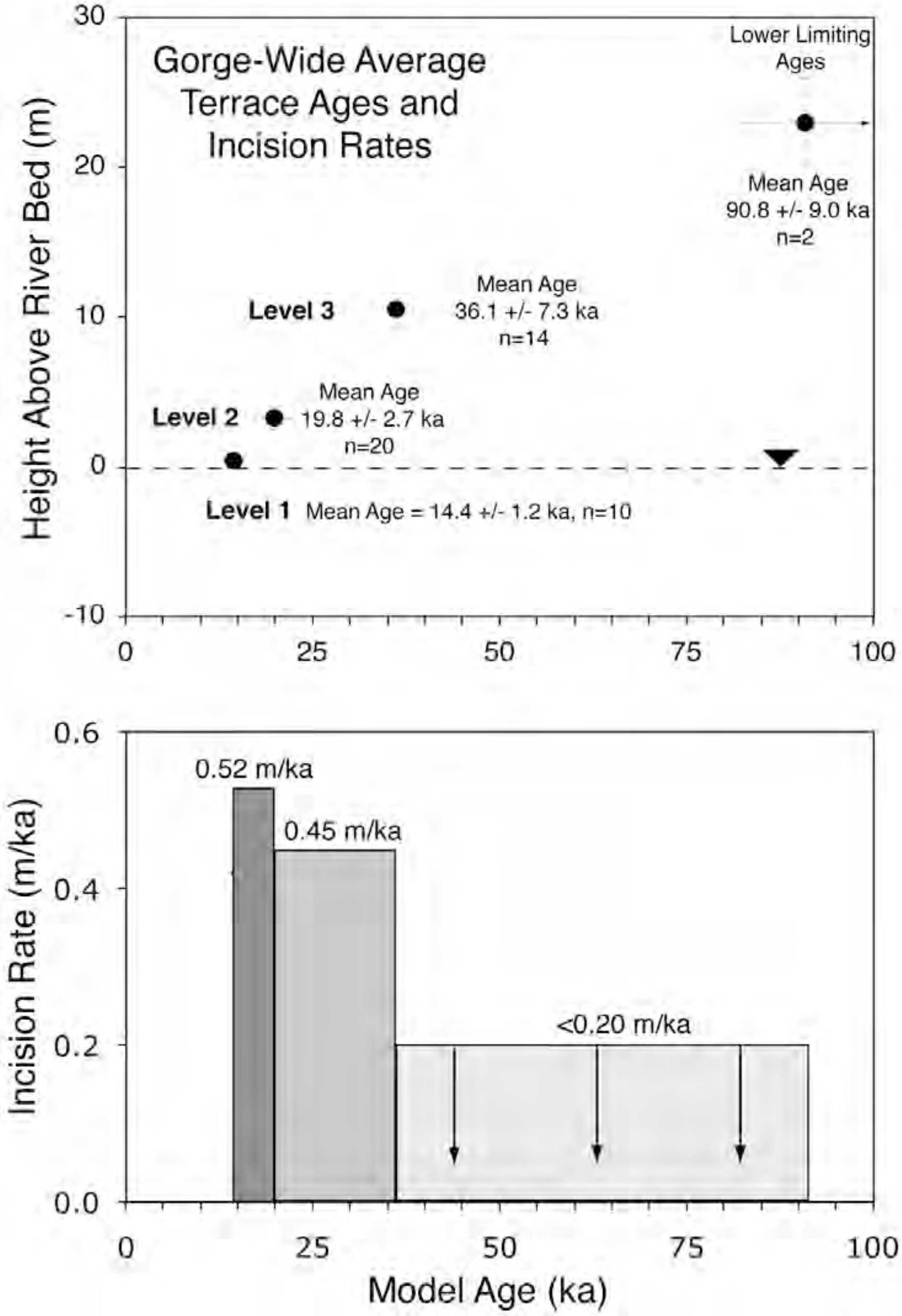


FIGURE 3. 9 Average ages for terraces with Holtwood Gorge were calculated from multiple samples collected longitudinally along each terrace level.

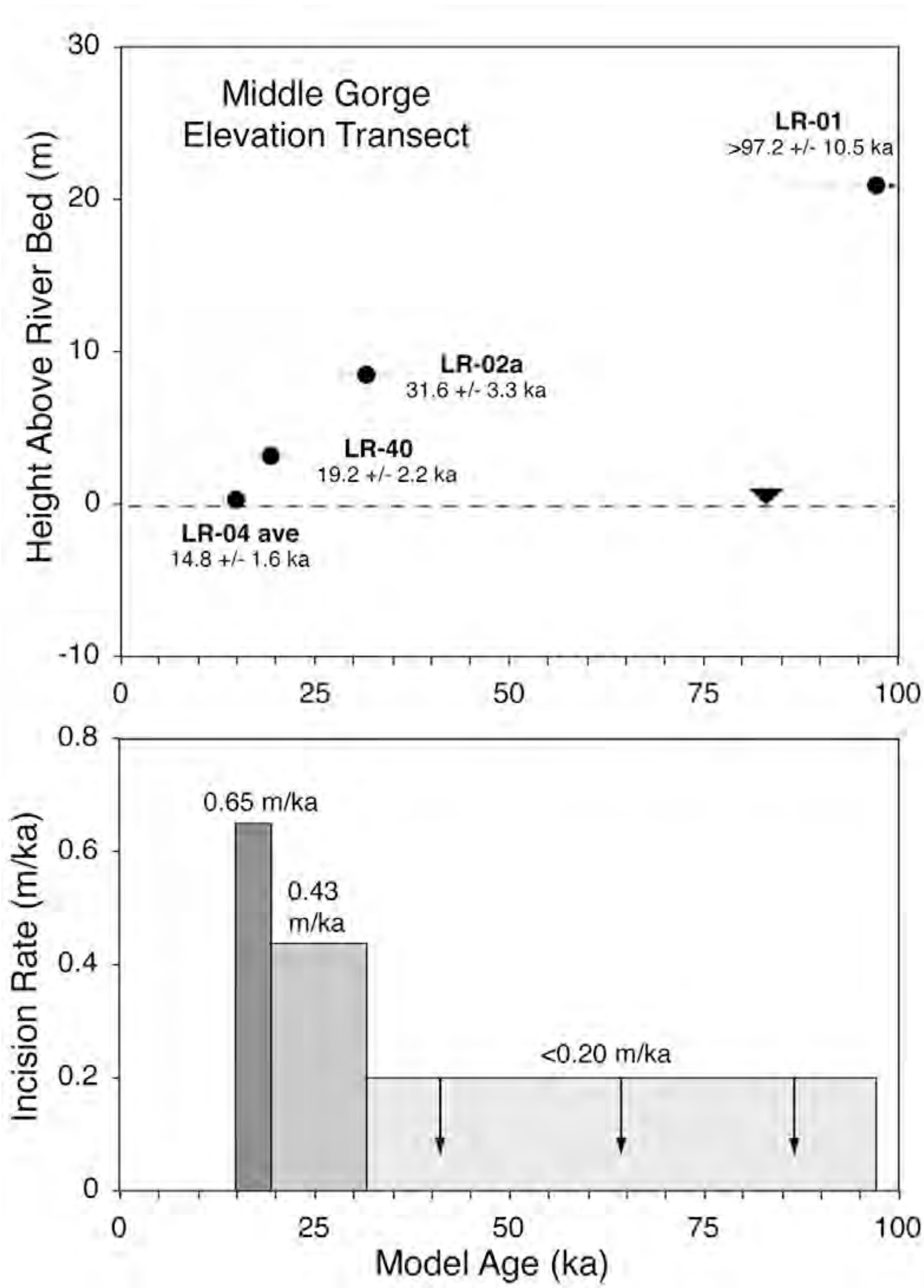


FIGURE 3. 10   Model ages for four samples collected from each of the prominent terrace levels along an elevation transect in the middle gorge.

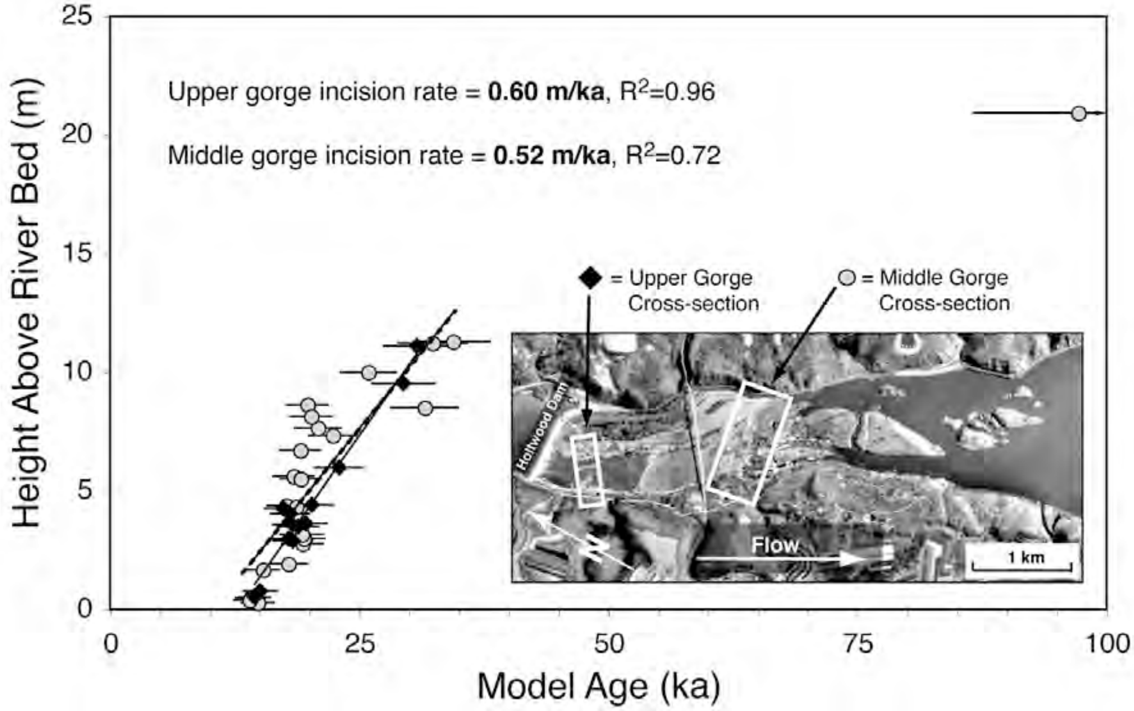


FIGURE 3. 11 Plots of incision rates along cross-sections at specified locations within Holtwood Gorge.

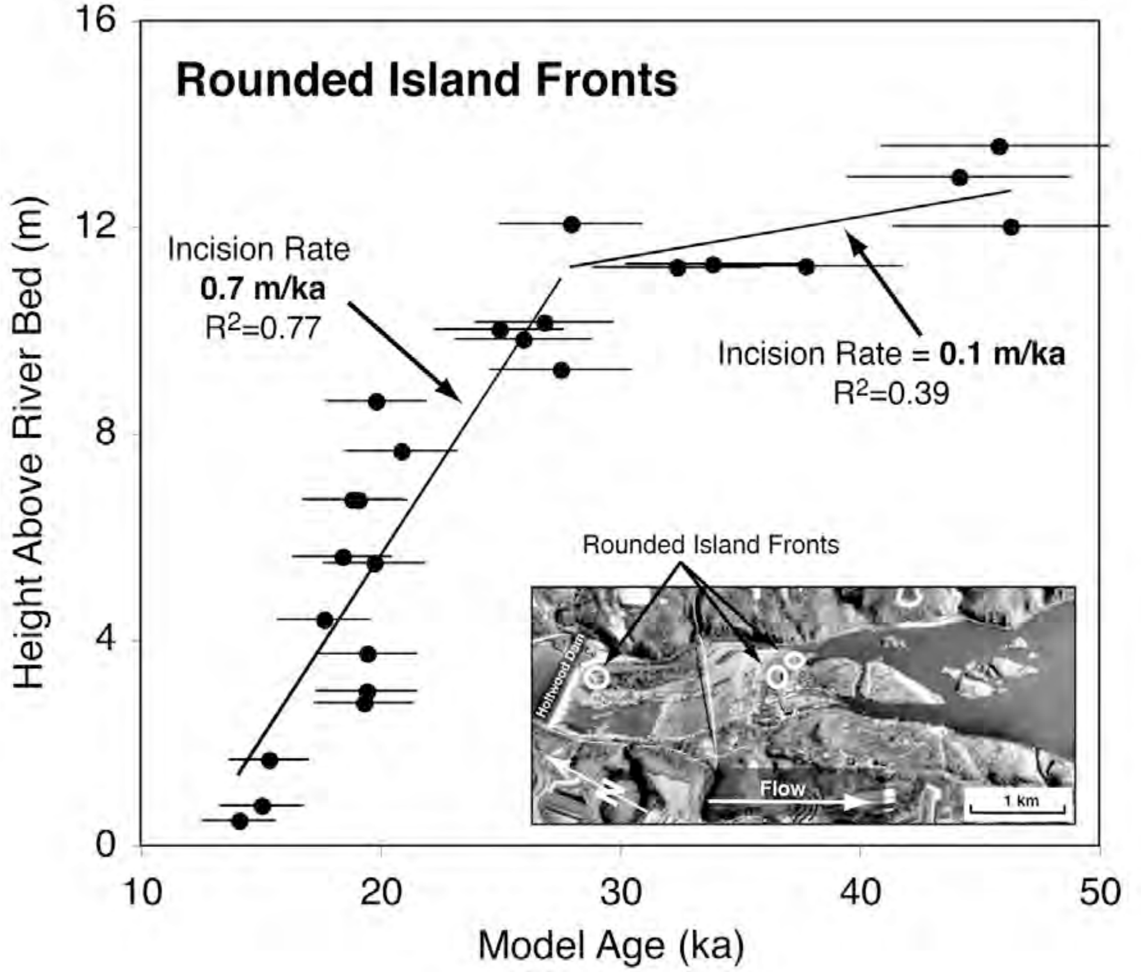


FIGURE 3. 12 Incision rates determined from 25 samples collected down the rounded fronts of three separate mid-channel islands.

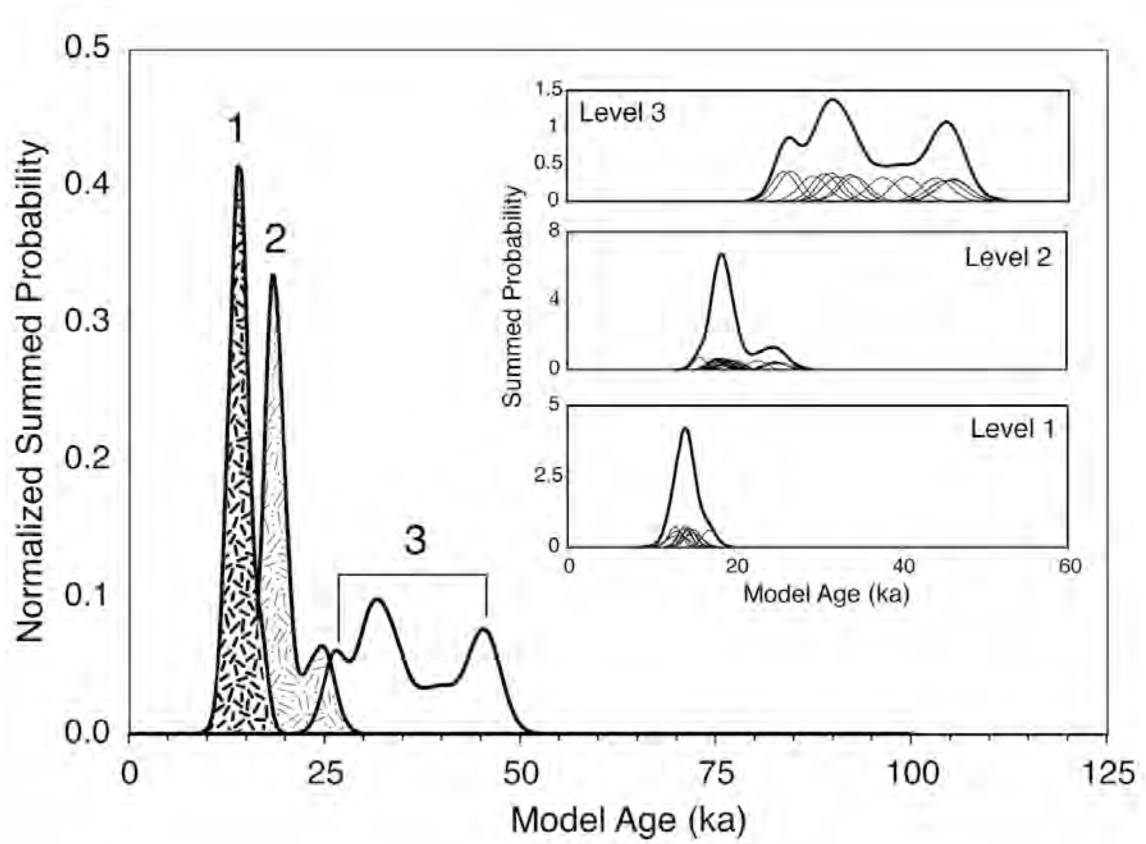


FIGURE 3. 13 Summed model age probability plots for multiple samples collected along each of the three well-preserved terrace levels within Holtwood Gorge.

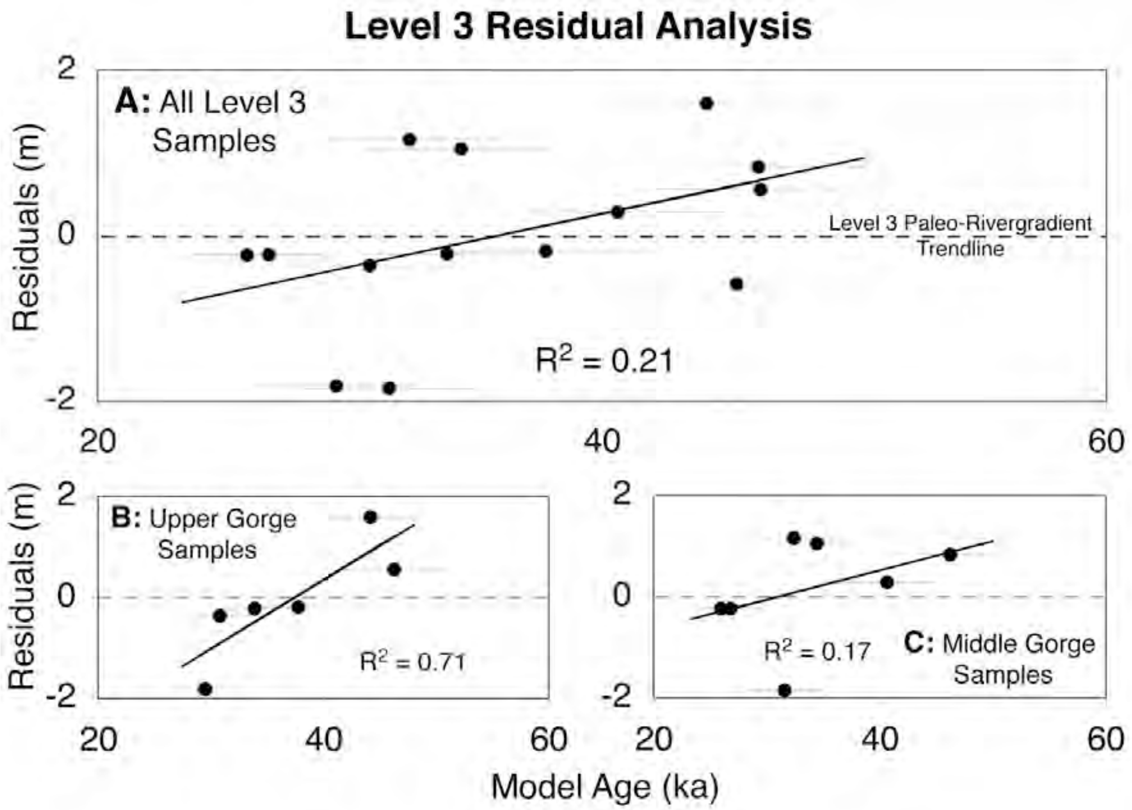


FIGURE 3. 14 Residual analysis of multiple samples collected along the level 3 terrace.

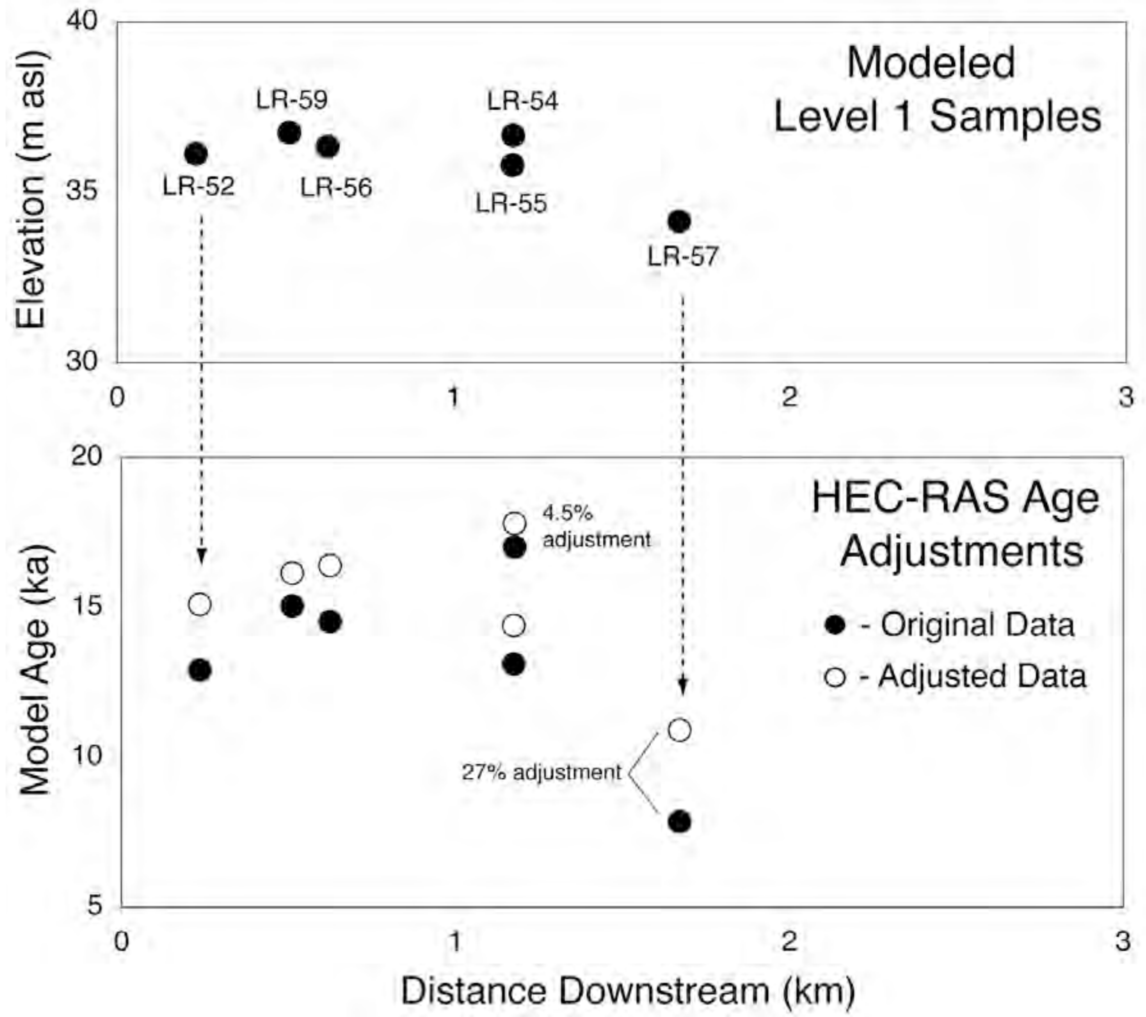


FIGURE 3. 15 Summary of the model age adjustments made to samples collected along the level 1 terrace based on HEC-RAS modeling.

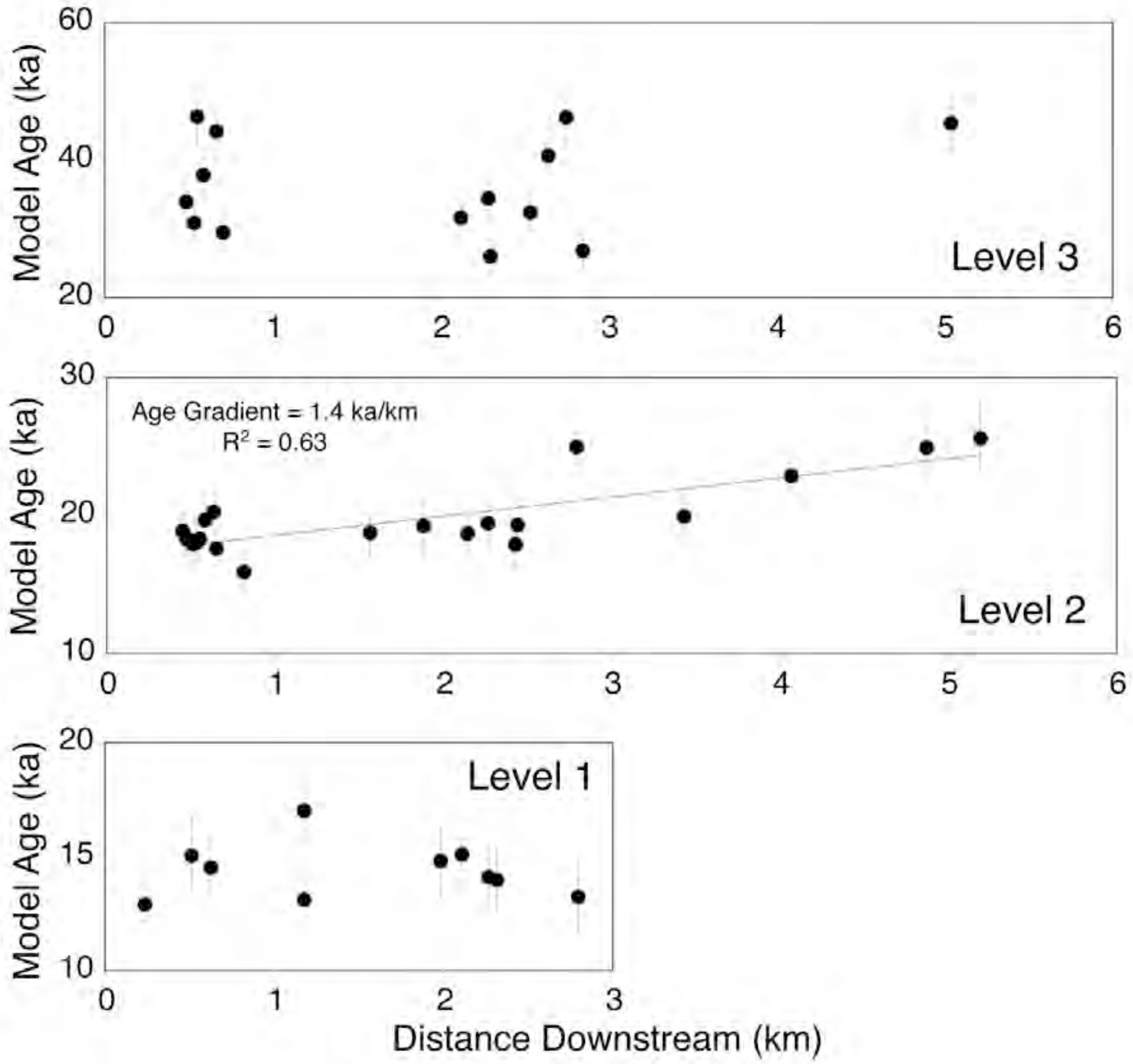


FIGURE 3. 16 Distance downstream from Holtwood Dam vs. model age for multiple samples collected along each of the prominent terrace levels in the gorge.

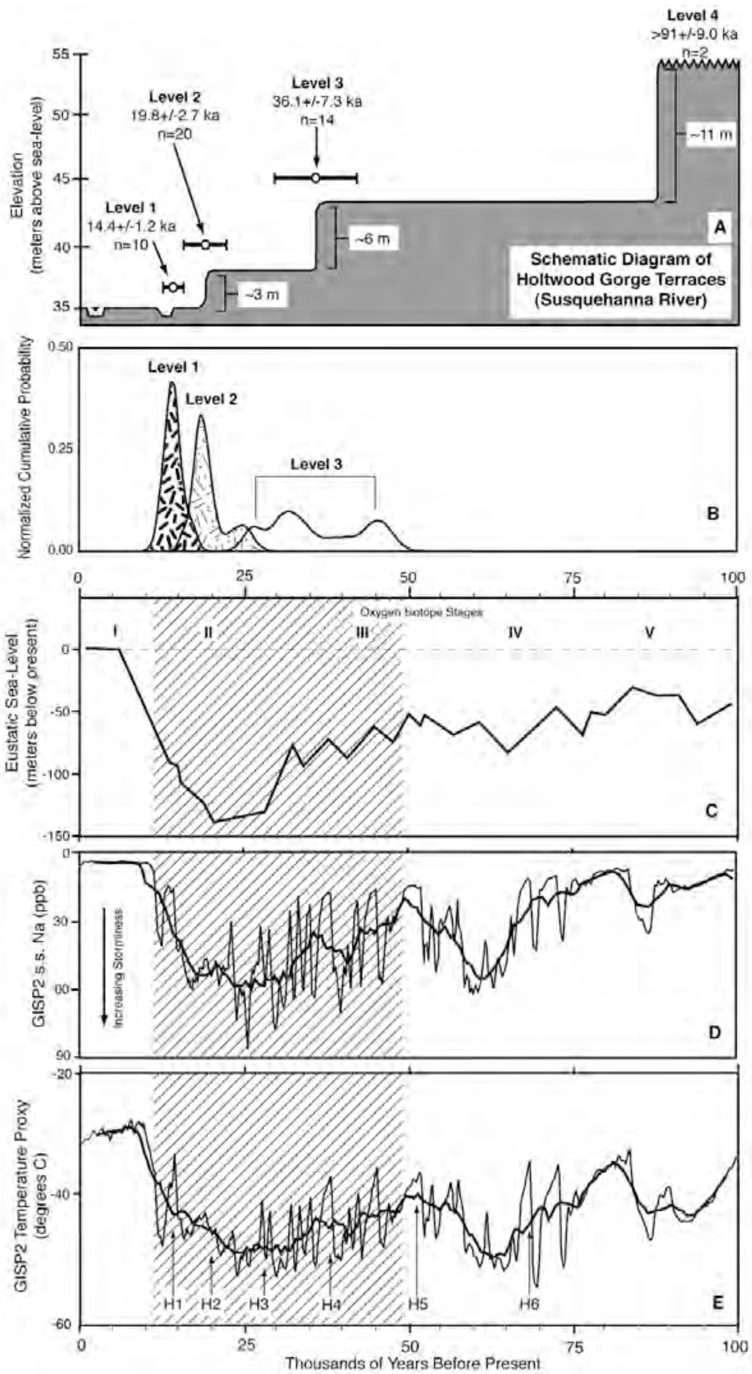


FIGURE 3. 17 Summary of the timing of incision and terrace abandonment within Holtwood Gorge in relation to otherwise documented changes in climate and sea-level.

TABLE 3. 1 GPS and isotopic data for bedrock samples collected in Holtwood Gorge.

Sample ID	Terrace Level	Elevation (masl)	Easting (m)	Northing (m)	Downstream Distance (km) [1]	Height Above Riverbed (m) [2]	^{10}Be Measured (10^4 atoms g^{-1})	Model Age (ka) [3]
LR-01	4	54.6	386953.0	4407462.2	2.30	20.9	47.4 ± 1.6	97.2 ± 10.5
LR-02a	3	42.4	386788.5	4407571.0	2.12	8.5	15.5 ± 0.5	31.6 ± 3.3
LR-02b [4]	3	42.4	386788.0	4407558.2	2.13	8.5	11.5 ± 0.4	23.4 ± 2.5
LR-03a	cobble [6]	159.0	370679.0	4433323.0	na	na	54.0 ± 1.9	100 ± 10.9
LR-04a	1	34.5	386688.9	4407670.0	1.98	0.5	7.98 ± 0.31	16.4 ± 1.8
LR-04b	1	34.3	386692.4	4407681.1	1.98	0.2	6.75 ± 0.29	13.9 ± 1.5
LR-04c	1	34.2	386685.2	4407663.3	1.99	0.2	6.82 ± 0.28	14.0 ± 1.5
LR-04cX [5]	1	34.2	386685.2	4407663.3	1.99	0.2	6.90 ± 0.33	14.2 ± 1.6
LR-06	2	35.1	388254.2	4406974.9	3.43	2.9	9.68 ± 0.41	19.9 ± 2.2
LR-07	in [7]	34.6	388175.5	4407140.2	3.25	2.2	12.8 ± 0.4	26.2 ± 2.8
LR-08	in	34.9	388047.8	4407068.9	3.24	2.5	14.0 ± 0.5	28.8 ± 3.1
LR-09	2	34.7	387834.0	4407463.1	2.79	1.7	12.1 ± 0.4	24.9 ± 2.7
LR-10	in	39.0	387552.1	4407676.7	2.46	5.6	9.06 ± 0.40	18.4 ± 2.0
LR-11	in	42.0	387586.9	4407661.8	2.49	8.6	9.73 ± 0.32	19.8 ± 2.1
LR-12	3	44.6	387600.3	4407614.9	2.54	11.2	15.8 ± 0.6	32.4 ± 3.5
LR-13	in	35.2	387503.0	4407684.8	2.42	1.7	7.50 ± 0.27	15.3 ± 1.6
LR-14	boulder [8]	35.1	387506.8	4407682.4	2.43	1.6	11.8 ± 0.5	24.0 ± 2.6
LR-15	2	36.2	387508.8	4407667.6	2.44	2.8	9.48 ± 0.33	19.3 ± 2.1
LR-16	1	34.2	387275.9	4407723.9	2.27	0.5	6.92 ± 0.26	14.1 ± 1.5
LR-17a	3	43.8	387273.3	4407683.6	2.30	10.2	13.3 ± 0.5	26.8 ± 2.9
LR-17b	3	43.7	387275.5	4407684.1	2.30	10.0	12.4 ± 0.4	25.0 ± 2.7
LR-17c	3	43.5	387278.0	4407682.9	2.30	9.8	12.7 ± 0.5	26.0 ± 2.8
LR-18	in	41.3	387265.8	4407674.7	2.30	7.7	10.2 ± 0.5	20.9 ± 2.3
LR-19	in	40.4	387254.0	4407680.4	2.29	6.7	9.39 ± 0.33	19.1 ± 2.0
LR-20	in	38.1	387263.5	4407700.2	2.28	4.4	8.56 ± 0.33	17.6 ± 1.9
LR-21	2	36.7	387295.8	4407738.5	2.26	3.0	9.42 ± 0.36	19.4 ± 2.1
LR-22	2	38.2	386998.1	4407684.9	2.14	4.3	9.18 ± 0.29	18.7 ± 2.0
LR-23	in	42.0	386904.8	4407614.7	2.15	8.1	9.90 ± 0.39	20.2 ± 2.2
LR-24	in	39.1	387079.6	4407552.8	2.30	5.5	9.19 ± 0.33	19.1 ± 2.0
LR-25	3	45.0	387161.8	4407622.8	2.29	11.3	17.0 ± 0.6	34.4 ± 3.7
LR-26	2	38.9	385609.2	4408766.8	0.47	2.9	9.02 ± 0.30	18.3 ± 1.9
LR-27	2	39.0	385653.1	4408747.9	0.51	3.0	8.82 ± 0.29	17.9 ± 1.9
LR-28	boulder	38.1	385646.1	4408750.9	0.51	2.2	7.67 ± 0.33	15.5 ± 1.7
LR-29	3	47.0	385827.6	4408840.9	0.53	11.1	15.3 ± 0.5	30.8 ± 3.3
LR-30	in	43.7	385769.0	4408811.4	0.52	7.8	17.5 ± 0.6	35.7 ± 3.8
LR-31	in	42.0	385724.8	4408806.3	0.50	6.0	11.3 ± 0.4	23.0 ± 2.4
LR-32	2	40.2	385755.3	4408670.9	0.63	4.4	9.92 ± 0.35	20.2 ± 2.2
LR-33	2	39.5	385688.2	4408725.2	0.55	3.6	8.98 ± 0.31	18.3 ± 1.9
LR-34	2	39.5	385714.2	4408704.4	0.58	3.6	9.63 ± 0.34	19.7 ± 2.1
LR-35	2	39.6	385465.8	4408700.2	0.45	3.5	9.19 ± 0.35	18.9 ± 2.0
LR-36a	2	40.2	385491.4	4408616.8	0.53	4.3	8.92 ± 0.34	18.2 ± 2.0
LR-36b	2	39.8	385496.2	4408627.5	0.53	3.9	8.60 ± 0.32	17.4 ± 1.9
LR-36c	2	39.9	385500.4	4408612.7	0.54	4.0	9.07 ± 0.35	18.6 ± 2.0
LR-37	2	40.0	385575.8	4408529.6	0.65	4.3	8.57 ± 0.31	17.4 ± 1.9
LR-37X [5]	2	40.0	385575.8	4408529.6	0.65	4.3	8.79 ± 0.36	17.8 ± 1.9
LR-38	3	45.2	385602.8	4408484.3	0.70	9.5	14.6 ± 0.6	29.4 ± 3.2
LR-39	2	39.1	386233.0	4407871.0	1.56	4.5	9.15 ± 0.34	18.7 ± 2.0
LR-40	2	37.4	386635.0	4407757.1	1.88	3.2	9.45 ± 0.50	19.2 ± 2.2
LR-41	in	41.4	386720.3	4407708.3	1.97	7.3	11.0 ± 0.4	22.3 ± 2.4
LR-42	2	35.4	387265.1	4407521.2	2.43	1.9	8.78 ± 0.34	17.9 ± 1.9
LR-43	4	58.3	387248.6	4407329.7	2.58	25.0	41.7 ± 1.4	84.5 ± 9.1
LR-44	2	33.6	388723.1	4405554.8	4.87	3.3	12.0 ± 0.5	24.9 ± 2.7
LR-45	2	33.0	389026.6	4405373.1	5.19	3.1	12.2 ± 0.5	25.6 ± 2.8
LR-47	3	37.8	389447.6	4405836.4	5.04	7.7	22.1 ± 0.7	45.3 ± 4.8
LR-48	2	33.3	388150.8	4406141.5	4.07	1.9	11.1 ± 0.4	22.8 ± 2.4
LR-49	1	32.9	387846.1	4407466.7	2.80	0.1	6.43 ± 0.46	13.2 ± 1.6
LR-50	1	33.2	387431.1	4407765.7	2.32	0.4	6.79 ± 0.29	14.0 ± 1.5
LR-51	1	33.9	387055.9	4407765.8	2.11	0.0	7.34 ± 0.31	15.1 ± 1.6
LR-52	1	36.1	385435.2	4408936.8	0.23	0.2	6.29 ± 0.27	12.9 ± 1.4
LR-53	2	39.0	385889.7	4408541.7	0.82	3.4	7.75 ± 0.26	15.9 ± 1.7
LR-54	1	36.7	386178.3	4408299.6	1.18	1.6	8.28 ± 0.32	17.0 ± 1.8
LR-55	1	35.8	386179.7	4408302.7	1.18	0.7	6.44 ± 0.34	13.1 ± 1.5
LR-56	1	36.3	385697.8	4408642.9	0.63	0.5	7.08 ± 0.27	14.5 ± 1.6
LR-57 [4]	1	34.2	386368.5	4407832.7	1.67	0.3	3.83 ± 0.21	7.9 ± 0.9
LR-58	in	37.0	388628.3	4406401.2	4.12	5.7	10.5 ± 0.4	21.5 ± 2.3
LR-59	1	36.7	386058.1	4409019.7	0.51	0.8	7.40 ± 0.40	15.1 ± 1.7
LR-60	in	49.6	385939.8	4409026.8	0.44	13.6	22.5 ± 0.7	45.8 ± 4.8
LR-61	in	48.1	385941.2	4409036.8	0.43	12.1	13.9 ± 0.5	27.9 ± 3.0
LR-62	in	45.3	385938.6	4409066.2	0.41	9.2	13.5 ± 0.5	27.5 ± 2.9
LR-63	in	42.8	385938.9	4409077.7	0.40	6.7	9.23 ± 0.41	18.8 ± 2.1
LR-64	in	41.6	385935.2	4409082.7	0.39	5.5	9.66 ± 0.32	19.7 ± 2.1
LR-65	in	39.9	385931.6	4409090.8	0.38	3.7	9.57 ± 0.34	19.4 ± 2.1
LR-66	3	47.3	385902.0	4408946.6	0.49	11.3	16.7 ± 0.5	33.9 ± 3.6
LR-67	3	47.1	385955.4	4408860.9	0.59	11.2	18.6 ± 0.6	37.8 ± 4.0
LR-68	3	48.7	386013.3	4408806.1	0.66	13.0	21.8 ± 0.6	44.1 ± 4.6
LR-69	3	47.9	386074.3	4408983.8	0.55	12.0	22.8 ± 0.6	46.3 ± 4.9
LR-70	3	42.5	387533.7	4407196.4	2.85	9.6	13.3 ± 0.5	26.8 ± 2.9
LR-71	3	43.8	387475.6	4407274.1	2.75	10.8	22.8 ± 0.7	46.2 ± 4.9
LR-72	in	36.1	387471.9	4407257.5	2.76	3.1	14.7 ± 0.6	30.1 ± 3.3
LR-73	in	34.9	387468.1	4407253.9	2.76	1.9	11.6 ± 0.5	23.6 ± 2.6
LR-74	3	43.5	387412.2	4407360.9	2.64	10.3	20.0 ± 0.6	40.6 ± 4.3

1-Distance downstream (km) from Holtwood Dam. 2-Height above the river bed is measured relative to a distinctive watermark in upper Holtwood Gorge under no-flow conditinos. The watermark was traceable over approximately 2 km. 3-Age uncertainties include propagated analytic errors (1 sigma) in carrier addition and AMS measurement, and +/-10% (1 sigma) uncertainties in 10-Be production rate. 4-Two samples were excluded because of suspected measurement error. They will be re-run on the next trip to LLNL. 5-Two independently processed and measured laboratory replicates were run on the accelerator to ensure reproducibility of lab and measurement techniques. 6-LR-03a is a quartz cobble colleced from a middle Miocene age gravel terrace on the piedmont uplands. 7-"in" in the Terrace Level field indicates that samples were collected from bedrock surfaces between the three prominent levels of terraces. 8-LR-14 and LR-28 were collected from the top surfaces of fluvially rounded boulders currently resting on remnants of the level 2 terrace.

CHAPTER 4: Conclusions

SUMMARY OF FINDINGS

Over the past two and a half years, I have collected, processed, and measured activities of ^{10}Be in >80 samples collected from fluvially-carved bedrock terraces within Holtwood Gorge in order to decipher when, how fast, and why the Susquehanna River incised into rocks of the Appalachian Piedmont along the Atlantic Passive Margin. Findings from this research of particular import are:

- Results from a variety of spatial tests indicate that cosmogenic isotopes (^{10}Be in this study) can be used successfully to investigate the timing and rate at which rivers incise through quartz bearing bedrock in passive margin settings. Nuclide activities and model exposure ages increase with height above the river, demonstrating that they do indeed track the pace at which the Susquehanna River incised through rock during the late Pleistocene. In addition, small-scale variance studies provide evidence that single samples represent well the exposure histories of entire fluvially-carved bedrock outcrops.
- Based on the exposure histories of bedrock terraces, rates of incision (0.8 to 0.4 m/ka) within Holtwood Gorge accelerated dramatically beginning between ~45 and ~35 ka; incision continued at a rapid rate until ~14 ka. These findings demonstrate that even along the Atlantic passive margin, large rivers are capable of incising through rock for short periods of time at rates approaching those

recorded in the tectonically active Himalayas (Burbank and others, 1996; Leland and others, 1998).

- Similarities in the timing and rate of incision along the glaciated Susquehanna River and the unglaciated Potomac River to the south suggest that fluctuation in regional boundary conditions caused both rivers to incise through bedrock. Glacial ice and associated meltwater within drainage basins during and after glaciation are not prerequisite for rapid river incision through bedrock.
- The phase of rapid incision along the Susquehanna River (~45 ka to ~14 ka), as well as that on the Potomac River, correlates well with a period of cold and stormy climate recorded by the GISP2 ice core, central Greenland. Deteriorating climate during the late Pleistocene appears to have increased the frequency and magnitude of flood events capable of exceeding thresholds for bedrock erosion. Records of Holocene paleostorminess recorded in lake cores in northeastern North America during the Holocene also correlate with the Greenland record, suggesting that it is a reasonable proxy for geomorphically effective floods in North America.
- Rates of incision within Holtwood Gorge (0.8 to 0.4 m/ka) are almost two orders of magnitude greater than long-term estimates of bedrock incision since the middle Miocene (~15 Ma). Discordance between long-term estimates and shorter-term measurements of incision rates, as well as the existence of terraces reported in this thesis indicate that the Susquehanna River incises episodically.

- The lower reaches of the Susquehanna River have remained oversteepened since the middle Miocene. Because river gradients are critically important to stream power, and a river's ability to erode its bed, the Susquehanna River is primed to incise given the correct changes in boundary conditions. The pulse of incision measured with ^{10}Be represents an episode of erosion during an ongoing period of river adjustment. When interpreting rates of incision through bedrock, particularly in passive margin settings, initial boundary conditions are an important determinant.

SUGGESTIONS FOR FUTURE RESEARCH

Results from this study provide previously unattainable information regarding the timing and rate at which large rivers draining a prominent passive margins incise through bedrock in this tectonically quiescent setting. However, it is not clear that these findings can be directly applied to bedrock channels along other passive margins around the globe. Numerous studies along a variety of passive margins will further our understanding of how these complex geomorphic systems respond to fluctuating boundary conditions, and modify ancient landscapes. Below are a few suggestions for future research into this problem:

- Results discussed in this thesis, as well as work conducted by Paul Bierman, Milan Pavich, and E-an Zen shed light upon the timing and nature of bedrock channel incision along the Susquehanna and Potomac Rivers. The Susquehanna River Basin straddles at the Wisconsinan glacial margin, while the Potomac lies immediately to the south allowing investigation not only the timing and rate of incision, but also the effects of basin glaciation. However, there are several other major river systems draining the central Appalachian Mountains near the glacial margin that have not been sampled. Similar to the Susquehanna and Potomac Rivers, the lower reaches of the Rappahannock and James Rivers, immediately to the south of the Potomac, are oversteepened and flow though bedrock valleys (Reed, 1981). While all rivers share the peculiar and long-lived oversteepening of their lower reaches, thought to represent flexural upwarping of the Atlantic margin over geologic time scales (Pazzaglia and Gardner, 1994a and 1994b), their distance from the glacial margin differs considerably. Sampling of fluvial-carved bedrock surfaces along the Rappahannock and James may help determine the relative importance of a variety of climate-related boundary conditions. For instance, the magnitude of glacial isostasy and the glacial forebulge vary both temporally and spatially, and would thus likely have different effects on bedrock channel incision along rivers progressively farther outside of the glacial margin.

- There is evidence to suggest that not only large rivers near the glacial margin along the Atlantic seaboard incised into rock during the late Pleistocene, but also smaller tributaries. A single sample collected from the lip of a bedrock knickpoint along Principio Creek which drains into Chesapeake Bay yields an exposure age of ~26 ka. This finding suggests that the creek, which drains no more than 100 km^2, incised several m into bedrock near the knickpoint sometime following 26 ka, during the same period of time that the Susquehanna and

Potomac Rivers (basin areas are 70,200 and 29,900 km^2 respectively) were incising rapidly. This finding suggests small rivers with lower discharges and less stream power were also affected by changing boundary conditions during the late Pleistocene. Identifying and systematically sampling bedrock knickpoints within tributaries draining a range of basin areas near the glacial margin may help us understand better what exactly causes rivers to incise into bedrock along the Atlantic Passive margin.

- We have recently received additional funding from the National Science Foundation for LIDAR coverage of Holtwood Gorge. High-resolution elevation information provided by this coverage can and will be utilized in a number of ways. For example, DEMs produced from LIDAR altimetry can be used to greatly improve the accuracy of the HECRAS modeling of Holtwood Gorge.
- Finally, in order to generalized these findings to passive margins elsewhere around the globe, and to further our understanding of fluvial incision through bedrock, similar comprehensive studies utilizing cosmogenic isotopes need to be undertaken wherever possible.

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APPENDIX A: Water Inundation Modeling
(HECRAS Modeling)

During and following periods of incision, river water covered bedrock surface within and above the active channel for varying periods of time. Incoming cosmic rays, responsible for the production of ^{10}Be, were absorbed by this water when it covered surfaces we later sampled. Since nuclide production rates decrease exponentially with depth as a function of the density of the material through which cosmic rays pass (Lal, 1991), we need to consider the effect of water shielding on our model exposure ages. If the integrated average water depth that covered sampled outcrops through time is substantial, our model ages will be too young.

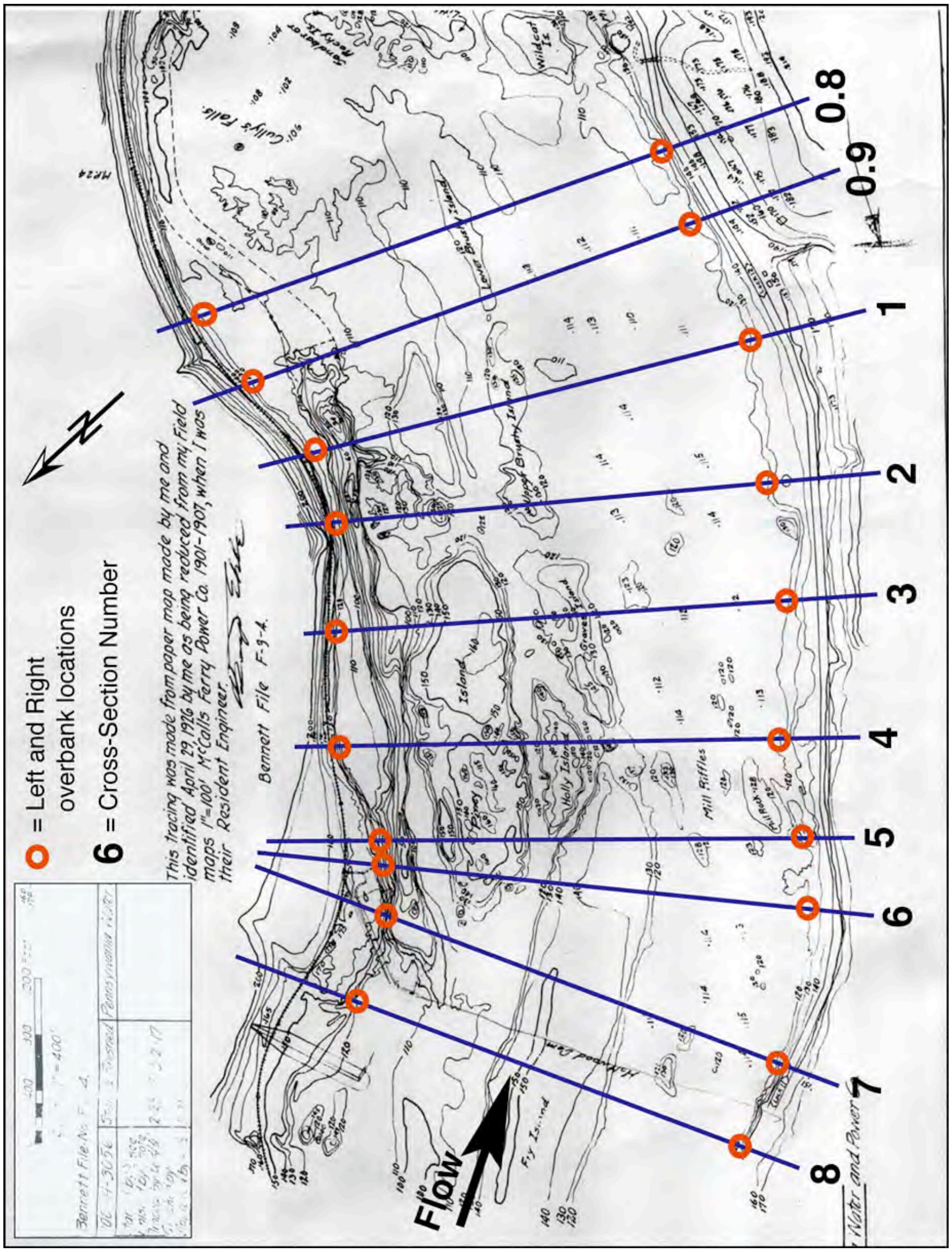
We used HEC-RAS River Analysis System (3.1) developed by the US Army Corps of Engineers (www.hec.usace.army.mil) to estimate the amount of cosmic radiation absorbed by outcrop-covering floodwaters in Holtwood Gorge through time. We created a working model of the upstream half of Holtwood gorge using 10 cross sections taken from detailed surveys drafted during the planning of Holtwood Dam (Bennett File No. F-3-4; Pennsylvania Water & Power Co.). Using HEC-RAS, we modeled the depth of water covering the lowest strath (level 1) for an appropriate range of discharges. Rating curves for each of the ten cross-sections were generated from the model and used to estimate the daily water depth covering each level 1 sample in the upper gorge based on ~75 years of daily flow records from the Marietta gauging station (USGS 01576000) located ~30 km upstream from the gorge. We constrained the model using observed water depths along a cross section at known discharges (fig. 3.7).
The effective production rate for each sample site for each day of record was calculated using the modeled water depth according to Lal (1991):

$$P_x = P_o e^{-(x\rho/\Lambda)} \tag{1}$$

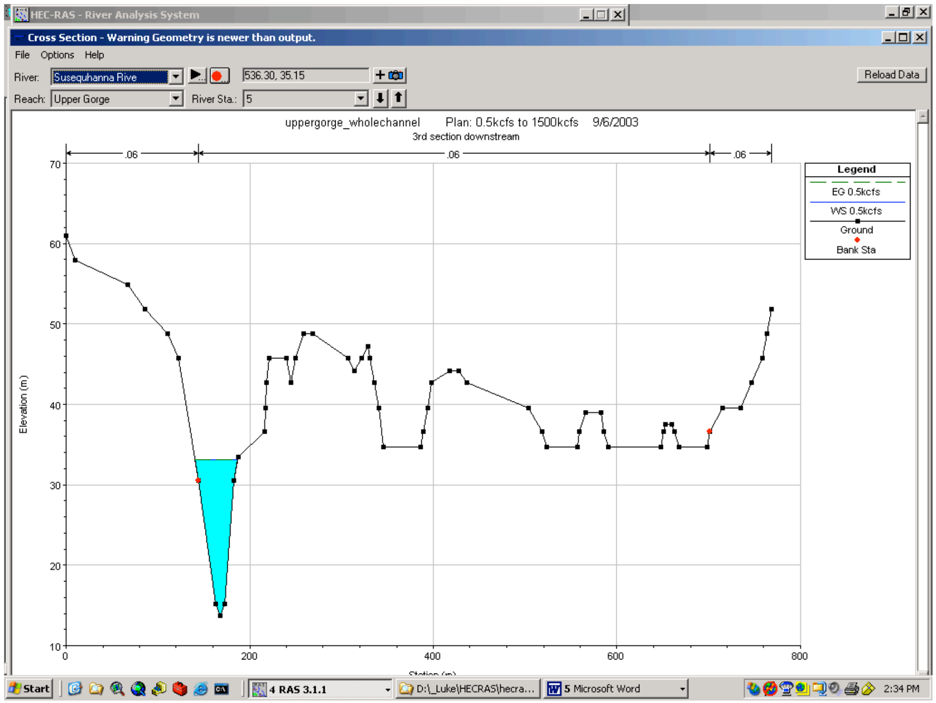
Where (P_o) is the surface production rate, (P_x) represents the effective production rate at water depth x over the sampled surface, (ρ) is the density of water (1.0 g/cm^3), and (Λ) represents the attenuation length for fast neutrons (~165 g/cm^2). For each sample site, the effective daily production rates were summed and divided by the total possible production rate (100% exposure for everyday of record). The resulting ratio is an expression of how much exposure history is recorded by the model age for each sample under modern hydrologic conditions; a sample site yielding a ratio of 0.93 for example, indicates that approximately 7% of the total exposure history has been lost to absorption of cosmic rays by an overlying column of water.

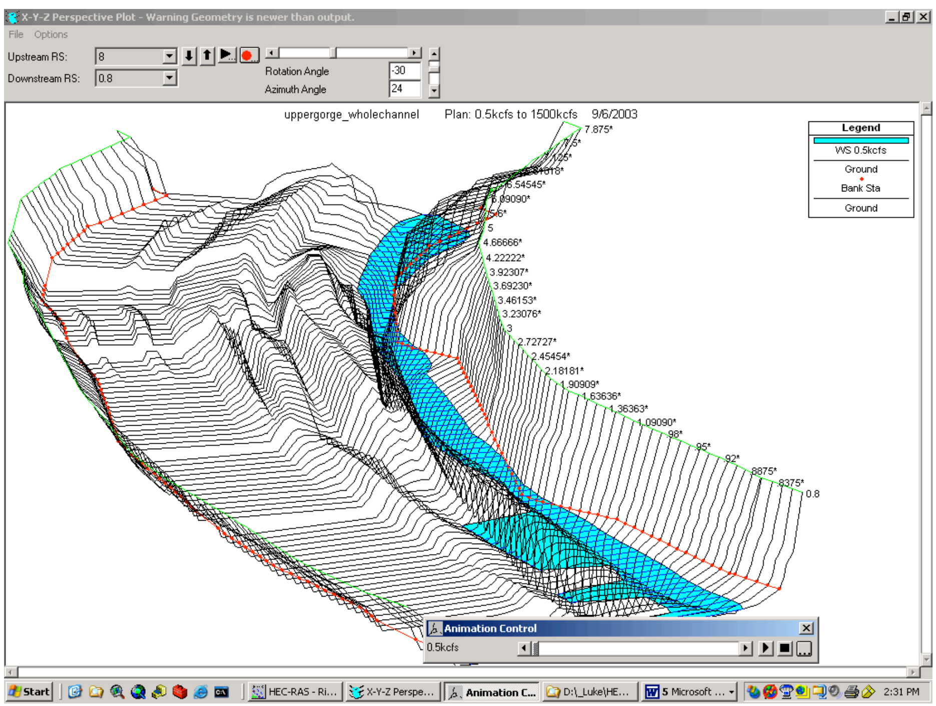
This approach assumes that the last 75 years of discharge records can be extrapolated through time. Although there are no discharge estimates for the Susquehanna during the late Pleistocene, we speculate that water shielding had an equal or lesser effect on samples from higher terraces. During the last glacial, the channel bed was actively and rapidly lowering; thus exposed rock surfaces were quickly removed from inundating flood waters.

The figures and tables on the following pages provide the data, and explain how the HECRAS model of Holtwood Gorge was created.

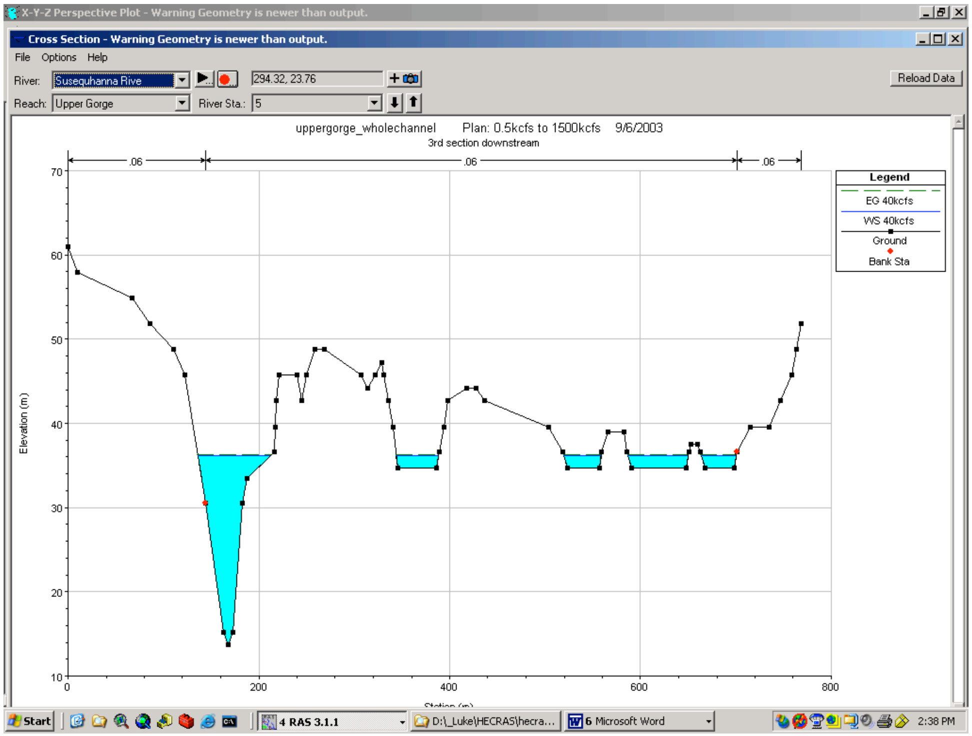


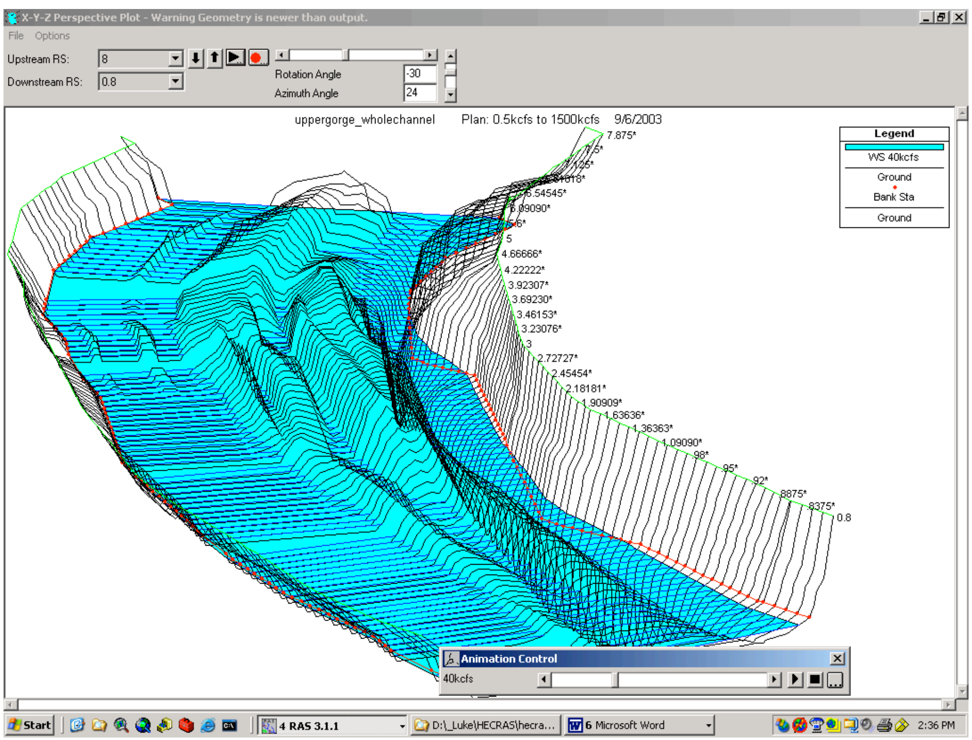
Cross-Section Locations: Location of the ten cross-sections used in the HECRAS model. The topographic survey was constructed by Pennsylvania Water and Power Co. during the planning of Holtwood Dam. Horizontal scale is 1" = 400'.



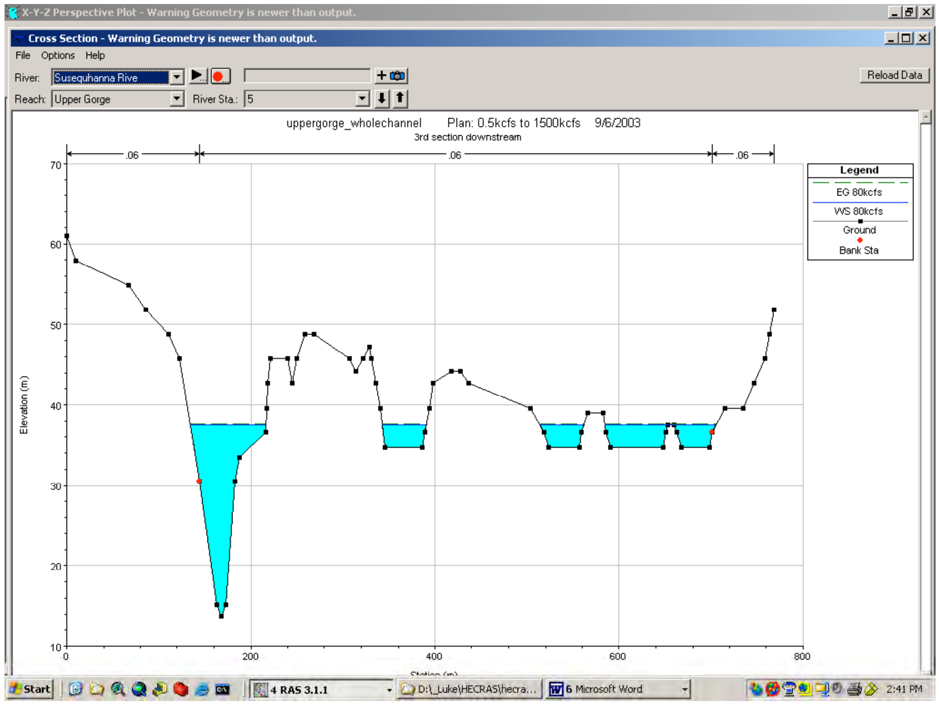


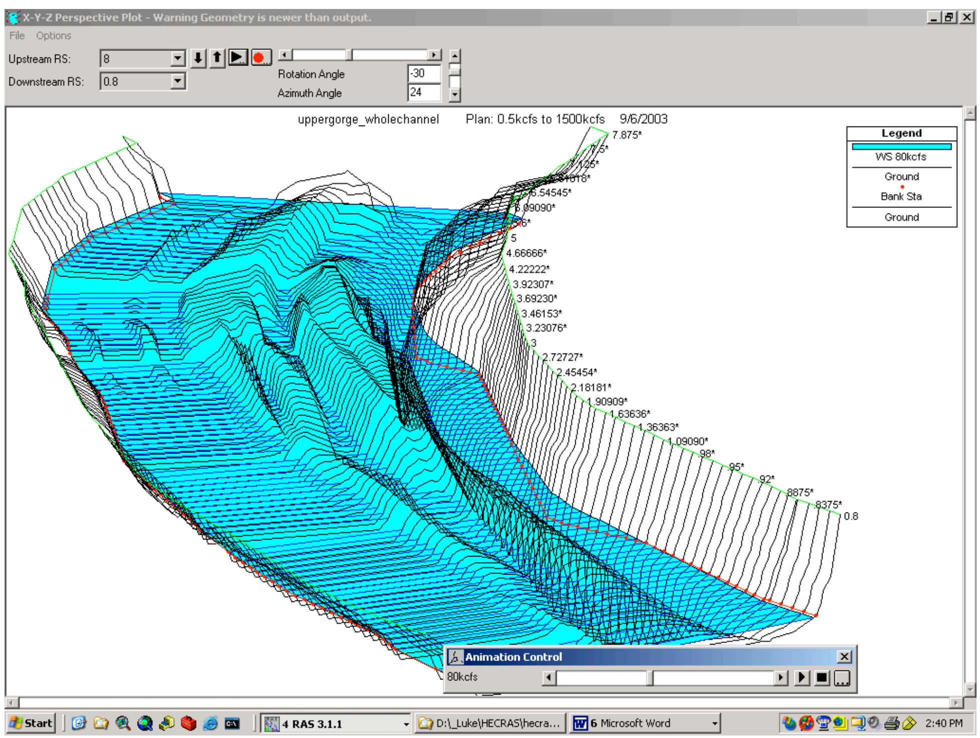
HECRAS Model Output at 0.5 kcfs:



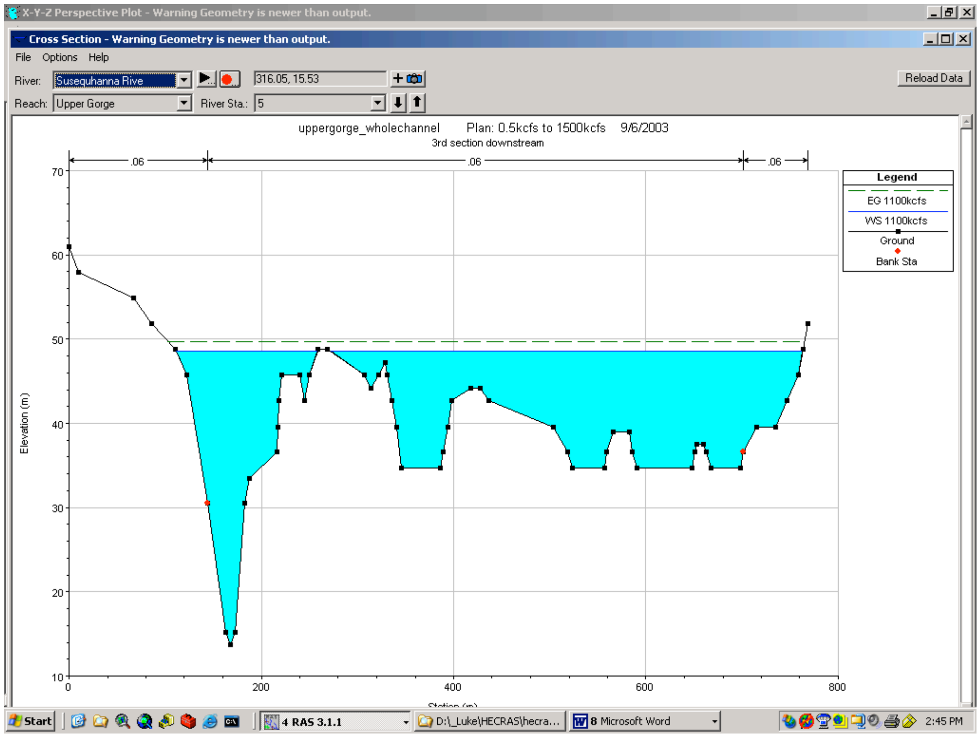


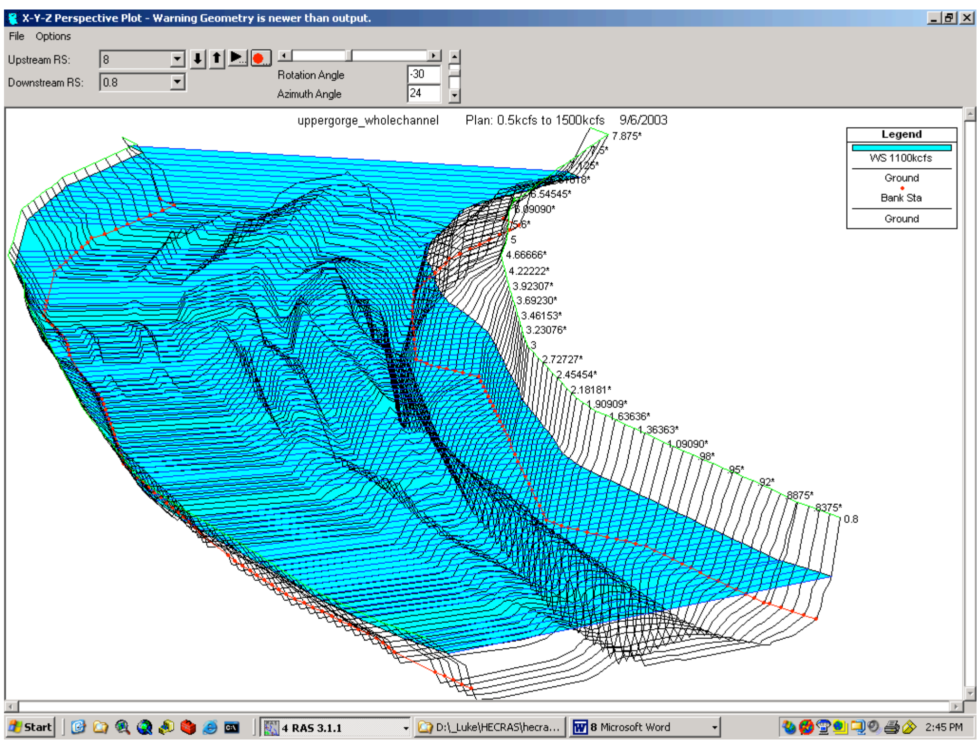
HECRAS Model Output at 40 kcfs





HECRAS Model Output at 80 kcfs:





HECRAS Model Output at 1100 kcfs: 1100 kcfs is the approximate peak daily discharge recorded during Hurricane Agnes in 1972, the flood of record.

Summary of Age Adjustments Made to Specified Samples Resulting From HECRAS Modeling of Holtwood Gorge

LR-52	
elevation	36.112
level	1
total possit	25568
acutal	21868.38
%total	85.53026
model age	12.9
adj age	15.08238

LR-56	
elevation	36.339
level	1
total poss	25568
actual	23276.78
% total	91.03873
model age	14.9
adjusted ag	16.36666

LR-54	
elevation	36.674
level	1
total poss	25568
actual	24400.41
% total	95.43341
model age	17
adjusted ag	17.81347

LR-55	
elevation	35.797
level	1
total poss	25568
actual	23260.77
% total	90.9761
model age	13.1
adjusted ag	14.39939

LR-57	
elevation	34.151
level	1
total poss	25568
actual	18712.33
% total	73.18651
model age	7.9
adjusted ag	10.79434

LR-59	
elevation	36.747
level	1
total poss	25568
actual	23837.71
% total	93.2326
model age	15.05
adjusted ag	16.14242

LR-34	
elevation	39.5
level	2
total poss	25568
actual	25280.89
% total	98.87709
model age	19.66
adjusted ag	19.88327

LR-36ave	
elevation	40.04
level	2
total poss	25568
actual	25388.96
% total	99.29977
model age	17.6
adjusted ag	17.72411

LR-29	
elevation	47.05
level	3
total poss	25568
actual	25567.25
% total	99.99708
model age	30.78
adjusted ag	30.7809

LR-38	
elevation	45.3
level	3
total poss	25568
actual	25565.84
% total	99.99157
model age	29.45
adjusted ag	29.45248

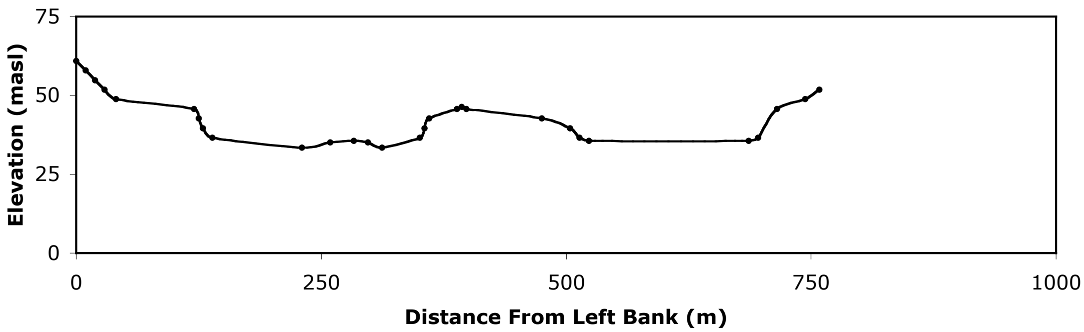
HECRAS Age Adjustments: In total, 6 samples from the Level 1 terrace (lowest), and 2 samples from each of the Level 2 and 3 terraces were analyzed using results from the HECRAS model. These tables show how the percentage of age adjustment required for each modeled sample were determined. Note that model ages samples from Levels 2 and 3 represent between 98% and 99% of their total possible exposure histories.

Summary of HECRAS Adjustments for Level 1 Samples

	Original Model Age (ka)	Adjusted Model Age (ka)	Difference (ka)
LR-52	12.9	15.1	2.2
LR-56	14.9	16.4	1.5
LR-54	17.0	17.8	0.8
LR-55	13.1	14.4	1.3
LR-57	7.9	10.8	2.9
LR-59	15.5	16.1	0.6
mean	13.6	15.1	1.5
stdev	3.2	2.4	
% of mean	23.4	16.0	7.4

CROSS-SECTIONS PLOTS

Cross-Section 8

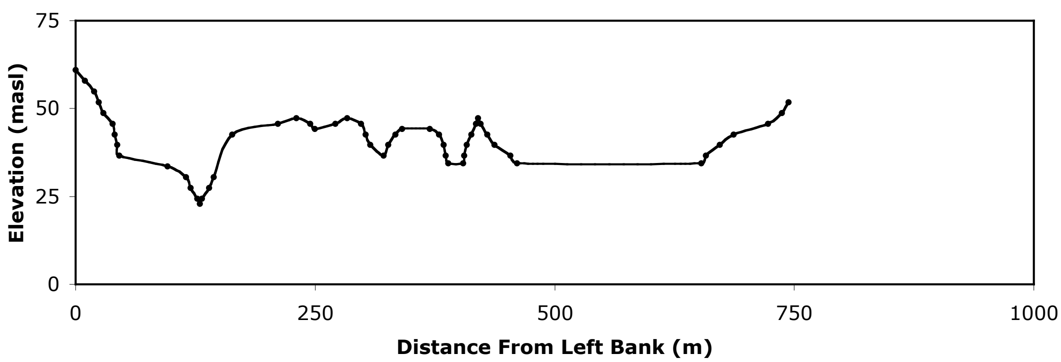


Cross-Section 7

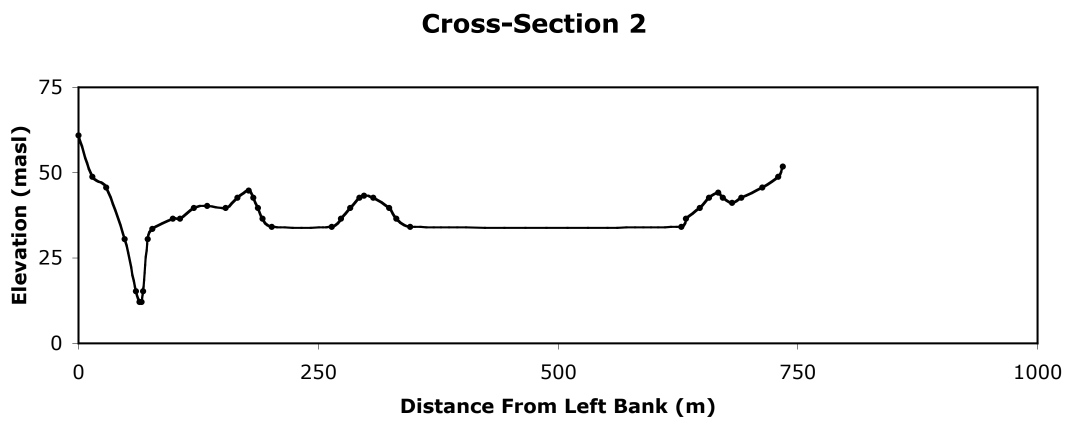
Cross-Section 6

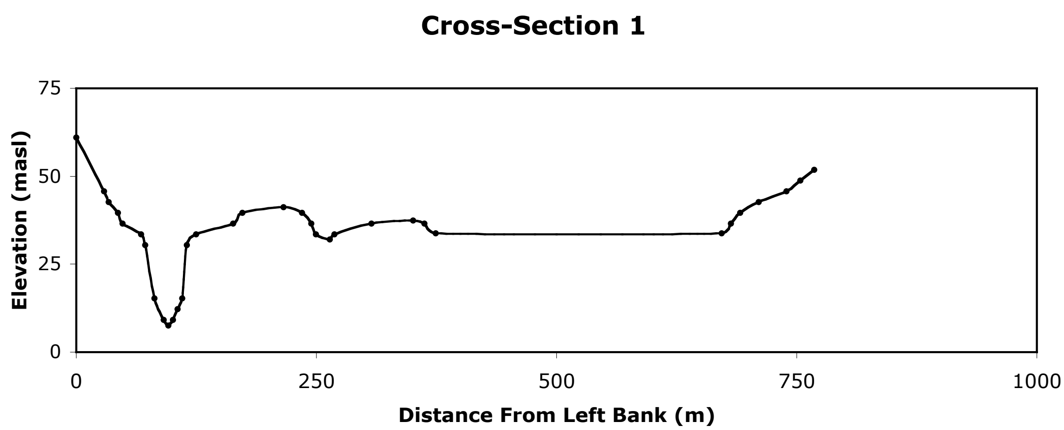
Cross-Section 5

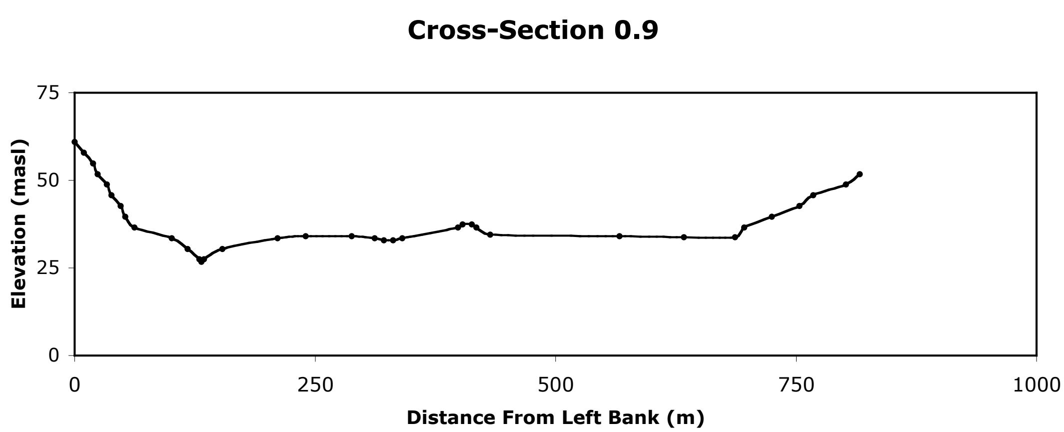
Cross-Section 4



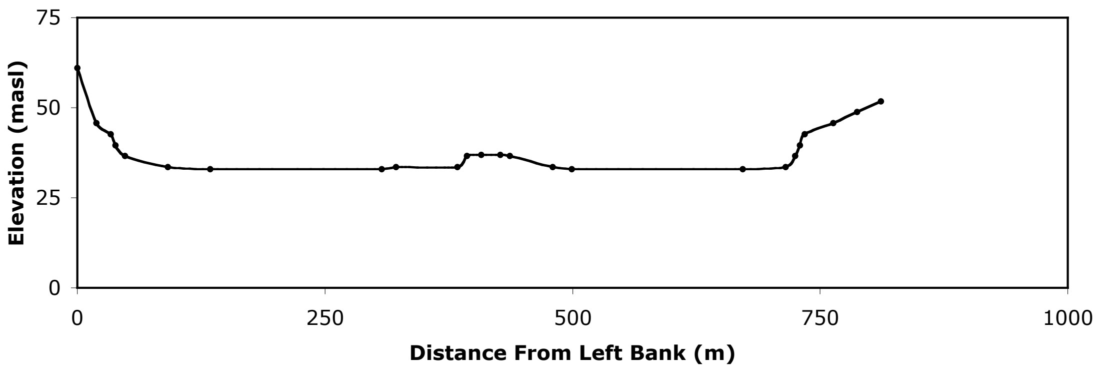
Cross-Section 3


Cross-Section 2
75
50
25
0
Elevation (masl)
0
250
500
750
1000
Distance From Left Bank (m)


Cross-Section 1
75
50
25
0
Elevation (masl)
0
250
500
750
1000
Distance From Left Bank (m)


Cross-Section 0.9
75
50
25
0
Elevation (masl)
0
250
500
750
1000
Distance From Left Bank (m)

Cross-Section 0.8



Cross-Section data taken from topographic survey of Holtwood Gorge

Cross-Section 8.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
1	0	0	200	61.0
2	2	9.6	190	57.9
3	4	19.2	180	54.9
4	6	28.8	170	51.8
5	8.5	40.8	160	48.8
6	25	120	150	45.7
7	26	124.8	140	42.7
8	27	129.6	130	39.6
9	29	139.2	120	36.6
10	48	230.4	110	33.5
11	54	259.2	115	35.1
12	59	283.2	117	35.7
13	62	297.6	115	35.1
14	65	312	110	33.5
15	73	350.4	120	36.6

16	74	355.2	130	39.6
17	75	360	140	42.7
18	81	388.8	150	45.7
19	82	393.6	152	46.3
20	83	398.4	150	45.7
21	99	475.2	140	42.7
22	105	504	130	39.6
23	107	513.6	120	36.6
24	109	523.2	117	35.7
25	143	686.4	117	35.7
26	145	696	120	36.6
27	149	715.2	150	45.7
28	155	744	160	48.8
29	158	758.4	170	51.8

Cross Section 7.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
43	0	0	200	61.0
42	4	19.2	190	57.9
41	19	91.2	180	54.9
40	22	105.6	170	51.8
39	25	120	170	51.8
38	33	158.4	160	48.8
37	34	163.2	150	45.7
36	35	168	140	42.7
35	35.5	170.4	130	39.6
34	36.25	174	120	36.6
33	36.75	176.4	110	33.5
32	37	177.6	100	30.5
31	38	182.4	90	27.4
30	44	211.2	80	24.4
29	45	216	75	22.9
28	50	240	75	22.9
27	51	244.8	80	24.4
26	52	249.6	90	27.4
25	54.5	261.6	100	30.5
24	58	278.4	110	33.5
23	80	384	120	36.6
22	81	388.8	130	39.6
21	83	398.4	140	42.7
20	86	412.8	150	45.7
19	88	422.4	155	47.2
18	89	427.2	150	45.7
17	108	518.4	140	42.7

16	109	523.2	130	39.6
15	111	532.8	120	36.6
14	112	537.6	115	35.1
13	127	609.6	115	35.1
12	128	614.4	120	36.6
11	129.25	620.4	130	39.6
10	130	624	130	39.6
9	132	633.6	120	36.6
8	134	643.2	115	35.1
7	155.5	746.4	115	35.1
6	157	753.6	120	36.6
5	158.5	760.8	130	39.6
4	159	763.2	140	42.7
3	163	782.4	150	45.7
2	165	792	160	48.8
1	167	801.6	170	51.8

Cross-Section 6.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
52	0	0	200	61.0
51	2	9.6	190	57.9
50	15.5	74.4	180	54.9
49	20	96	170	51.8
48	28	134.4	160	48.8
47	29	139.2	150	45.7
46	30	144	140	42.7
45	31	148.8	130	39.6
44	32	153.6	120	36.6
43	32.25	154.8	110	33.5
42	33	158.4	100	30.5
41	33.5	160.8	90	27.4
40	34	163.2	80	24.4
39	35	168	70	21.3
38	35.5	170.4	60	18.3
37	36	172.8	50	15.2
36	37	177.6	45	13.7
35	37.5	180	45	13.7
34	38	182.4	50	15.2
33	39	187.2	60	18.3
32	39.25	188.4	70	21.3
31	39.5	189.6	90	27.4
30	40	192	100	30.5
29	41	196.8	110	33.5
28	49	235.2	120	36.6
27	51	244.8	130	39.6
26	53	254.4	140	42.7

25	56	268.8	150	45.7
24	57	273.6	155	47.2
23	61	292.8	155	47.2
22	62	297.6	150	45.7
21	66	316.8	140	42.7
20	70	336	130	39.6
19	72	345.6	120	36.6
18	73	350.4	115	35.1
17	76	364.8	115	35.1
16	77	369.6	120	36.6
15	79	379.2	130	39.6
14	81	388.8	140	42.7
13	83	398.4	145	44.2
12	84	403.2	145	44.2
11	86	412.8	140	42.7
10	107	513.6	130	39.6
9	109	523.2	120	36.6
8	110	528	115	35.1
7	153	734.4	115	35.1
6	154	739.2	120	36.6
5	157	753.6	130	39.6
4	158.5	760.8	140	42.7
3	161	772.8	150	45.7
2	163.5	784.8	160	48.8
1	166	796.8	170	51.8

Cross-Section 5.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
59	0	0	200	61.0
58	2	9.6	190	57.9
57	14	67.2	180	54.9
56	18	86.4	170	51.8
55	23	110.4	160	48.8
54	25.5	122.4	150	45.7
53	30	144	100	30.5
52	34	163.2	50	15.2
51	35	168	45	13.7
50	36	172.8	50	15.2
49	38	182.4	100	30.5
48	39	187.2	110	33.5
47	45	216	120	36.6
46	45.25	217.2	130	39.6
45	45.5	218.4	140	42.7
44	46	220.8	150	45.7
43	50	240	150	45.7
42	51	244.8	140	42.7

41	52	249.6	150	45.7
40	54	259.2	160	48.8
39	56	268.8	160	48.8
38	64	307.2	150	45.7
37	65.5	314.4	145	44.2
36	67	321.6	150	45.7
35	68.5	328.8	155	47.2
34	69	331.2	150	45.7
33	70	336	140	42.7
32	71	340.8	130	39.6
31	72	345.6	114	34.7
30	80.5	386.4	114	34.7
29	81	388.8	120	36.6
28	82	393.6	130	39.6
27	83	398.4	140	42.7
26	87	417.6	145	44.2
25	89	427.2	145	44.2
24	91	436.8	140	42.7
23	105	504	130	39.6
22	108	518.4	120	36.6
21	109	523.2	114	34.7
20	116	556.8	114	34.7
19	116.5	559.2	120	36.6
18	118	566.4	128	39.0
17	121.5	583.2	128	39.0
16	122	585.6	120	36.6
15	123	590.4	114	34.7
14	135	648	114	34.7
13	135.5	650.4	120	36.6
12	136	652.8	123	37.5
11	137.5	660	123	37.5
10	138	662.4	120	36.6
9	139	667.2	114	34.7
8	145.5	698.4	114	34.7
7	146	700.8	120	36.6
6	149	715.2	130	39.6
5	153	734.4	130	39.6
4	155.5	746.4	140	42.7
3	158	758.4	150	45.7
2	159	763.2	160	48.8
1	160	768	170	51.8

Cross-Section 4.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
54	0	0	200	61.0
53	2	9.6	190	57.9

52	4	19.2	180	54.9
51	5	24	170	51.8
50	6	28.8	160	48.8
49	8	38.4	150	45.7
48	8.5	40.8	140	42.7
47	9	43.2	130	39.6
46	9.5	45.6	120	36.6
45	20	96	110	33.5
44	24	115.2	100	30.5
43	25	120	90	27.4
42	26.5	127.2	80	24.4
41	27	129.6	75	22.9
40	27.5	132	80	24.4
39	29	139.2	90	27.4
38	30	144	100	30.5
37	34	163.2	140	42.7
36	44	211.2	150	45.7
35	48	230.4	155	47.2
34	51	244.8	150	45.7
33	52	249.6	145	44.2
32	56.5	271.2	150	45.7
31	59	283.2	155	47.2
30	62	297.6	150	45.7
29	63	302.4	140	42.7
28	64	307.2	130	39.6
27	67	321.6	120	36.6
26	68	326.4	130	39.6
25	69.5	333.6	140	42.7
24	71	340.8	145	44.2
23	77	369.6	145	44.2
22	79	379.2	140	42.7
21	80	384	130	39.6
20	80.5	386.4	120	36.6
19	81	388.8	113	34.4
18	84.25	404.4	113	34.4
17	84.5	405.6	120	36.6
16	85	408	130	39.6
15	86	412.8	140	42.7
14	87	417.6	150	45.7
13	87.5	420	155	47.2
12	88	422.4	150	45.7
11	89.5	429.6	140	42.7
10	91	436.8	130	39.6
9	94.5	453.6	120	36.6
8	96	460.8	113	34.4
7	136	652.8	113	34.4
6	137	657.6	120	36.6

5	140	672	130	39.6
4	143	686.4	140	42.7
3	150.5	722.4	150	45.7
2	153.5	736.8	160	48.8
1	155	744	170	51.8

Cross-Section 3.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
39	0	0	200	61.0
38	1.5	7.2	160	48.8
37	2	9.6	150	45.7
36	3.5	16.8	140	42.7
35	4.5	21.6	130	39.6
34	5.5	26.4	120	36.6
33	10.5	50.4	110	33.5
32	12.5	60	100	30.5
31	13.5	64.8	90	27.4
30	14.5	69.6	80	24.4
29	15.5	74.4	70	21.3
28	16.5	79.2	60	18.3
27	17.5	84	60	18.3
26	19.5	93.6	70	21.3
25	21	100.8	80	24.4
24	23.5	112.8	90	27.4
23	26.5	127.2	100	30.5
22	37.5	180	150	45.7
21	46.5	223.2	160	48.8
20	48.5	232.8	165	50.3
19	49.5	237.6	160	48.8
18	52.5	252	150	45.7
17	53.5	256.8	140	42.7
16	56.5	271.2	120	36.6
15	57.5	276	112	34.1
14	64.5	309.6	112	34.1
13	65.5	314.4	120	36.6
12	73.5	352.8	130	39.6
11	75.5	362.4	132	40.2
10	77.5	372	130	39.6
9	80.5	386.4	120	36.6
8	82.5	396	112	34.1
7	133.5	640.8	112	34.1
6	136	652.8	120	36.6
5	138	662.4	130	39.6
4	139.5	669.6	140	42.7
3	143	686.4	150	45.7
2	147.5	708	160	48.8

1	150.5	722.4	170	51.8

Cross-Section 2.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
41	0	0	200	61.0
40	3	14.4	160	48.8
39	6	28.8	150	45.7
38	10	48	100	30.5
37	12.5	60	50	15.2
36	13.25	63.6	40	12.2
35	13.75	66	40	12.2
34	14	67.2	50	15.2
33	15	72	100	30.5
32	16	76.8	110	33.5
31	20.5	98.4	120	36.6
30	22	105.6	120	36.6
29	25	120	130	39.6
28	28	134.4	132	40.2
27	32	153.6	130	39.6
26	34.5	165.6	140	42.7
25	37	177.6	147	44.8
24	38	182.4	140	42.7
23	39	187.2	130	39.6
22	40	192	120	36.6
21	42	201.6	112	34.1
20	55	264	112	34.1
19	57	273.6	120	36.6
18	59	283.2	130	39.6
17	61	292.8	140	42.7
16	62	297.6	142	43.3
15	64	307.2	140	42.7
14	67.5	324	130	39.6
13	69	331.2	120	36.6
12	72	345.6	112	34.1
11	131	628.8	112	34.1
10	132	633.6	120	36.6
9	135	648	130	39.6
8	137	657.6	140	42.7
7	139	667.2	145	44.2
6	140	672	140	42.7
5	142	681.6	135	41.1
4	144	691.2	140	42.7
3	148.5	712.8	150	45.7
2	152	729.6	160	48.8
1	153	734.4	170	51.8

Cross-Section 1.0

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
34	0	0	200	61.0
33	6	28.8	150	45.7
32	7	33.6	140	42.7
31	9	43.2	130	39.6
30	10	48	120	36.6
29	14	67.2	110	33.5
28	15	72	100	30.5
27	17	81.6	50	15.2
26	19	91.2	30	9.1
25	20	96	25	7.6
24	21	100.8	30	9.1
23	22	105.6	40	12.2
22	23	110.4	50	15.2
21	24	115.2	100	30.5
20	26	124.8	110	33.5
19	34	163.2	120	36.6
18	36	172.8	130	39.6
17	45	216	135	41.1
16	49	235.2	130	39.6
15	51	244.8	120	36.6
14	52	249.6	110	33.5
13	55	264	105	32.0
12	56	268.8	110	33.5
11	64	307.2	120	36.6
10	73	350.4	123	37.5
9	75.5	362.4	120	36.6
8	78	374.4	111	33.8
7	140	672	111	33.8
6	142	681.6	120	36.6
5	144	691.2	130	39.6
4	148	710.4	140	42.7
3	154	739.2	150	45.7
2	157	753.6	160	48.8
1	160	768	170	51.8

Cross-Section 0.9

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
1	0	0	200	61.0
2	2	9.6	190	57.9
3	4	19.2	180	54.9
4	5	24	170	51.8
5	7	33.6	160	48.8

6	8	38.4	150	45.7
7	10	48	140	42.7
8	11	52.8	130	39.6
9	13	62.4	120	36.6
10	21	100.8	110	33.5
11	24.5	117.6	100	30.5
12	27	129.6	90	27.4
13	27.5	132	88	26.8
14	28	134.4	90	27.4
15	32	153.6	100	30.5
16	44	211.2	110	33.5
17	50	240	112	34.1
18	60	288	112	34.1
19	65	312	110	33.5
20	67	321.6	108	32.9
21	69	331.2	108	32.9
22	71	340.8	110	33.5
23	83	398.4	120	36.6
24	84	403.2	123	37.5
25	86	412.8	123	37.5
26	87	417.6	120	36.6
27	90	432	113	34.4
28	118	566.4	112	34.1
29	132	633.6	111	33.8
30	143	686.4	111	33.8
31	145	696	120	36.6
32	151	724.8	130	39.6
33	157	753.6	140	42.7
34	160	768	150	45.7
35	167	801.6	160	48.8
36	170	816	170	51.8

Cross-Section 0.8

Station #	Distance (mm on map)	Distance (m on groud)	elevation (fasl)	Elevation (masl)
1	0	0	200	61.0
2	4	19.2	150	45.7
3	7	33.6	140	42.7
4	8	38.4	130	39.6
5	10	48	120	36.6
6	19	91.2	110	33.5
7	28	134.4	108	32.9
8	64	307.2	108	32.9
9	67	321.6	110	33.5
10	80	384	110	33.5
11	82	393.6	120	36.6
12	85	408	121	36.9

13	89	427.2	121	36.9
14	91	436.8	120	36.6
15	100	480	110	33.5
16	104	499.2	108	32.9
17	140	672	108	32.9
18	149	715.2	110	33.5
19	151	724.8	120	36.6
20	152	729.6	130	39.6
21	153	734.4	140	42.7
22	159	763.2	150	45.7
23	164	787.2	160	48.8
24	169	811.2	170	51.8

Distances Between Cross-Sections

DOWNSTREAM REACH LENTHS FOR X-SECTION 8.0

	mm on map	meters on ground
LOB	24	115.2
CHANNEL	25	120
ROB	25	120

DOWNSTREAM REACH LENTHS FOR X-SECTION 7.0

	mm on map	meters on ground
LOB	17	81.6
CHANNEL	32	153.6
ROB	47	225.6

DOWNSTREAM REACH LENTHS FOR X-SECTION 6.0

	mm on map	meters on ground
LOB	8	38.4
CHANNEL	15	72
ROB	23	110.4

DOWNSTREAM REACH LENTHS FOR X-SECTION 5.0

	mm on map	meters on ground
LOB	29	139.2
CHANNEL	27	129.6
ROB	27	129.6

DOWNSTREAM REACH LENTHS FOR X-SECTION 4.0

	mm on map	meters on ground
LOB	35	168
CHANNEL	38	182.4
ROB	39	187.2

DOWNSTREAM REACH LENTHS FOR X-SECTION 3.0

	mm on map	meters on ground
LOB	33	158.4
CHANNEL	34	163.2
ROB	35	168

DOWNSTREAM REACH LENTHS FOR X-SECTION 2.0

	mm on map	meters on ground
LOB	22	105.6
CHANNEL	34	163.2
ROB	40	192

DOWNSTREAM REACH LENTHS FOR X-SECTION 1.0

	mm on map	meters on ground
LOB	25	120
CHANNEL	30	144
ROB	37	177.6

DOWNSTREAM REACH LENTHS FOR X-SECTION 0.9

	mm on map	meters on ground
LOB	20	96
CHANNEL	23	110.4
ROB	24	115.2

DOWNSTREAM REACH LENTHS FOR X-SECTION 0.8

	mm on map	meters on ground
LOB		0
CHANNEL		0
ROB		0

Main Channel Bank Stations

Cross section	8.0
LB	139.2
RB	696
Cross section	7.0
LB	174
RB	753.6
Cross section	6.0
LB	153.6
RB	739.2
Cross section	5
LB	144
RB	700.8
Cross section	4
LB	45.6
RB	657.6
Cross section	3

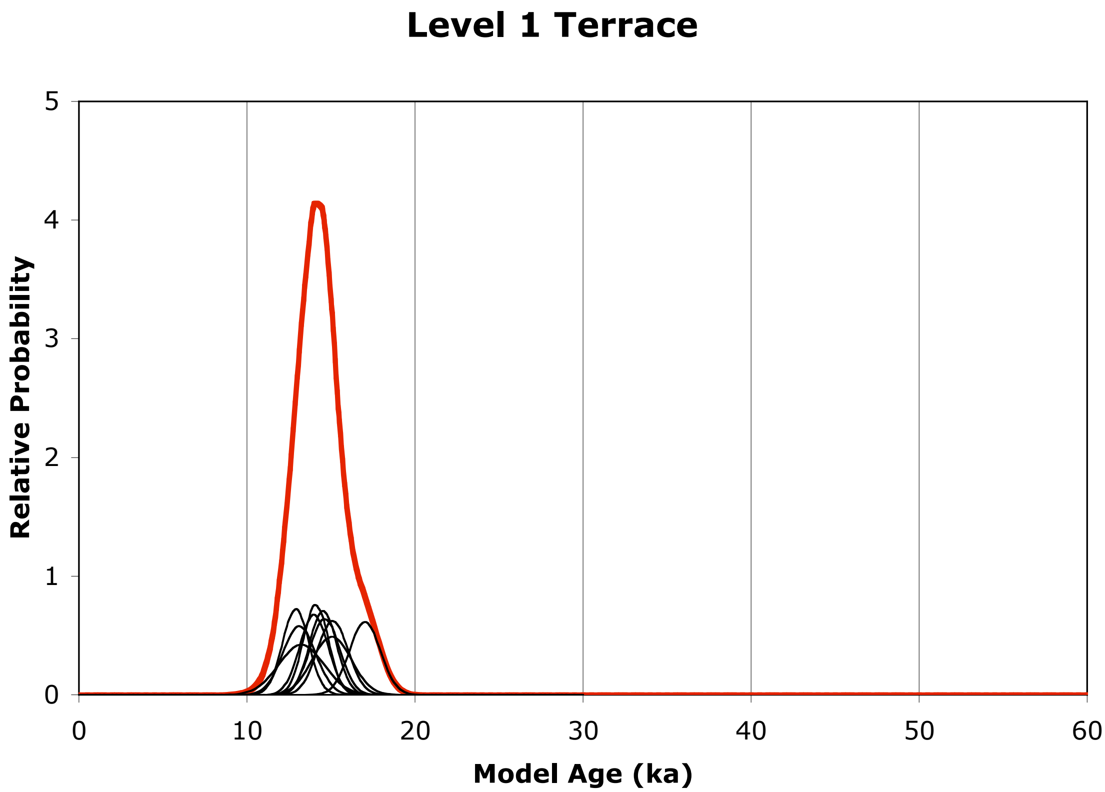
LB	26.4
RB	652.8
Cross section	2
LB	48
RB	633.6
Cross section	1
LB	48
RB	681.6
Cross section	0.9
LB	62.4
RB	696
Cross section	0.8
LB	48
RB	124.8

APPENDIX B: Probability Analysis

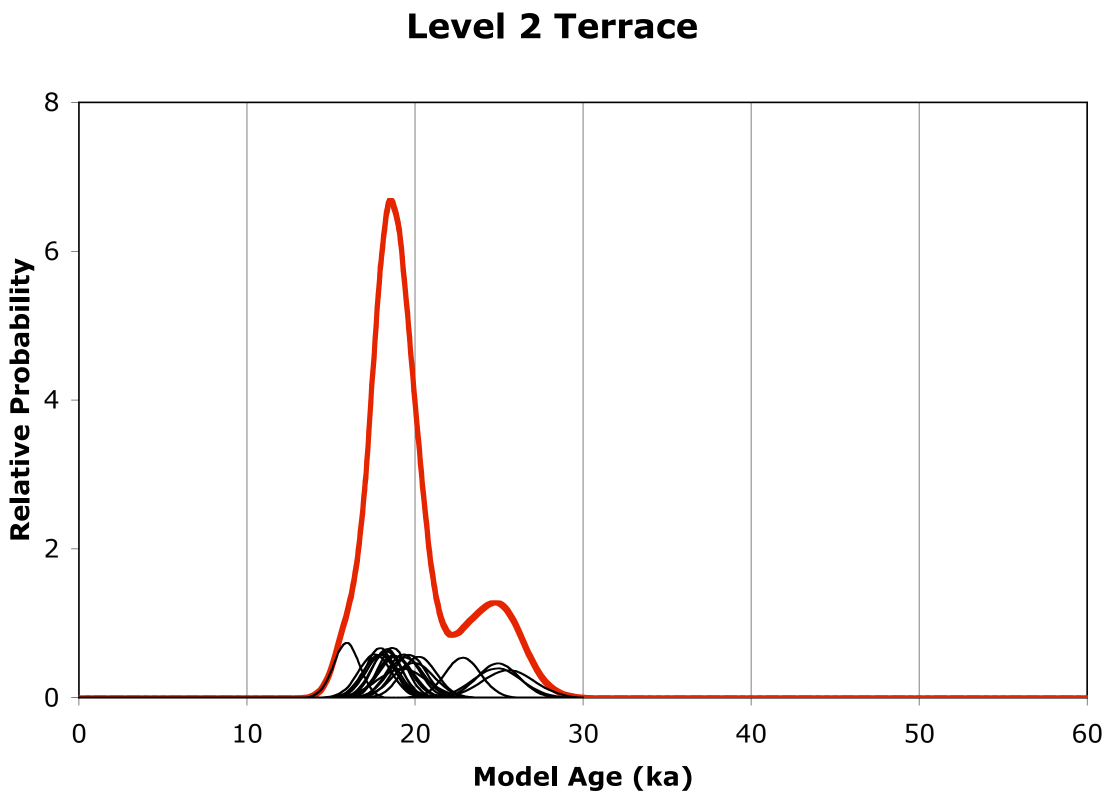
In addition to using common statistical methods such as descriptive statistics and regression analysis to interpret our model age data, we also consider the summed age probability for multiple samples collected along each of the three prominent terrace levels. When discussing the timing of incision and/or timing of abandonment for each terrace, this method allows us to detect multiple modes or "phases" of incision represented by a sub population of samples collected from a distinct level within the gorge. These multiple modes are not necessarily reflected by mean ages calculated for each level.

We constructed summed probability distributions by summing the Gaussian distributions (based on sample age and analytical uncertainty including carrier addition and AMS) for multiple samples collected along each prominent terrace level, following the method of Balco *et al.*, (2002). Summed probability distributions for each level were normalized (each age increment was divided by the number of samples collected from the given terrace) in order to allow us to compare the relative magnitude of probability peaks between levels.

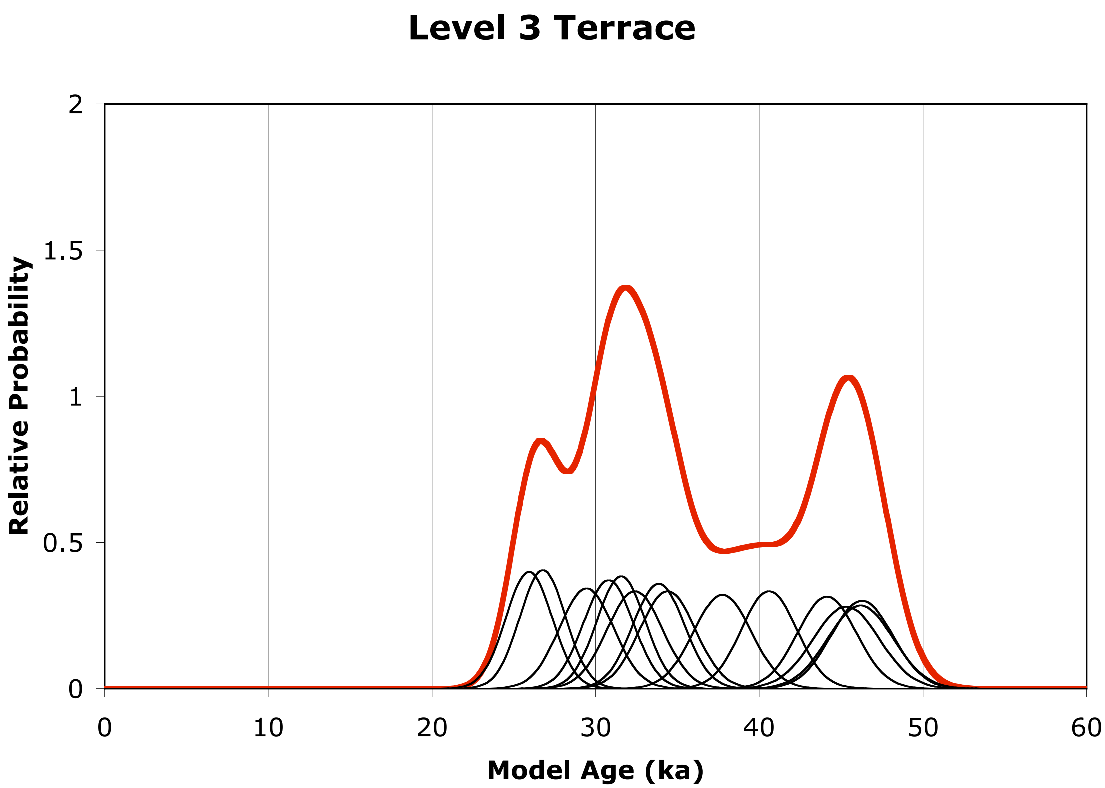
The summed probability plots on the following pages demonstrate how distributions for each of three prominent terraces levels were constructed, as well as how each curve was normalized allowing for comparison of the relative magnitude of each.



Probability distributions for the Level 1 terrace: The summed probability distribution (bold curve) for multiple samples collected along the lowest strath terrace level within Holtwood Gorge was generated by summing the Gaussian distributions for each individual sample (unbold black curves) at an age increment of 500 years. The peak in the cumulative curve is interpreted to represent the most probably timing of abandonment for this terrace level based on the model ages of the samples I collected. The peak is centered around ~14 ka and matches the mean age of the terrace almost exactly (14.4 ± 1.2 ka).

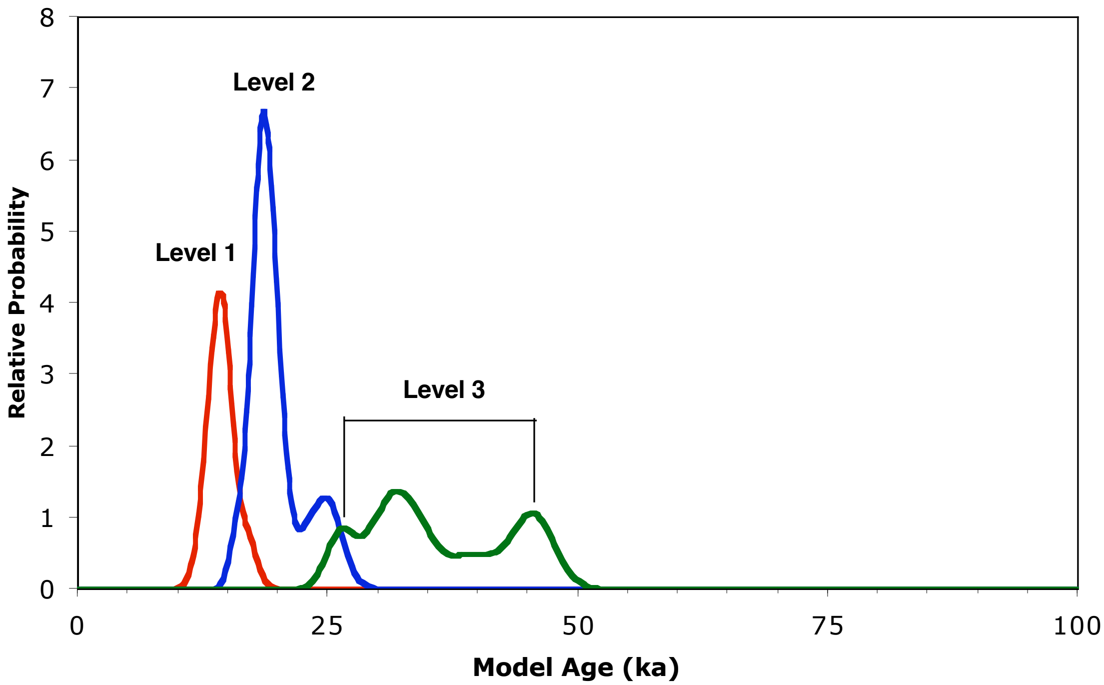


Probability distributions for the Level 2 terrace: The summed probability distribution (bold curve) for multiple samples collected along the middle strath terrace level within Holtwood Gorge was generated by summing the Gaussian distributions for each individual sample (unbold black curves) at an age increment of 500 years. Although the magnitude of the largest peak in cumulative probability is greater than that for the Level 1 terrace, this reflects the greater number of samples collected from this terrace level (n=20). The smaller secondary peak suggest that the history of exposure of individual bedrock surfaces within the gorge is more complex for the Level 2 terrace which stands higher above the bed than the level 1 terrace. Because the prominent summed probability peak and the mean age for the terrace are in relatively good agreement (peak ~18 ka; mean age 19.8 $\pm$ 2.7 ka), the peak represents well the timing of abandonment for this terrace level.



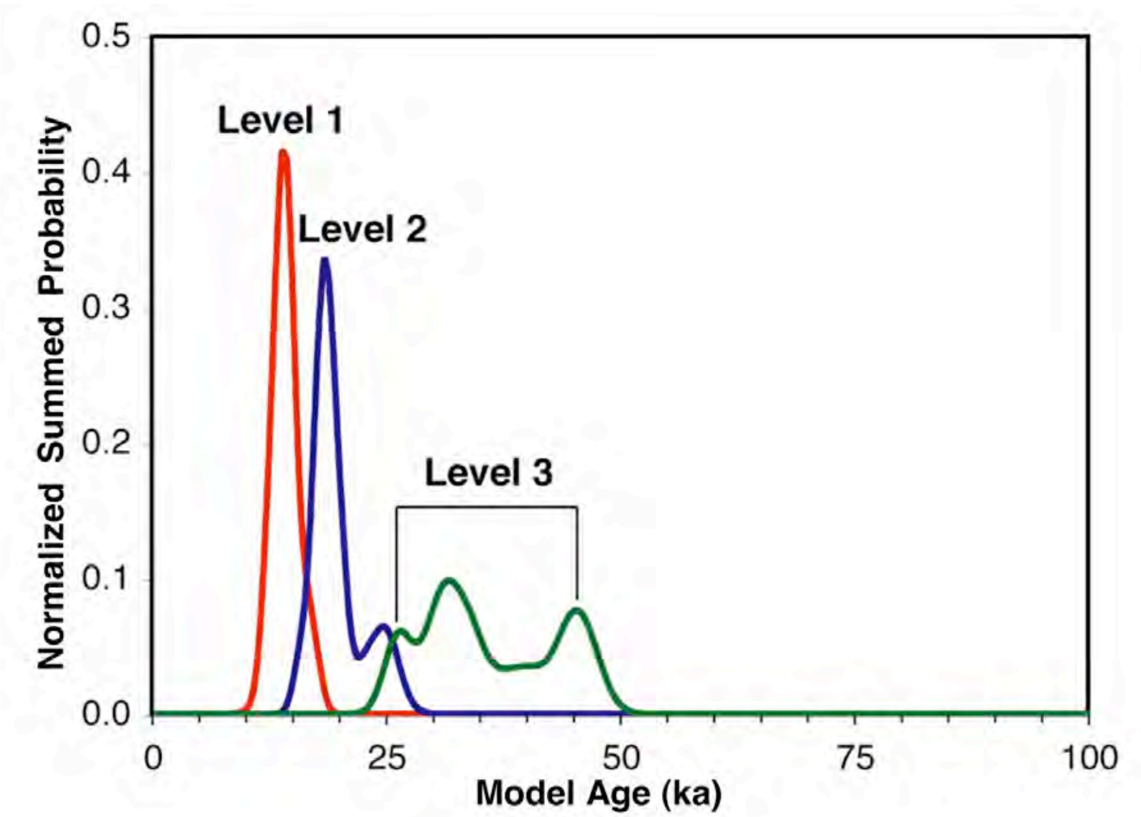
Probability distributions for the Level 3 terrace: The summed probability distribution (bold curve) for multiple samples collected along the highest well-preserved strath terrace within Holtwood Gorge was generated by summing the Gaussian distributions for each individual sample (unbold black curves) at an age increment of 500 years. The multiple peaks in cumulative probability for the level 3 terrace suggest that abandonment of this terrace level was substantially more complex than for lower levels. The mean age (36.1 $\pm$ 7.3 ka) for this terrace does not correlate with either of the prominent peaks at ~45 and ~32 and probably doesn't accurately represent the timing of abandonment. Because ages for multiple samples cluster around ~45 ka and ~32 ka in both the upper and middle gorge, it appears that these probability peaks represent multiple 'real' phases of incision into the highest terrace level.

Summed Probability



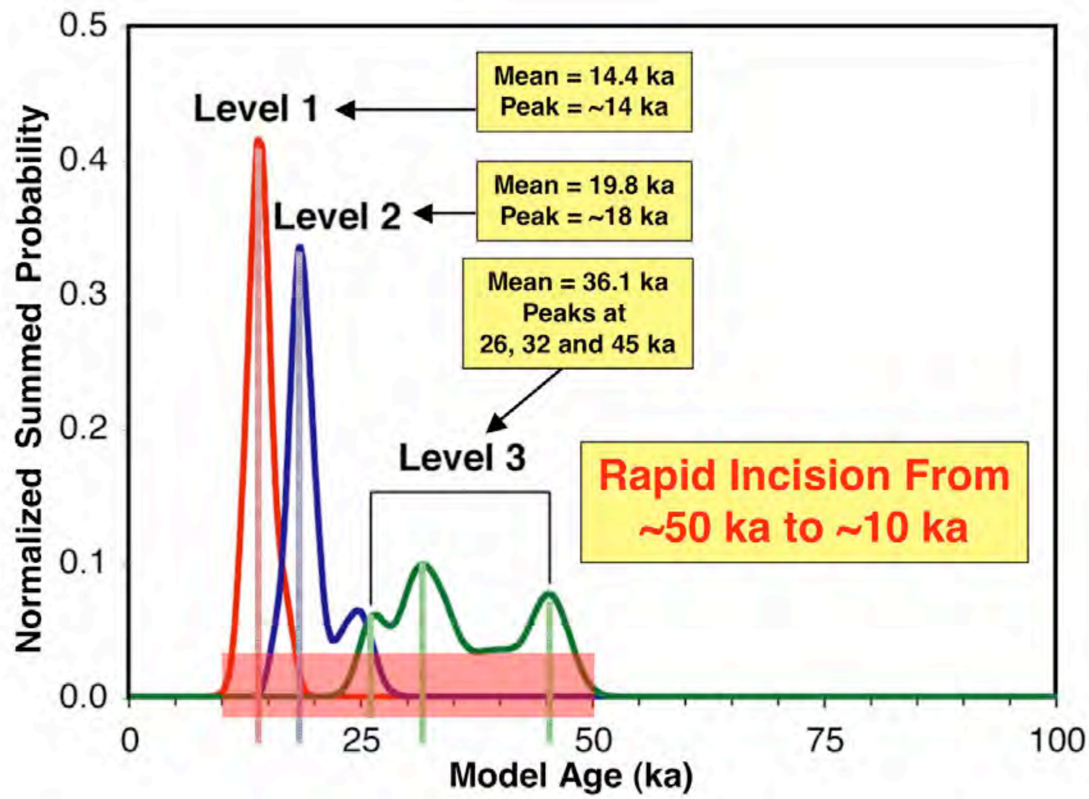
Summed probability distributions: When the probability distributions for all three terrace levels are plotted together, the incision recorded within Holtwood Gorge appears to have occurred in three to four major phases, beginning around 45 or 50 ka and ending around 14 or 10 ka. The magnitude of each curve reflects the number of samples collected from each terrace level (Level 1, n=10; Level 2, n=20; Level 3, n=14).

Normalized Summed Probability



Normalized summed probability plots: In order to normalized the relative magnitude of peaks on different terrace levels (remove the bias associated with a greater number of samples collected from a terrace level), the probability value for each age increment for each terrace level (500 yr) was divided by the number of samples collected along the given terrace level. In essence, this allows us to compare the exposure history of different levels. The history of abandonment is simplest for the lowest and youngest (level 1) terrace, and becomes more and more complex for terrace standing higher above the modern river bed.

Normalized Summed Probability



Comparison of probability peaks to mean terrace ages: The tight clustering of model ages for multiple samples collected along both the level 1 and 2 terraces, and the good agreement between mean terraces ages and peaks in probability suggest that both methods provide a good estimation of the timing of terrace abandonment in Holtwood Gorge. However, model ages along the level 3 terrace yield multiple peaks in probability, none of which correspond to the mean terrace age. This finding demonstrates that, for this older terrace, which stands more than 10 m above the channel floor, the mean age does not accurately describe the timing of its abandonment. The probability modeling illustrates that incision into the level 3 paleo riverbed began earlier than is suggested by the mean terrace age, and that the abandonment of the level 2 terrace was more complex than for lower, younger levels.