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AN EPISODE OF RAPID BEDROCK CHANNEL INCISION DURING THE LAST GLACIAL CYCLE, MEASURED WITH ^{10}Be

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ABSTRACT. **We use ^{10}Be to infer when, how fast, and why the Susquehanna River incised through bedrock along the U.S. Atlantic seaboard, one of the world's most prominent and ancient passive margins. Although the rate at which large rivers incise rock is a fundamental control on the development of landscapes, relatively few studies have directly measured how quickly such incision occurs either in tectonically active environments or along passive margins.**

Exposure ages of fluvially carved, bedrock strath terraces, preserved along the lower Susquehanna River, demonstrate that even along a passive margin, large rivers are capable of incising through rock for short periods of time at rates approaching those recorded in tectonically active regions, such as the Himalayas. Over eighty samples, collected along and between three prominent levels of strath terraces within Holtwood Gorge, indicate that the Susquehanna River incised more than 10 meters into the Appalachian Piedmont during the last glacial cycle. Beginning ~36 ka, incision rates increased dramatically, and remained elevated until ~14 ka. The northern half of the Susquehanna basin was glaciated during the late Wisconsinan; however, similar rates and timing of incision occurred in the unglaciated Potomac River basin immediately to the south. The concurrence of incision periods on both rivers suggests that glaciation and associated meltwater were not the primary drivers of incision. Instead, it appears that changing climatic conditions during the late Pleistocene promoted an increase in the frequency and magnitude of flood events capable of exceeding thresholds for rock detachment and bedrock erosion, thus enabling a short-lived episode of rapid incision into rock.

Although this study has constrained the timing and rate of bedrock incision along the largest river draining the Atlantic passive margin, the dates alone cannot explain fully why, or by what processes, this incision occurred. However, cosmogenic dating offers compelling evidence that episodes of rapid incision into bedrock are tied to glacial cycles and changes in global climate. These results, and the methods we employ, provide valuable insights into the nature of bedrock channel incision, not only along the Susquehanna River and passive margins, but also across a wide range of settings around the globe. Because river incision into bedrock transmits the effects of changing climate and tectonics through fluvial networks to hillslopes, comprehending when, where, and why rivers incise has important implications for the evolution of landscapes.

INTRODUCTION

The timing and rate at which rivers cut through rock have important implications for the large-scale development of landscapes in both passive and tectonically active

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settings (Tinkler and Wohl, 1998). River incision into bedrock transmits the effects of changing boundary conditions, such as climate and tectonics, through fluvial networks to hillslopes, and thus constitutes an important control on rates of landscape evolution (Howard and others, 1994; Tinkler and Wohl, 1998; Whipple and others, 2000). Yet, we know relatively little about the timing, rate, and style of river incision through rock in either tectonically active terrains, or along ancient passive margins.

Although our understanding of bedrock channel incision and landscape change has increased remarkably in recent decades (for example, Merritts and Vincent, 1989; Bull, 1991; Burbank and others, 1996; Hancock and others, 1998; Hancock and Anderson, 2002; Hartshorn and others, 2002; Wegmann and Pazzaglia, 2002; Pan and others, 2003; Whipple, 2004), direct measurements of the timing and rate of incision are relatively few, and identifying the time frame over which the most rapid incision occurs often remains difficult. Consideration of long-term landscape development and the evolution of mountain ranges, accomplished with numerical models (for example, Baldwin and others, 2003; Snyder and others, 2003; Whipple, 2004) and proxies for rates of exhumation (for example, Zimmermann, 1979; Doherty and Lyons, 1980) offer intriguing results, but both temporal and spatial resolutions often are 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 be representative of the rate at which rivers shape landscapes because of the short duration of time and the small spatial scales over which such studies are done (for example, Wohl, 1993; Hancock and others, 1998; Hartshorn and others, 2002).

Concentrations 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 interval 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 (for example, Leland and others, 1994; Burbank and others, 1996; Hancock and others, 1998; Leland and others, 1998; Pratt and others, 2002; Burbank and others, 2003).

In this paper, we use concentrations of ^{10}Be measured in 81 samples collected mostly from fluvially eroded bedrock surfaces on and between prominent levels of strath-terraces within the largest gorge on the lower Susquehanna River to infer when, how quickly, and why the river incised through the Appalachian Piedmont during the late Pleistocene. We also introduce results from a similar study of Mather Gorge along the Potomac River, located south of the Susquehanna Basin, in order to elucidate the effects of drainage basin glaciation on the style and timing of river incision into bedrock (fig. 1). This study not only sheds light on the nature of incision along the North American central Atlantic passive margin, but also demonstrates that rates and patterns of bedrock incision are most likely tied to climatic changes during global glacial-interglacial cycles. Our findings therefore have implications for the study of bedrock channels around the world.

BACKGROUND

The Atlantic Passive Margin and The Susquehanna River

Building of the once lofty central and northern Appalachian Mountains progressed in several stages during the Paleozoic, culminating with the Permian Alleghenian Orogeny (Pazzaglia and Brandon, 1996). Subsequent topographic growth of the mountain belt, associated with continental rifting and the opening of the Atlantic in the Late Triassic and Early Jurassic, resulted in a drainage reversal establishing the west to east flow direction that persists to the present day (Judson, 1975). Several large, low

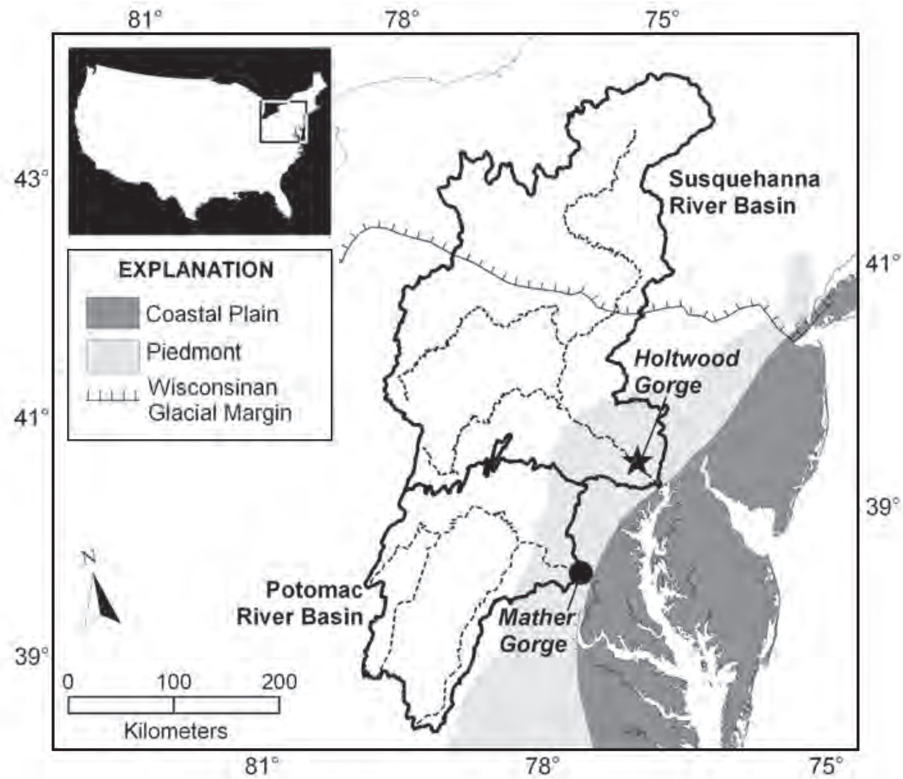


Fig. 1. Map of the Atlantic passive margin and the Susquehanna and Potomac River Basins. Both Holtwood (black star) and Mather Gorges (black circle) lie near the Appalachian Piedmont/ Coastal Plain transition. During the last glacial maximum, ice covered ~45% of the Susquehanna Basin; the Potomac Basin remained free of glacial ice (Braun, 1988).

gradient river systems drain the Atlantic Slope, including the Susquehanna River, where this study was conducted.

The Susquehanna River drains more than 70,000 km^2 of the central Appalachian Mountain System in New York State, central and eastern Pennsylvania, and northeastern Maryland, making it the largest Atlantic Slope drainage (fig. 1). Maximum and minimum discharges recorded at Marietta, Pennsylvania, approximately 80 km upstream from the mouth of the Susquehanna and the closest station to our study site, are 2.95×10^4 m^3/s and 39 m^3/s respectively. Across the Appalachian Plateau, and Ridge and Valley provinces of northeastern and northcentral Pennsylvania, the channel of the Susquehanna is broad and shallow with an average stream gradient of ~0.5 m/km (Scharnberger, 1990). Along 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 and the river's longitudinal profile becomes strongly convex-up (fig. 2) (Pazzaglia and Gardner, 1993, 1994a, 1994b). The northern half of the Susquehanna Basin was ice-covered during portions of all major Pleistocene glaciations (Richmond and Fullerton, 1986; Braun, 1988, 1994; Gardner and others, 1994), while the southern half of the basin remained ice-free. Peak Wisconsinan (LGM) glaciation covered ~45 percent of the Susquehanna Basin at ~20 ka (Braun, 1988; Mix, 1992; Winograd, 2001).

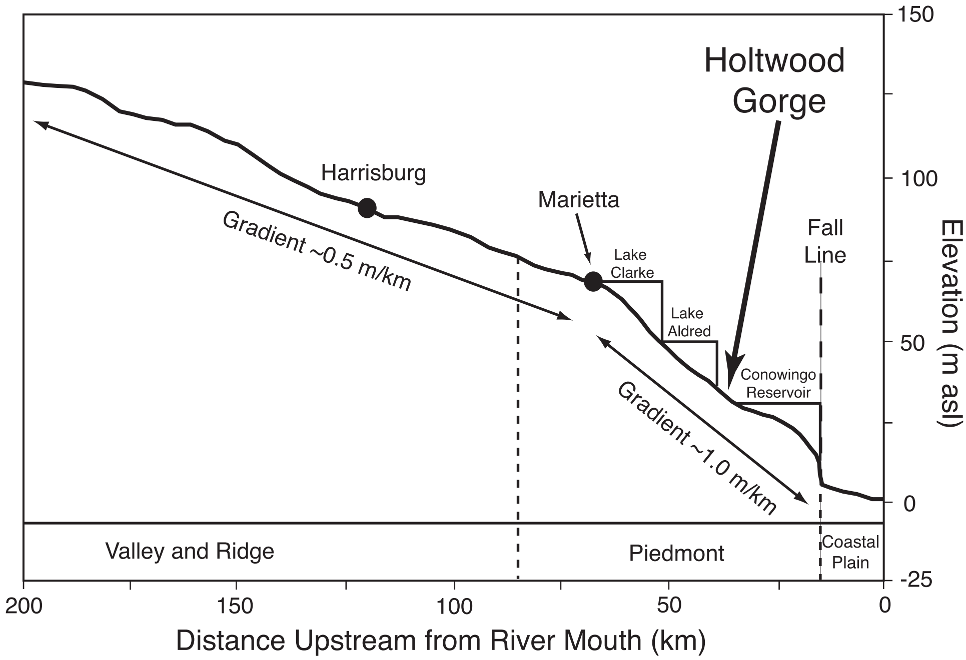


Fig. 2. Long-profile of the downstream 200 km of the Susquehanna River. Oversteepening of the lower reaches begins ~70 km upstream from the river's outlet into Chesapeake Bay. Holtwood Gorge is the longest length of river not currently inundated by hydroelectric dam reservoirs. Figure modified from Pazzaglia and Gardner (1993).

More than a century of research on fluvial features bordering this passive margin river helps 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 Gardner, 1993, 1994a, 1994b; Merritts and others, 1994; Pazzaglia and others, 1998; Engel and others, 1996; Kochel and others, 2000; Thompson and others, 2001). Two areas of investigation that are particularly relevant to the present study are: 1) detailed mapping and correlation of river terraces, and 2) flexural upwarping of the Appalachian Piedmont during the late Cenozoic.

Along its lower reaches, the Susquehanna River has carved a deep, steep-walled bedrock valley into the Piedmont (Pazzaglia and Gardner, 1993, 1994a, 1994b). Perched upon the Piedmont Uplands are remnants of several levels of Tertiary terraces comprised of heavily weathered fluvial gravels found from 80 to 140 m above the present river channel (Pazzaglia and Gardner, 1993). Six levels of inset strath and thin aggradational terraces occur along, and north of, the lower reaches of the river. These terraces, particularly well preserved at Marietta, Pennsylvania, occur within 50 m of the present channel floor, and are generally comprised of 1 to 6 m of stratified but mixed alluvium overlying strath benches (Pazzaglia and Gardner, 1993, 1994b; Engel and others, 1996). Downstream of Marietta, toward Holtwood Gorge where this study is set, the gradient of the Susquehanna doubles to ~1 m/km as the river cuts into metamorphic rocks of the High Piedmont. Along this reach, correlation of the low terraces is difficult because of their lack of exposure, and the presence of multiple hydroelectric dam reservoirs.

Correlation of upland gravel terraces to coastal plain deposits allows for calculation of long-term average river incision rates (~0.012 m/ky) for the Susquehanna

River, and an estimate of flexural deformation of the Atlantic passive margin since the middle Miocene (Pazzaglia and Gardner, 1993, 1994a, 1994b). Flexural upwarping of the Piedmont, driven largely by offshore deposition of sediment, maintains steep gradients along the downstream reaches of the river despite ongoing incision into bedrock. This condition has implications for the formation and dating of strath terraces, and the nature of incision, in that it primes the river for incision by increasing stream power needed to erode and remove rock. Continued vertical incision may also promote the preservation of isolated remnants of older terraces.

The channel of the lower Susquehanna River is bordered by flights of strath-terraces. Access to the rock-floored channel is limited by hydroelectric dam reservoirs, however, the river flows freely through Holtwood Gorge 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 the well-preserved bedrock terraces and other fluvial features within the gorge (Mathews, 1917; Thompson, 1987, 1988; Thompson and Sevon, 1999; Kochel and Parris, 2000; Thompson and Sevon, 2001), the timing and cause of their formation have remained enigmatic.

Holtwood Gorge

Holtwood Gorge is located approximately 50 km upstream of Chesapeake Bay and preserves several distinct levels of bedrock strath-terraces carved into the Wissahickon Schist, which exhibits a strong NE-striking foliation and is cut by a number of joint sets, both parallel and perpendicular to the direction of river 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, there is a cluster of islands and the gorge narrows to ~0.5 km. Backup from Conowingo Reservoir begins at this point in the gorge, restricting access to the terraces. Farther downstream, the gorge widens again, reaching a width of nearly 1.5 km at the mouth of an incoming tributary, Muddy Creek, ~5 km downstream from the Holtwood Dam. Below this point, most bedrock surfaces standing above the channel are inundated by backwater in the Conowingo Reservoir (fig. 3).

Fluvially-sculpted landforms, reflecting both present and past hydrologic conditions, dominate the gorge (Sevon and Thompson, 1987; Kochel and Parris, 2000; Thompson and Sevon, 2001). Upstream-dipping potholes are common, ranging from several cm up 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 below present water level. These depressions are ~1 km long and ~100 m wide; several are deep enough (~40 m) to extend below present day sea level (Mathews, 1917; Pazzaglia and Gardner, 1993). Although some have suggested that these scours could be the result of outburst flooding 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, as well as within the unglaciated Three Gorges channel along the Changjiang River, China (Yang and others, 2001), suggest that large rivers are capable of generating such features with or without the direct influence of basin glaciation.

Within Holtwood Gorge, three main levels of bare-rock terraces are preserved along the sides of the gorge and as isolated bedrock islands (dissected straths) within the gorge (fig. 4). The uppermost terrace (level 3) stands ~10 m above the modern channel floor and can be correlated 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 meters above the channel floor and also can be traced over nearly 5 km. The inferred river gradient of the level 2 terrace decreases to ~1.5 m/km. Dissected terrace remnants on both levels 3 and 2 preserve fluvially sculpted and streamlined forms. Level 1, the lowest level within the gorge, has been incised in

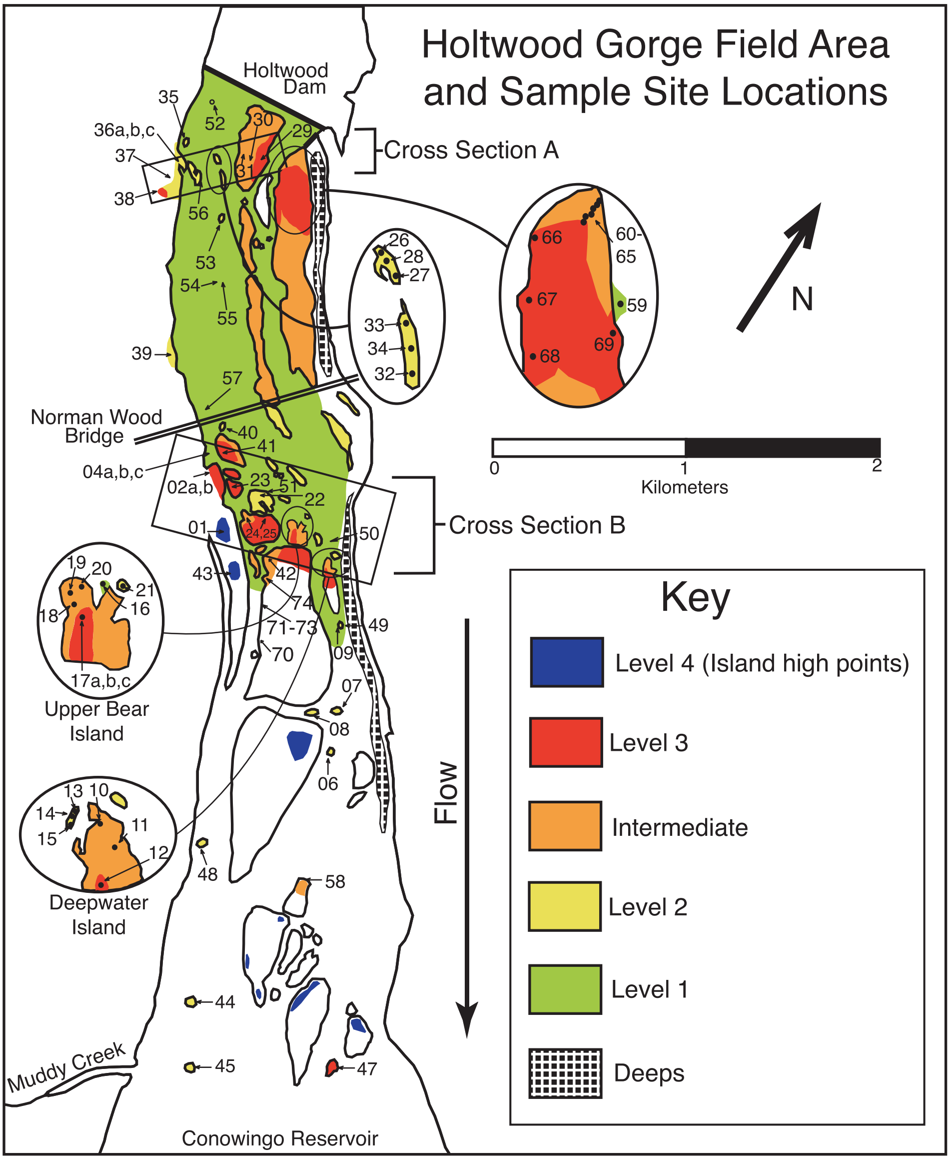


Fig. 3. Map of the Holtwood Gorge area, showing all sample sites, cross-sections, and the terrace levels assigned to bedrock surfaces in the gorge. Numbers indicate sample locations (for example: 54 = LR-54).

some places by numerous small channels, approximately 1 m in depth, that appear to carry the majority of base-flow. Level 1 can be traced approximately 2.5 km downstream from the dam at a gradient of ~1.5 m/km; farther downstream, backup from the Conowingo Reservoir prevents access to the level 1 surface. Bedrock surfaces exposed above these three well-preserved terrace levels are generally heavily weathered and eroded. They are restricted primarily to the western bank of the River and to island tops in the lower gorge. Because of their poor surface preservation, they are of limited use for cosmogenic exposure dating.

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. We collected bedrock samples above, along, and between each of the three main terrace levels. The position of each sample site was measured to decimeter-scale precision using real-time differential GPS (Trimble 4400). The GPS 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

Using a sledgehammer and chisel, we collected 78 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 within the gorge, and one cobble exposed on the uplands gravel terraces above Holtwood Gorge. In total, 81 samples were collected and analyzed during the course of the study.

We devised a 'nested' sampling strategy in order to investigate efficiently nuclide concentration 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 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 calculate average terrace ages, and 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 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 meters downstream of Holtwood Dam, consists of 13 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 2.5 km downstream from the dam) is comprised of 17 samples covering the lower three terraces levels, as well as a heavily eroded island top standing about 20 m above the river bed along the western shore of the river (fig. 3).

In order to investigate the relationship between rates of incision calculated along cross-sections oriented perpendicular to flow, and the rate of incision calculated from fluvially carved features oriented parallel to flow, we collected transects of samples (n = 22) down the rounded fronts of several large mid-channel islands. The upstream noses of many islands, particularly those clustered in the middle gorge (fig. 3), are comprised of either gradually sloping or stepped bedrock surfaces that extend from the lowest (level 1) to the highest prominent terrace. This analysis allows us to investigate whether the fronts of large mid-channel bedrock islands, which constitute substantial obstacles to flow, erode similarly or differently than terrace remnants and gorge walls between the islands.

Large, fluvially-rounded boulders of varying lithologies occur 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

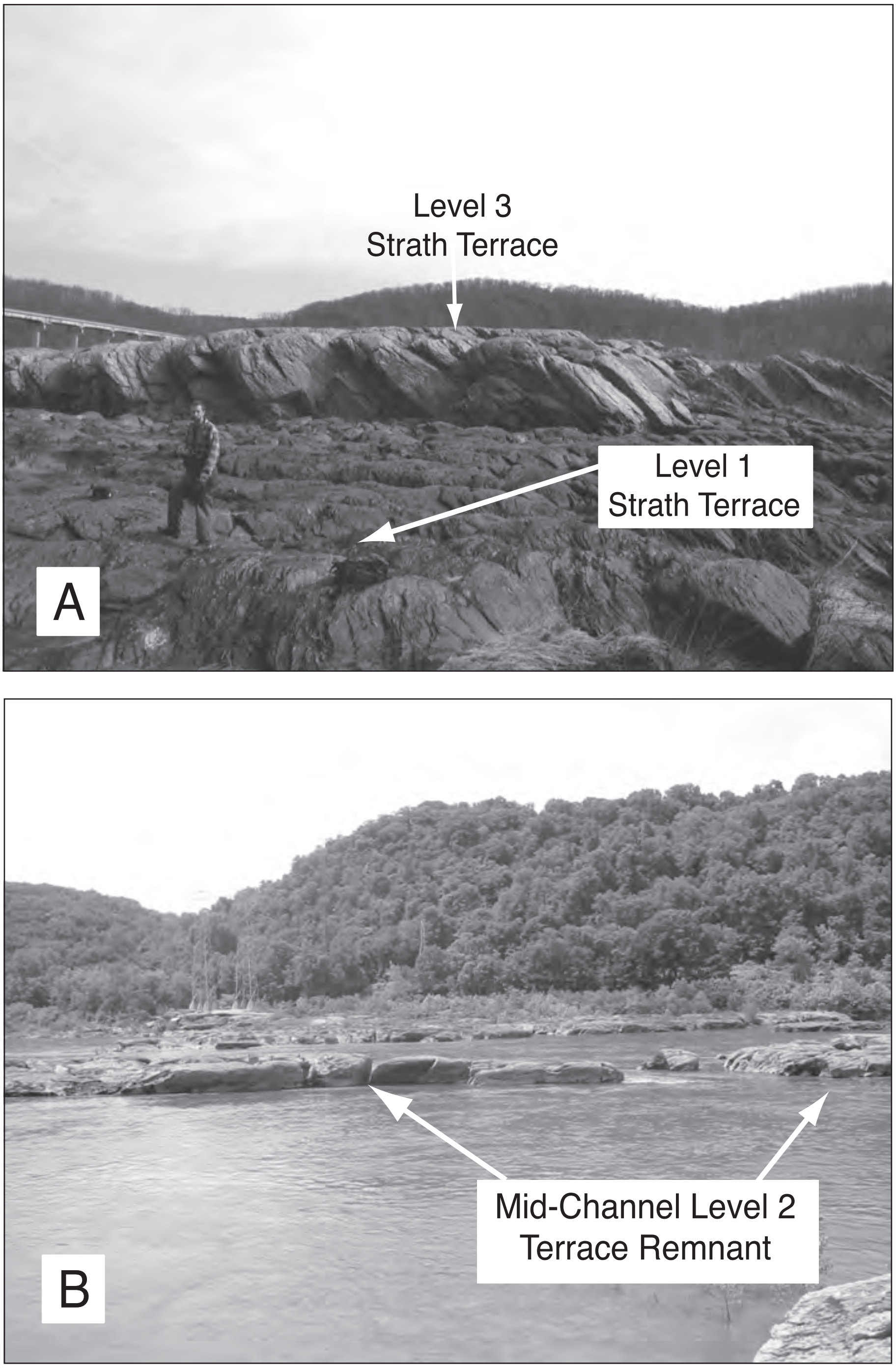


Fig. 4. Photographs of fluvially carved bedrock terraces within Holtwood Gorge. (A) View to the east of terrace levels 1 and 3 in the middle of Holtwood Gorge at low flow conditions. Level 2 is not preserved at this location. Flow from left to right. At higher discharges, lower strath is inundated. Sample site LR-04 is located just behind figure in photo. (B) Remnant of the Level 2 terrace preserved as a mid-channel island in the upper gorge. In July 2002, when this photo was taken, water was spilling over Holtwood Dam and covering the Level 1 terrace. Flow from right to left. Near sample site LR-26 and 27. (C) Terrace level 3 in the middle of Holtwood Gorge. Photograph taken looking downstream. (D) The upper-most surface (level 3) of Upper Bear Island in the middle of Holtwood Gorge. This sample site, LR-17, is also the location of the level 3 small-scale variance study.

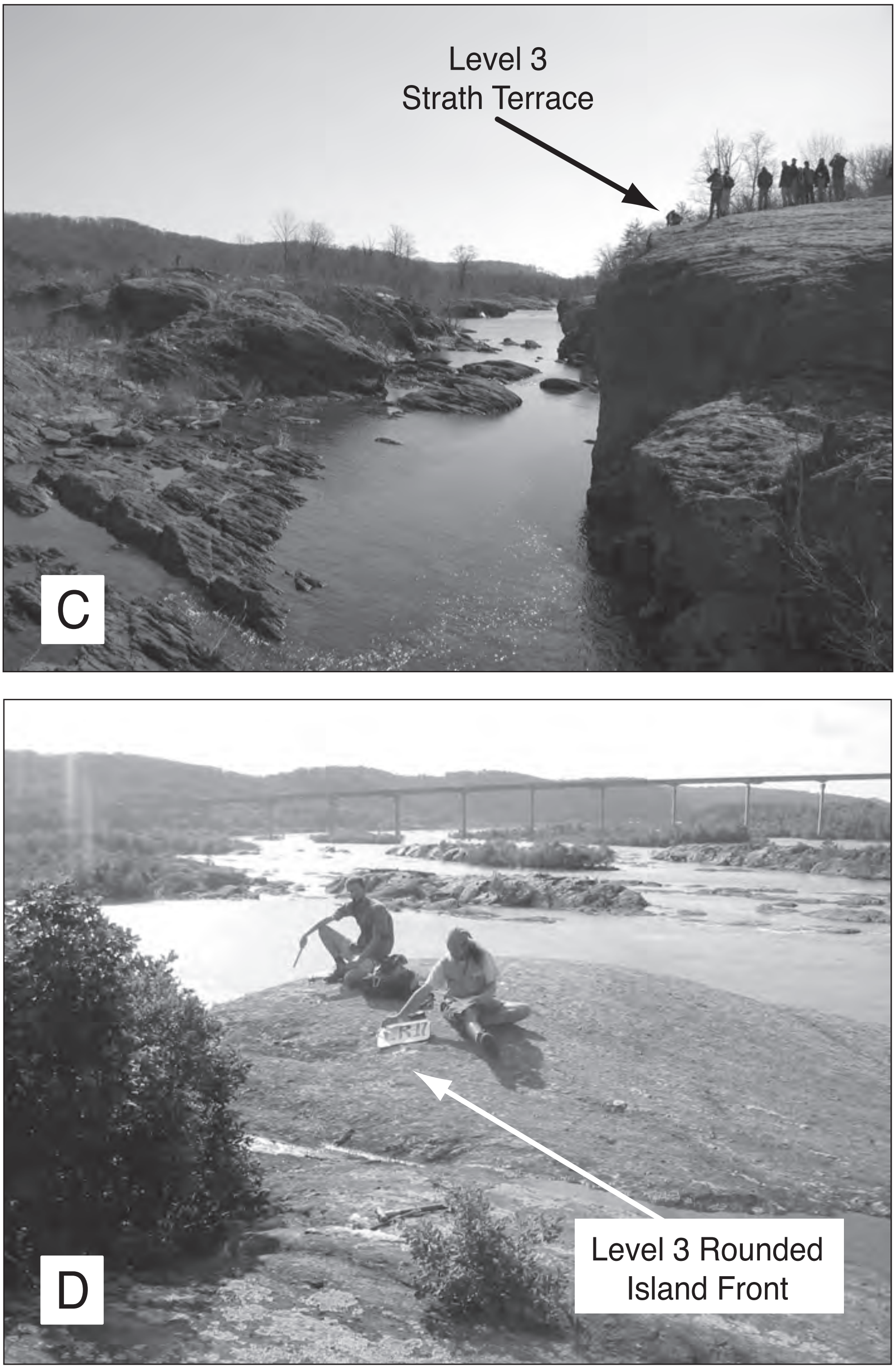


Fig. 4 (continued)

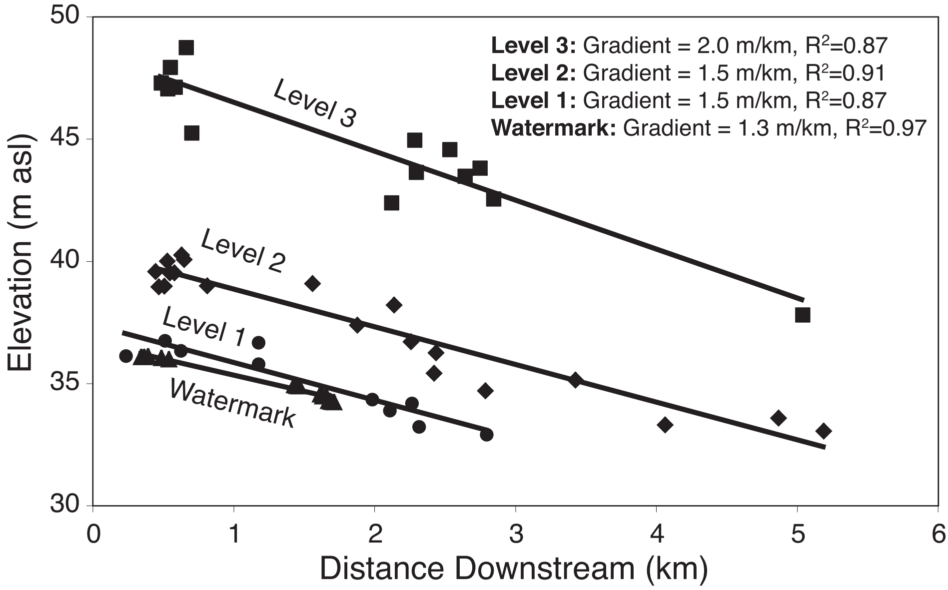


Fig. 5. Gradients for terrace levels 1, 2 and 3 derived from Trimble 4400 differential GPS data collected from all sample sites within the Holtwood Gorge field area. Watermark trendline constructed using GPS points of a distinctive watermark observed in the upper gorge (July, 2002). We consider this trendline to be the modern river gradient.

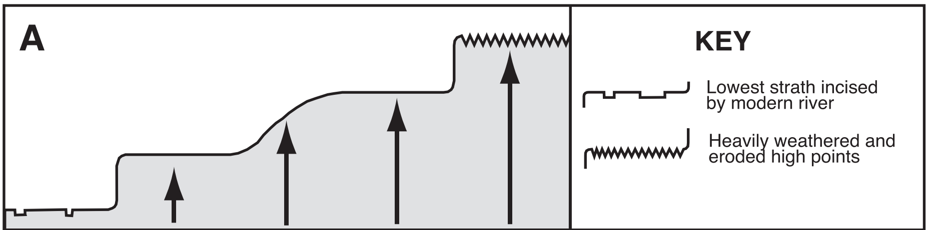
2 terrace in front of Deepwater Island in the middle gorge (fig. 3). Both boulders are quartz-pebble-conglomerate and were probably sourced from the Chickies Formation that crops out near Marietta, Pennsylvania ~35 km upstream from the gorge (Thompson, 1990).

Remnants of gravel terraces, interpreted to be middle Miocene in age (Pazzaglia and Gardner, 1993, 1994a, 1994b), can be found today topographically far above the downstream reaches of the Susquehanna channel in the Appalachian Piedmont. Although other lithologies have largely weathered away, quartz cobbles (referred to as "potato stones") occur 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 Nishiizumi, 1992). Beryllium was chemically isolated, precipitated as the hydroxide, and burned to produce BeO (Bierman and Caffee, 2002). The oxide 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 concentrations 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_{quartz}^{-1} yr^{-1} (Bierman and Steig, 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 (1σ) in carrier addition and AMS measurement, as well as a 10 percent (1σ) uncertainty in



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**

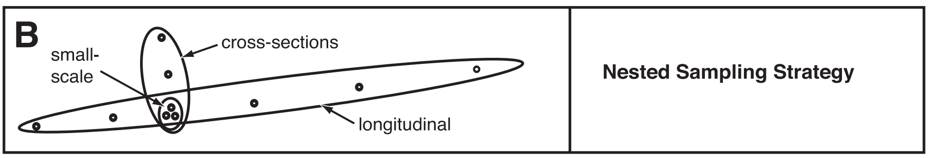


Fig. 6. Sample collection strategy within the Holtwood Gorge field area. (A) Schematic diagram of terrace levels within the gorge, number of samples collected at all variance scales, and the Paleo River Gradient for each level. (B) Schematic of nested sampling strategy.

^{10}Be production rate including calibration, normalization, and geometric corrections (Clark and others, 1995).

We independently prepared, processed, and measured two laboratory replicates to check the reproducibility of sample preparation and AMS measurement. ^{10}Be activities measured within both pairs of replicate samples (LR-04c & LR-04cX; LR-37 & LR-37X) agree within ± 2 percent (table 1), within measurement error.

In this paper, we present and interpret ages modeled from ^{10}Be concentrations (Lal, 1991). Such ages assume rapid erosion of overlying bedrock prior to exposure, continual exposure since that time, and no more than a few cm of bedrock surface erosion following initial exposure. Field observations suggest these assumptions are reasonable in Holtwood Gorge. The exposed bedrock is hard and fresh; quartz veins rarely protrude more than a cm from the sampled surface. Although strath surfaces farther upstream are often mantled by thin alluvium (Pazzaglia and Gardner, 1993; Engel and otherts, 1996), very little sediment exists within Holtwood Gorge along the over steepened lower reaches of the river. While changing sediment fluxes during and after the last glaciation likely played a role in the carving of Holtwood Gorge, there is no field evidence to suggest that model ages were affected by prolonged periods of burial by sediment.

Water Inundation Modeling

During and following periods of incision, river water covered bedrock surfaces within and above the active channel for varying periods of time. Incoming cosmic rays, responsible for the production of ^{10}Be, would have been absorbed by this water when it

Table 1

GPS and isotopic data for samples collected within and near Holtwood Gorge

Sample ID	Terrace Level	Elevation (masl)	Easting (m) [1]	Northing (m) [1]	Downstream Distance (km) [2]	Height Above Riverbed (m) [3]	^{10}Be Measured (10^4 atoms g^{-1})	Model Age (ka) [4]
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-16	1	34.2	387275.9	4407723.9	2.27	0.5	6.92 ± 0.26	14.1 ± 1.5
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-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 [6]	1	34.2	386368.5	4407832.7	1.67	0.3	3.83 ± 0.21	7.9 ± 0.9
LR-59	1	36.7	386058.1	4409019.7	0.51	0.8	7.40 ± 0.40	15.1 ± 1.7
LR-06	2	35.1	388254.2	4406974.9	3.43	2.9	9.68 ± 0.41	19.9 ± 2.2
LR-09	2	34.7	387834.0	4407463.1	2.79	1.7	12.1 ± 0.4	24.9 ± 2.7
LR-15	2	36.2	387508.8	4407667.6	2.44	2.8	9.48 ± 0.33	19.3 ± 2.1
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-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-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-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-42	2	35.4	387265.1	4407521.2	2.43	1.9	8.78 ± 0.34	17.9 ± 1.9
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-48	2	33.3	388150.8	4406141.5	4.07	1.9	11.1 ± 0.4	22.8 ± 2.4
LR-53	2	39.0	385889.7	4408541.7	0.82	3.4	7.75 ± 0.26	15.9 ± 1.7
LR-08	in [7]	34.9	388047.8	4407068.9	3.24	2.5	14.0 ± 0.5	28.8 ± 3.1
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-13	in	35.2	387503.0	4407684.8	2.42	1.7	7.50 ± 0.27	15.3 ± 1.6
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-23	in	42.0	386904.8	4407614.7	2.15	8.1	9.90 ± 0.39	20.2 ± 2.2

covered surfaces that 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, Hydrologic Engineering Center River Analysis System software version 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 and Power Co.). Using HEC-RAS, we modeled the depth of water covering the

TABLE 1

(continued)

Sample ID	Terrace Level	Elevation (masl)	Easting (m) 1	Northing (m) 1	Downstream Distance (km) 2	Height Above Riverbed (m) 3	^{10}Be Measured (10^4 atoms g^{-1})	Model Age (ka) 4
LR-24	in	39.1	387079.6	4407552.8	2.30	5.5	9.19 ± 0.33	19.1 ± 2.0
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-41	in	41.4	386720.3	4407708.3	1.97	7.3	11.0 ± 0.4	22.3 ± 2.4
LR-58	in	37.0	388628.3	4406401.2	4.12	5.7	10.5 ± 0.4	21.5 ± 2.3
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-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-07	in	34.6	388175.5	4407140.2	3.25	2.2	12.8 ± 0.4	26.2 ± 2.8
LR-02a	3	42.4	386788.5	4407571.0	2.12	8.5	15.5 ± 0.5	31.6 ± 3.3
LR-02b 5	3	42.4	386788.0	4407558.2	2.13	8.5	11.5 ± 0.4	23.4 ± 2.5
LR-12	3	44.6	387600.3	4407614.9	2.54	11.2	15.8 ± 0.6	32.4 ± 3.5
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-25	3	45.0	387161.8	4407622.8	2.29	11.3	17.0 ± 0.6	34.4 ± 3.7
LR-29	3	47.0	385827.6	4408840.9	0.53	11.1	15.3 ± 0.5	30.8 ± 3.3
LR-38	3	45.2	385602.8	4408484.3	0.70	9.5	14.6 ± 0.6	29.4 ± 3.2
LR-47	3	37.8	389447.6	4405836.4	5.04	7.7	22.1 ± 0.7	45.3 ± 4.8
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-74	3	43.5	387412.2	4407360.9	2.64	10.3	20.0 ± 0.6	40.6 ± 4.3
LR-01	4	54.6	386953.0	4407462.2	2.30	20.9	47.4 ± 1.6	97.2 ± 10.5
LR-43	4	58.3	387248.6	4407329.7	2.58	25.0	41.7 ± 1.4	84.5 ± 9.1
LR-14	boulder 8	35.1	387506.8	4407682.4	2.43	1.6	11.8 ± 0.5	24.0 ± 2.6
LR-28	boulder 8	38.1	385646.1	4408750.9	0.51	2.2	7.67 ± 0.33	15.5 ± 1.7
LR-03a	cobble 9	159.0	370679.0	4433323.0	na	~80	54.0 ± 1.9	100 ± 10.9

1-All GPS locations provided in UTM NAD27 CONUS, zone 18N.
2-Distance downstream (km) from Holtwood Dam.
3-Height above the riverbed is measured relative to a distinctive watermark in upper Holtwood Gorge under no-flow conditions. The watermark was traceable for approximately 2 km.
4-Age uncertainties include propagated analytic errors (1 σ) in carrier addition and AMS measurement, and ± 10% (1 σ) uncertainties in ^{10}Be production rate.
5-Two independently processed and measured laboratory replicates were run on the accelerator to ensure reproducibility of lab and measurement techniques.
6-Two samples were excluded from statistical analysis because of suspected measurement error.
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.
9-LR-03a is a quartz cobble collected from a middle Miocene age gravel terrace on the piedmont uplands.

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 production rate for each sample site for each day of record was calculated using the modeled water depth according to Lal (1991):

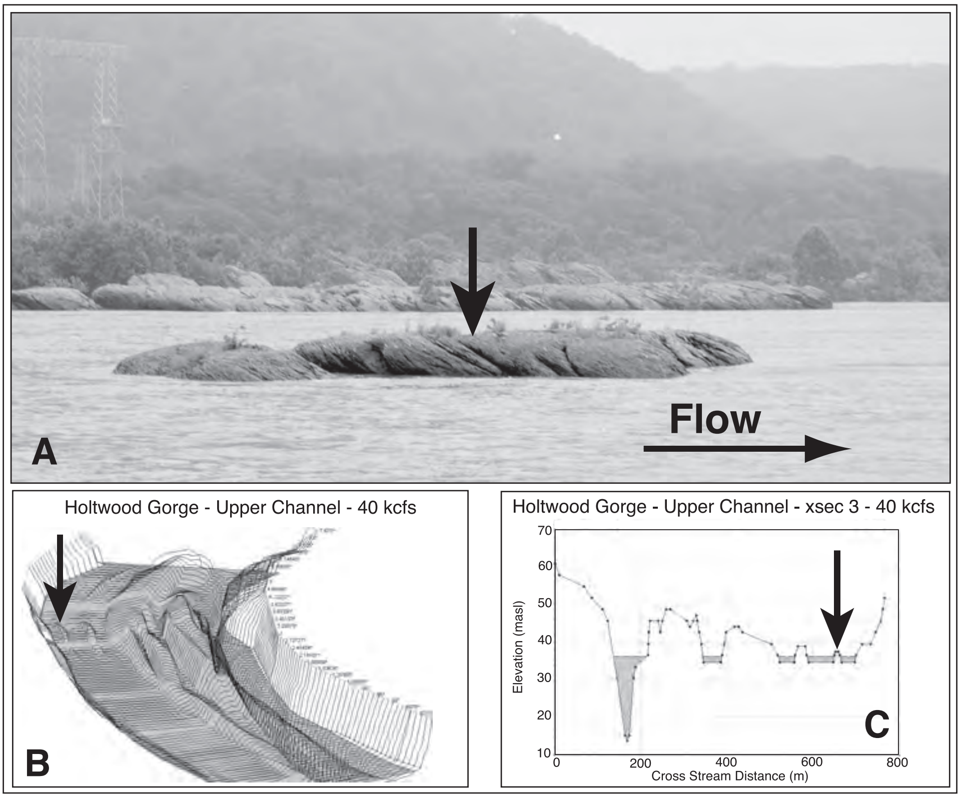


Fig. 7. Example of a calibration photo used to constrain water depths for the HEC-RAS model of Holtwood Gorge at known discharges. (A) Photo taken from the western shore of the Susquehanna River in the upper gorge at a discharge of ~40 kcfs. River flow is from left to right (NW to SE). (B) X-Y-Z reconstruction, and (C) a representative cross-section of Holtwood Gorge show the modeled water depth at 40 kcfs. The black arrows in A, B and C are the same point within the gorge.

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

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 (bedrock surface production rate under depth x of water) 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 7 percent of the impinging cosmic ray neutrons have been absorbed by an overlying column of water through time.

This approach assumes that the last 75 years of discharge records can be extrapolated through time, a tenuous assumption. 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 (Reusser and others, 2004); thus exposed rock surfaces were presumably removed more quickly from inundating flood waters. For a more detailed discussion of HEC-RAS modeling of Holtwood

Gorge, refer to Reusser (ms, 2004). Finally, if a thick cover of river ice remained on strath surfaces for extended periods of each year during glacial times, cosmic-ray dosing of the underlying rock would have been diminished and our dates would be underestimates; we have no way of quantifying this effect.

Probability Distributions

In addition to commonly used statistical methods for cosmogenic data analysis (regression analysis and calculating mean terraces ages from multiple samples), we consider summed model age probability resulting from multiple samples collected along each of the three prominent terrace levels (Balco and others, 2002). When discussing the timing of incision and/or timing of abandonment for each terrace, this analysis allows us to investigate patterns in the distribution of ages from a distinct terrace within the gorge that are not necessarily reflected by mean terrace ages.

We constructed summed probability curves by combining the Gaussian distributions (based on sample age and analytical uncertainty including carrier addition and AMS measurement) for multiple samples collected along each prominent terrace level. The model age probability for all samples was summed over 0.5 ky 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 modes between levels.

RESULTS

Measurement of cosmogenically produced ^{10}Be in 78 bedrock samples shows that all exposed rock surfaces in Holtwood Gorge are late Pleistocene features (table 1). The ^{10}Be activity measured in each sample, considered along with its location within the gorge, provide us with a context in which to investigate not only the timing and rate of incision, but also the pattern of erosion at different spatial scales.

Variance At Small Spatial Scales

Measured ^{10}Be activities for spatially replicated samples on each of the three prominent strath-terraces are in close agreement (table 1 and fig. 8). 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 percent and $\pm$3.7 percent (1 σ), 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 meters 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 percent, 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 characteristic of higher terrace levels. This observation suggests that once the active channel bed has lowered, older and higher bedrock outcrops are abraded and smoothed over time. Nevertheless, agreement of three samples within 10 percent indicates that a single sample from

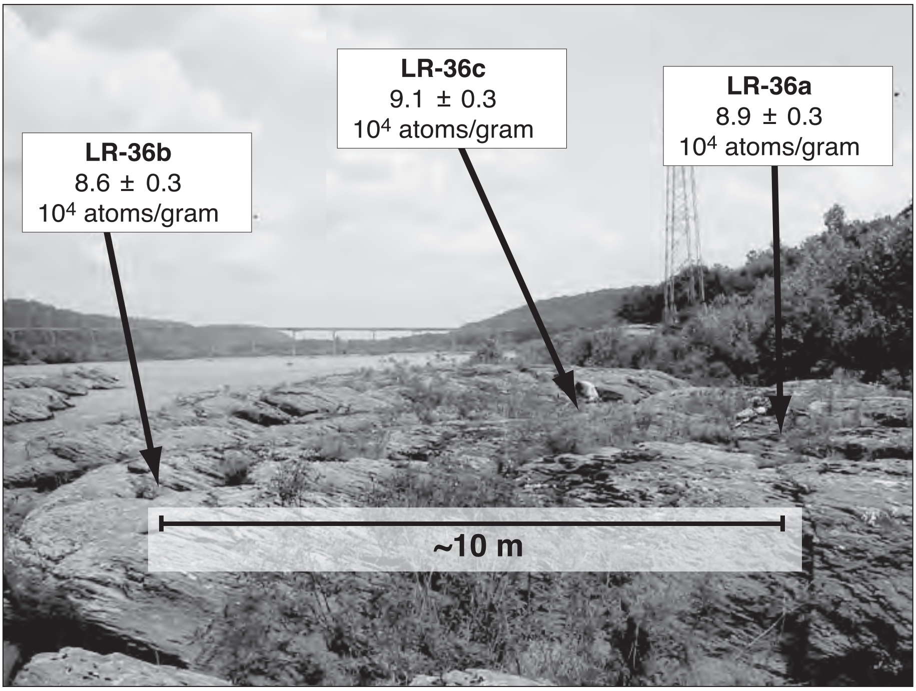


Fig. 8. Example of a small-scale variance study on the Level 2 terrace in upper Holtwood Gorge. Similar studies also were conducted on the lowest (Level 1) and highest (Level 3) well-preserved terrace levels in the gorge. On the level 2 terrace, model ages for three samples collected within 5 to 10 m of one another agree within ±2.7%, confirming that a single sample represents the exposure history of a bedrock surface at small spatial scales.

the level 1 surface still represents well the ^{10}Be concentration in the area from which it was collected.

Mean Exposure Ages of Terrace Surfaces

Exposure ages modeled from ^{10}Be concentrations 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 (1σ) 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 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 meters 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 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, generally increasing in age with height above the channel floor.

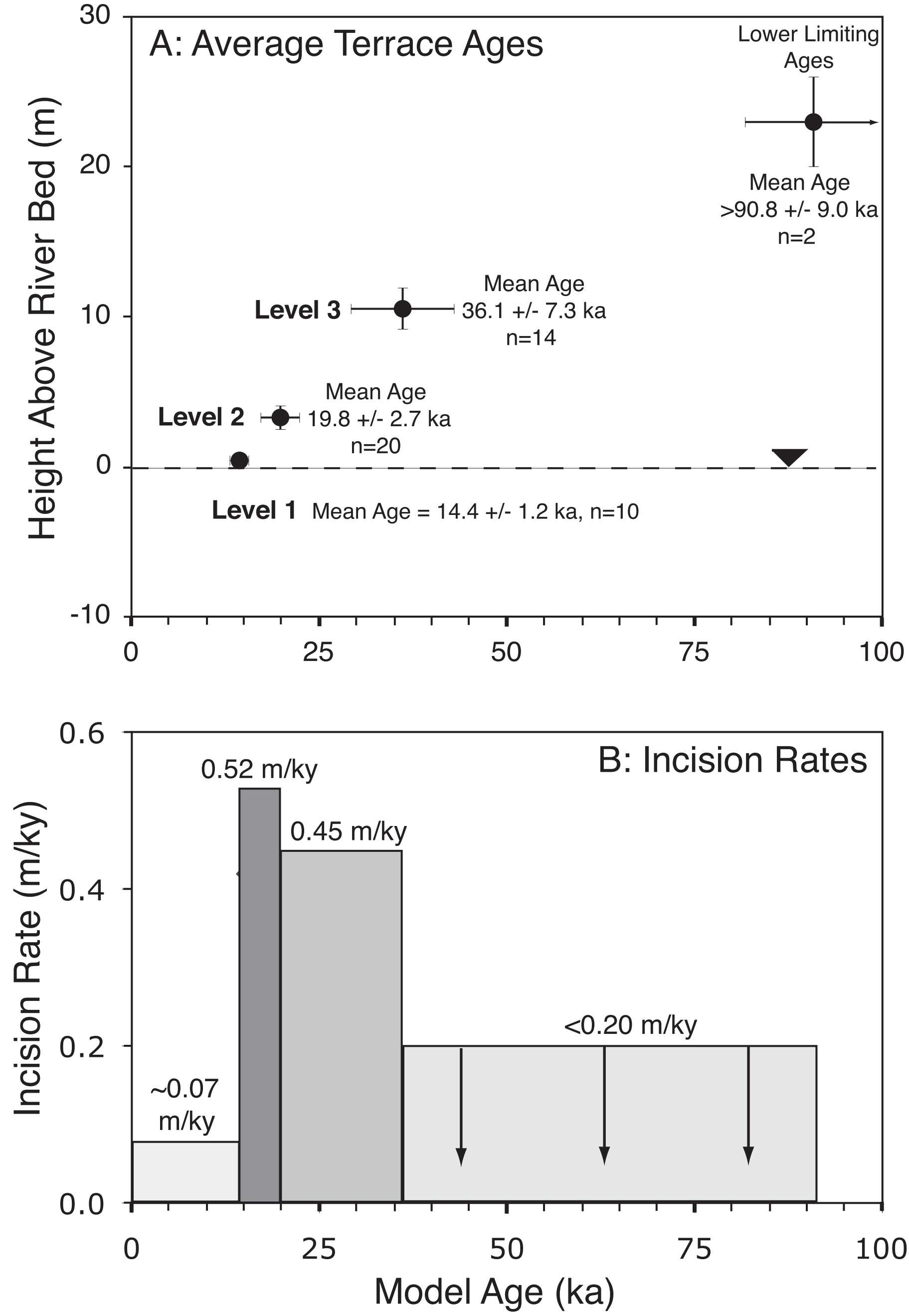


Fig. 9. (A) Average ages for terraces within Holtwood Gorge were calculated from multiple samples collected longitudinally along each terrace level. 1σ error bars. Mean age for 2 samples collected from heavily weathered and eroded high points above the three well preserved levels reported as lower limit because we can not determine how much rock has been removed from these surfaces. (B) Average incision rates calculated with average terraces ages and average heights above the riverbed. Due to the poor surface preservation of the highest samples, the incision rate (<0.2 m/ky) prior to 36 ka is given as an upper estimate. Small channels cut into the lowest (level 1) terrace are approximately 1 m in depth suggesting an approximate incision rate of 0.07 m/ky from 14.4 ka to present.

Boulder and Cobble Ages

Exposure ages for two rounded boulders (each having a long axis of ~1.5 m) are late Pleistocene, similar to 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 ^{10}Be equivalent to ~9 ky of exposure 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. We collected bedrock samples on either side of the boulder (LR-26: 18.3 ± 1.9 ka; LR-27: 17.9 ± 1.9 ka). Although ages, with uncertainties, for the bedrock surfaces and the boulder overlap, it appears that this boulder is younger, if only slightly, than the surface upon which it sits.

The quartz cobble (LR-03a) collected from the degraded middle Miocene upland gravel terrace (Pazzaglia, 1993) yielded an exposure age of 100 ± 11 ka. This young age suggests significant erosion of the terrace and exposure of the clast long after the terrace was abandoned. This one sample suggests that such cobbles retain no useful age information regarding earlier phases of river stability and incision.

DISCUSSION

Our model ages record an episode of rapid river incision through bedrock along the lower Susquehanna River during and after the late Wisconsinan glaciation. We use results from Holtwood Gorge, as well as from Mather Gorge along the unglaciated 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. In this passive margin setting, fluctuations in a number of climate-related boundary conditions hold the potential to initiate and maintain fast rates of fluvial incision during the last glacial-interglacial cycle.

The Timing and Rate of Rapid Incision Within Holtwood Gorge

Rates of vertical incision dramatically increased within Holtwood Gorge between ~36 ka and ~14 ka (fig. 9B). Lower limiting ages for samples collected from eroded high points (LR-01 and LR-43; mean = 90.0 ± 9.0 ka) imply that prior to ~36 ka, the Susquehanna was incising at a maximum rate of 0.2 m/ky. Average model age data and mean terrace elevations from multiple samples collected along the three well preserved straths suggest that from ~36 ka to ~20 ka, incision accelerated to a rate of 0.45 m/ky. Incision between the level 2 terrace and the level 1 strath appears to have increased again to ~0.52 m/ky between ~20 ka and ~14 ka. A mean age of ~14 ka for the lowest terrace (level 1) suggests that rapid incision ceased around that time. Small channels incised into the level 1 strath are generally ~1 m deep, suggesting an incision rate of ~0.07 m/ky since ~14 ka.

The initiation (~36 ka) and cessation (~14 ka) of rapid incision inferred from average terrace ages are supported by incision rates calculated along cross-sections within the gorge. Samples collected in cross-section 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/ky, R^2 = 0.96, n = 13; Middle Gorge: 0.56 m/ky, R^2 = 0.84, n = 17; figs. 10 and 3).

Along each cross-section, we collected samples not only from prominent terrace levels, but also from bedrock surfaces between each level. Trendlines through these data suggest that the Susquehanna River incised quickly and steadily beginning approximately 36 ka, without detectable lags between the abandonment of one terrace level and the formation of a lower strath (fig. 10). Accordingly, we interpret the mean

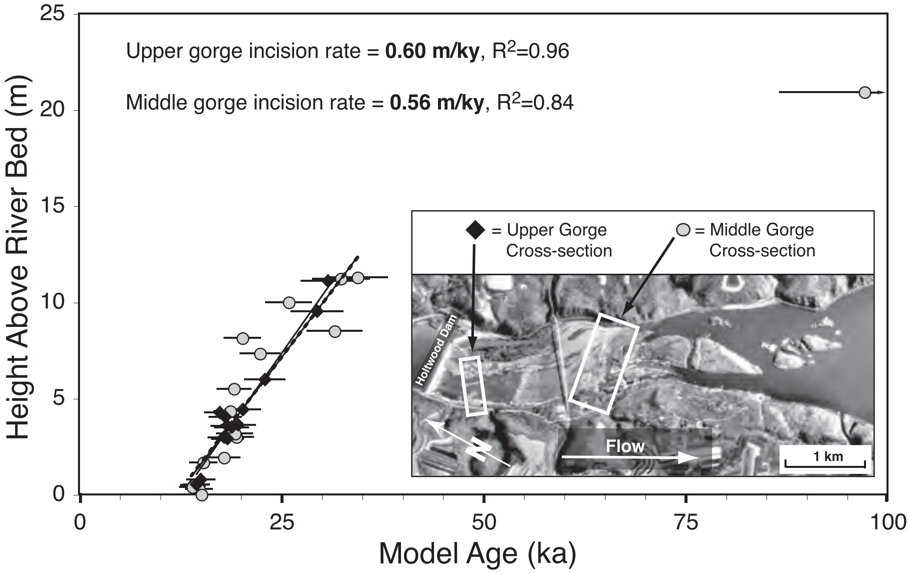


Fig. 10. Plots of incision rates along cross-sections at specified locations within Holtwood Gorge. Data points labeled as black diamonds represent 13 samples collected in the upper gorge and data points labeled as shaded circles represent 17 samples collected in the middle gorge. Solid and dashed trendlines 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.

ages for the Holtwood Terraces as reasonable approximations for the timing of their abandonment.

Twenty-two samples collected down the rounded fronts of three separate mid-channel islands suggest that during the carving of Holtwood Gorge, obstacles oriented parallel to flow (for example, islands) eroded differently than gorge walls and the tops of terrace remnants (figs. 11A and B). Samples collected from the level 1 terrace immediately in front of the rounded fronts are consistent with the gorge-wide average terrace age of ~14 ka. Similarly, samples collected from the island tops agree with the average age (~36 ka) of the highest well-preserved terrace (level 3; figs. 11C, D and E). However, samples collected down the rounded fronts between the level 3 and level 2 terraces, and spanning more than 5 m in elevation, show little variation in model age. This pattern is not seen along cross-sections oriented perpendicular to flow.

These 9 intermediate samples collected parallel to flow suggest that island fronts were last eroded around 19 ka (fig. 12). Interestingly, the model ages of these samples are in good agreement with the average abandonment age of the level 2 terrace (~20 ka). This finding could be evidence that during incision into the level 2 terrace at ~20 ka, the upstream noses of prominent pre-existing level 3 terrace remnants (mid-channel islands), which constitute major obstacles to flow, were re-eroded sufficiently to erase any prior exposure history. Further supporting this notion, is the observation that large erratic boulders are often found perched on the level 2 terrace but are very seldom found on the lower level 1 surface. If ~20 ka, the beginning of glacial recession changed sediment dynamics within the gorge during the abandonment of the level 2 terrace, the prominent island fronts, oriented directly into flow, presumably would have borne the brunt of boulder-bedrock impacts.

An alternative approach to interpreting the timing of rapid incision.—Considering the probability distribution of model ages for multiple samples collected along each

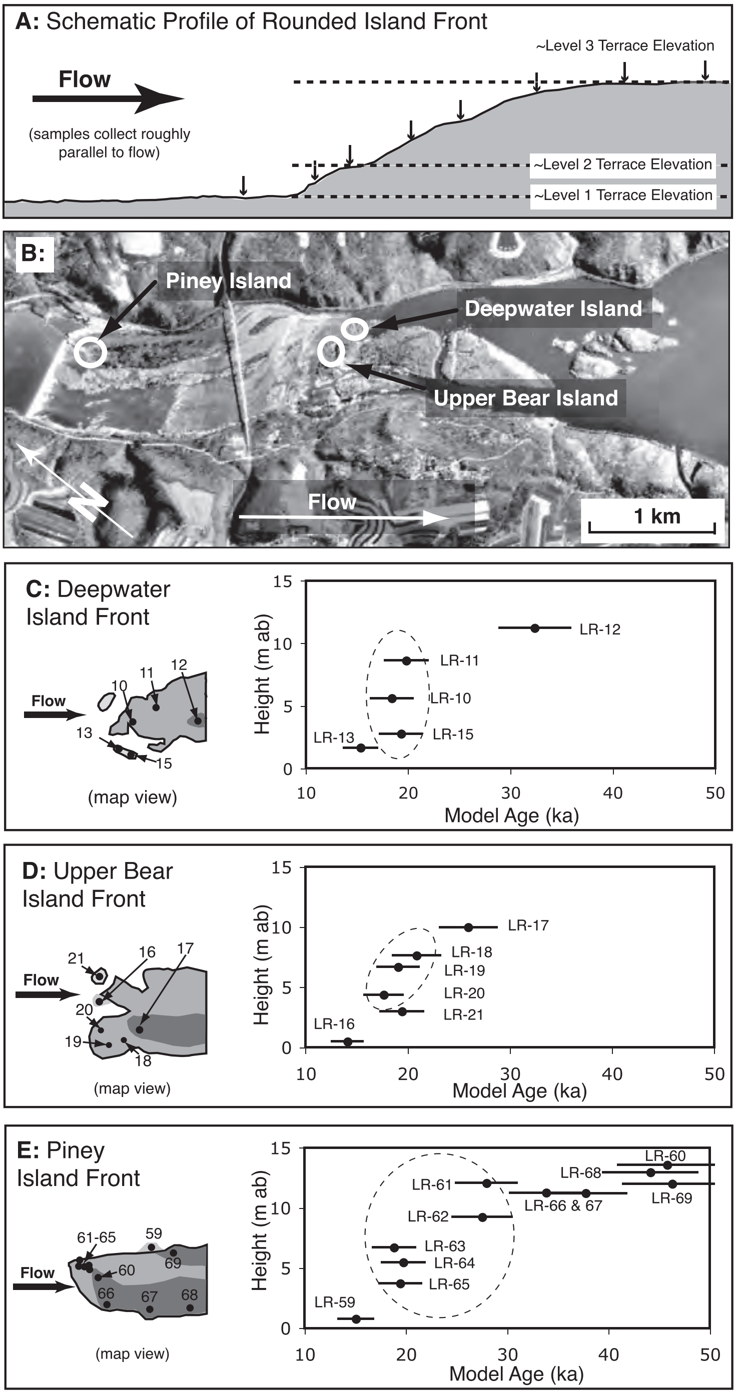


Fig. 11. (A) Cartoon of a rounded island front sloping from the highest well-preserved terrace (level 3) to the lowest terrace (level 1). Small arrows represent how we collected samples down the rounded front oriented parallel to flow. The heavy flow arrow indicates the direction of river flow. (B) Overview of the gorge displaying the location of each of the three rounded fronts we sampled. (C), (D) and (E): Each panel shows sample site locations on each of the three island fronts, as well as model age and height above the modern riverbed (m ab) for all samples. Dashed circles overlying model age vs. height plots indicate which samples from each island were collected down the rounded fronts themselves. Most other samples were collected in front of each island (level 1 terrace), or along the island tops (level 3).

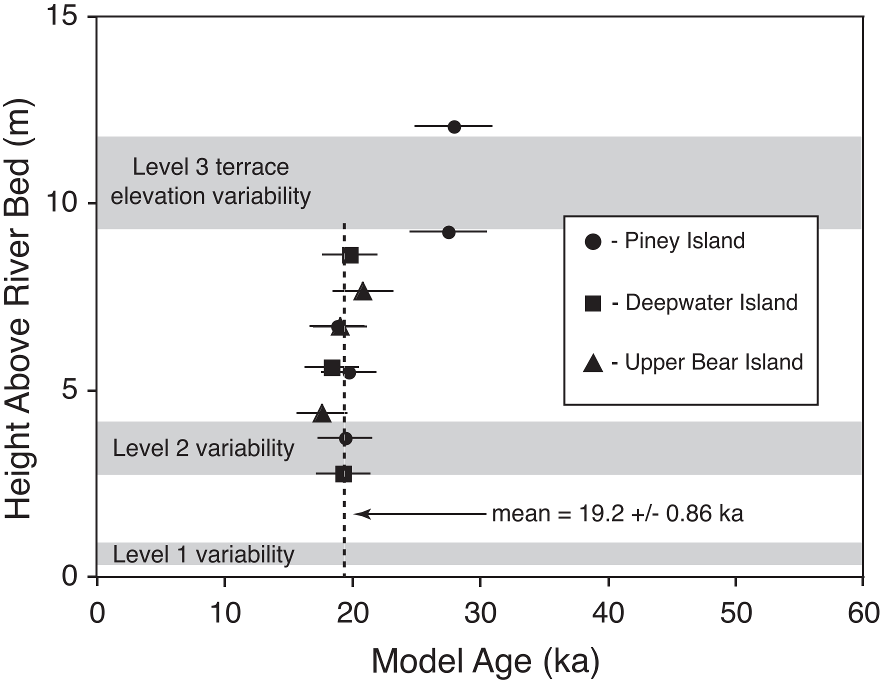


Fig. 12. The data displayed in this figure represent only those samples collected down each of the rounded fronts (data points are those that are within dashed circles in figs. 11 C, D and E). Although the samples span more than 5 meters in elevation above the channel floor, all show little variability in model age, suggesting that they either were exposed instantaneously ~19 ka, or that they have been re-eroded since their initial exposure during incision toward the level 2 terrace. Gray bands represent the variability in height above the riverbed for all samples collected from the three prominent terrace levels with Holtwood Gorge.

terrace level affords the opportunity to detect more complex patterns in the model age data. For example, the summed probability plot for samples collected along the Level 3 terrace reveals two prominent modes, ~45 ka and ~32 ka, and a lesser mode at ~26 ka (fig. 13). In contrast, dominant unimodal probability peaks for both the level 2 and 1 terraces are in relatively good agreement with their respective mean ages (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 investigate further the importance of, and cause for the complexity in the timing of incision inferred from multiple age modes for samples collected along the level 3 terrace, we consider each individual sample's position with respect to the level 3 riverbed trendline (fig. 5). If bedrock surfaces standing slightly above 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 channel floor (R^2 = 0.21; fig. 14), suggesting that topography does not play a large role in controlling 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 diverted through a maze of smaller channels (fig. 3). While it is not possible to quantify past hydraulics within the gorge, the complex channel geometry between the mid-channel islands likely focused erosion in different places at different times,

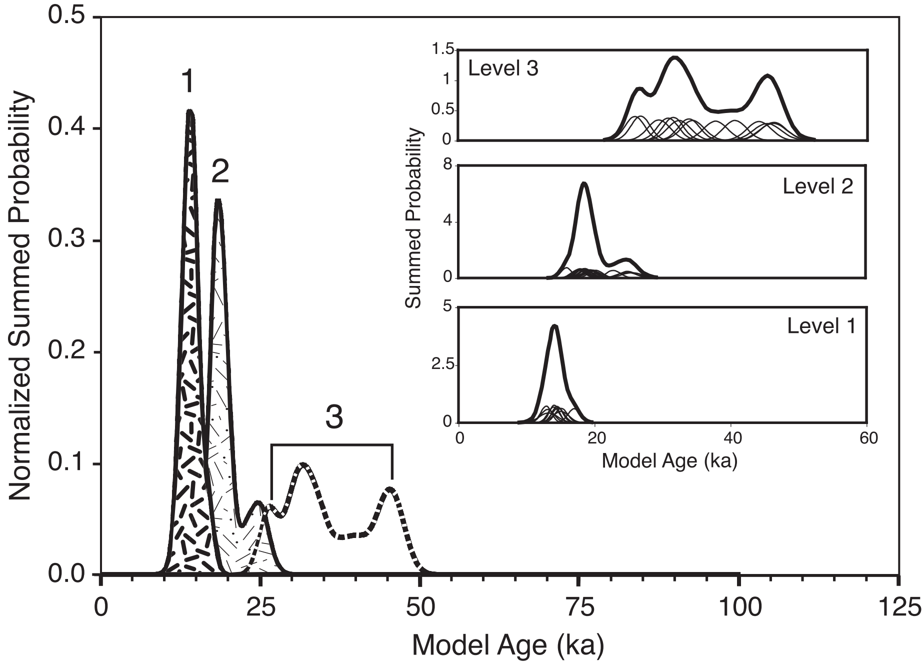


Fig. 13. Summed model age probability plots for multiple samples collected along each of the three well-preserved terrace levels (levels 1 through 3). Probability curves were constructed by summing the Gaussian distributions of all samples. 1 σ errors associated with each model age reflect uncertainties, including carrier addition and AMS measurement only. Probability curves in the main plot were normalized (each age increment was divided by the number of samples collected from the terrace) to allow for comparison of the magnitude of peaks.

resulting in more variability in the timing of abandonment for individual bedrock surfaces. 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 than for level 3 in general. 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 level 3 sample elevation and age ($R^2 = 0.71$; fig. 14).

While the mean terrace age of ~36 ka likely best describes the overall abandonment age of the level 3 terrace, probability distributions suggest that incision could have begun as early as ~45 ka. The multiple age modes for level 3 terrace samples could be evidence that abandonment was not a discrete event, or the modes could reflect episodic flushing of alluvial fills over a prolonged period of adjustment between water and sediment discharge during the last glacial period.

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 completely their exposure histories. If the overlying meter or so of rock were eroded slowly prior to the final exposure of a bedrock surface, its model age would appear too old as significant ^{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 would appear too young. Below, in the specific context of Holtwood

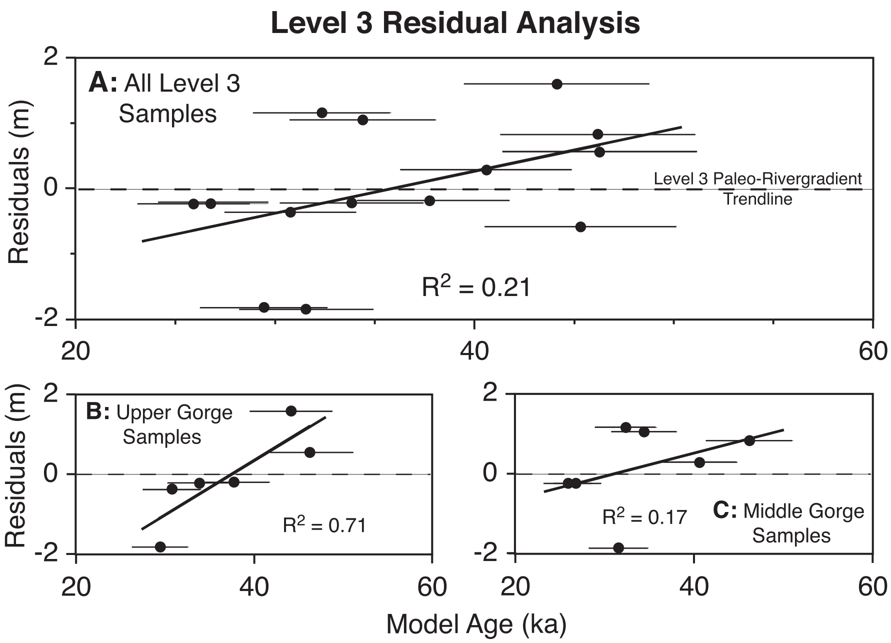


Fig. 14. Using the level 3 river gradient constructed from GPS data for all sample sites, we consider the age of each sample vs. its height above or below the ancient riverbed (residual). (A) Model age vs. residual (m) for all samples collected along the level 3 terrace. (B) Model age vs. residual for 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 flow is diverted and dissected by numerous mid-channel islands.

Gorge, we consider 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 bedrock prior to terrace abandonment. First, bedrock samples collected from the modern channel of the Potomac River near Great Falls have very low ^{10}Be activities, corresponding to young model ages ($\leq$4 ka). Such low activity suggests rapid erosion and exposure of rock (Bierman and others, 2002, 2004) 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, the prominent jointing and foliation patterns, and rough surface texture of the lowest and youngest terrace (level 1) suggest that quarrying of meter-scale joint blocks was responsible for the majority of incision into the Wissahickon Schist within Holtwood Gorge. Rapid removal of large bedrock blocks during periods of rapid downcutting and terrace abandonment would quickly expose underlying bedrock containing little ^{10}Be.

While we see ample evidence for fluvial retouching of plucked bedrock, we see no evidence of 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 above the active channel bottom are rounded, suggesting that surfaces were abraded after plucking, perhaps when they were no longer on the channel floor. However, in most instances, the 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.

While prodigious amounts of sediment most likely passed through Holtwood during the carving of the gorge, it is difficult to quantify what effect its presence would have had on our model ages. Today, very little sediment occurs on or between the three prominent terrace levels. Many of the alluvial deposits that do occur are confined to the western bank of the gorge and were exploited during canal construction. Because most substantial fills exist above the level 3 terrace, we suggest that sediment burial did not affect our model ages. Furthermore, dated bedrock surfaces within the gorge yield a progressive increase in model age with increasing height above the channel floor (spanning ~20 m; fig. 10). This finding, similar to other cosmogenic studies of river incision (Burbank and others, 1996; Leland and others, 1998; Bierman and others, 2004), suggests that sediment did not substantially shield surfaces from cosmic ray dosing after abandonment or greatly re-erode already abandoned surfaces during periods of incision.

Water inundation through time, modeled with HEC-RAS, did not substantially affect cosmic ray dosing and exposure ages of bedrock surfaces within Holtwood Gorge. Model results suggest that exposure ages represent between ~95 percent and ~75 percent (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 Tropical Storm Agnes in 1972, or during ice jam flooding in the past, these rare, high-magnitude events have little effect on isotope production due to their short duration (Hancock and others, 1998). Model ages for samples from sites higher above the riverbed in Holtwood Gorge (terrace levels 2 and 3) reflect between 99 percent and 100 percent of their total unshielded exposure history, indicating 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 migration of knickpoints (for example, Gardner, 1983; Zen, 1997a; Hancock and others, 1998; Whipple and others, 2000; 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 marched headward. If, however, the rate of knickpoint retreat were fast enough or the longitudinal distance over which samples are collected were too short, the temporal resolution of cosmogenic dating might not be sufficient to detect age gradients.

Model ages for multiple samples collected longitudinally along each of the three terrace levels argue both for and against the passage of knickpoints through Holtwood Gorge during the late Pleistocene. 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 along the entire length of Holtwood Gorge. In contrast, the level 2 terrace data display an age gradient (~1.4 ky/km, R^2 = 0.63) consistent with knickpoint retreat, implying that the surface is time transgressive. On this one terrace, bedrock outcrops located farther downstream were exposed before surfaces closer to Holtwood Dam. Together, these results suggest that different erosional processes were responsible for incision in the gorge at different times, or that correlation of terraces over longer distances is required in order to detect rapid rates of knickpoint retreat along the upper and lower terraces.

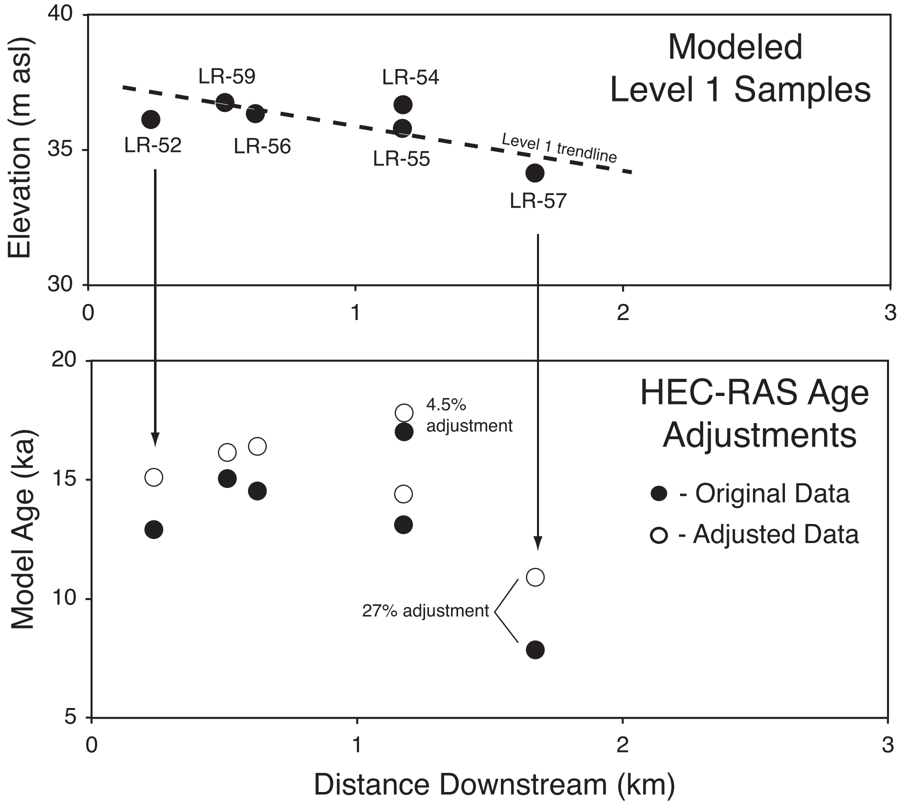


Fig. 15. To estimate the amount of exposure history lost to an overlying column of water through time, we modeled water depth for ~75 years of daily flow data with HEC-RAS. Using the integrated depth of water, we estimate the percentage of exposure history missing from each level 1 sample site located in the upper gorge. Note that, in general, sample sites lower with respect to the level 1 riverbed trendline have been shielded from cosmic ray bombardment to a great degree, presumably 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.

Episodic Fluvial Incision Through Bedrock

Short- versus long-term rates of incision on the Atlantic passive margin.—Rates of late Pleistocene incision implied by cosmogenic data (up to 0.6 m/ky) are more than an order of magnitude greater than long-term estimates of fluvial incision into the Piedmont since the middle Miocene (~0.012 m/ky) (Pazzaglia and Gardner, 1993; Zen, 1997b; Pazzaglia and others, 1998). Short- and long-term estimates are clearly discordant. Even slower Holocene rates of ~0.07 m/ky (fig. 9) appear far too fast, and, if sustained since the Miocene, would have resulted in a km deep gorge. Short-lived, rapid incision must be complimented by periods of little to no vertical channel bed lowering. Beginning around 36 ka, and ending ~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, 2004; Reusser and others, 2004) to rapidly incise into rock.

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

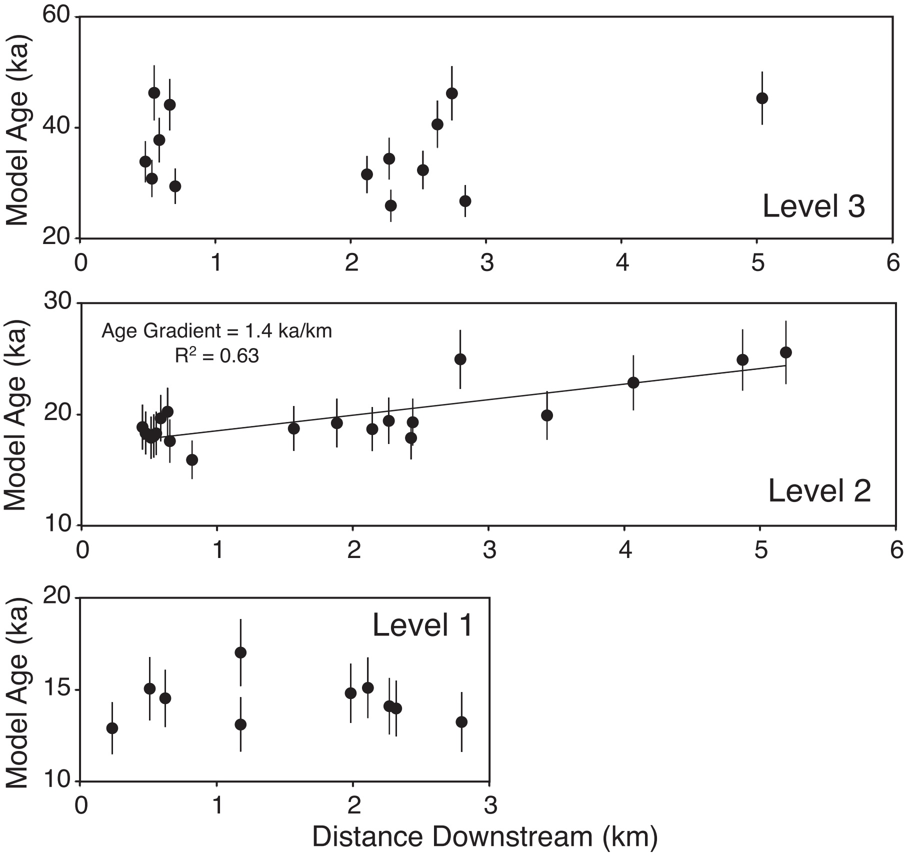


Fig. 16. Distance downstream vs. model age for multiple samples collected along each of the prominent terraces in Holtwood Gorge. No significant age gradient is detectable along the highest (level 3) or lowest (level 1) terrace. However, an age gradient of ~1.4 ka/km exists for samples along the middle (level 2) terrace, supporting a model of knickpoint propagation through the gorge during the abandonment of this level.

recorded in Holtwood Gorge is not yet possible, it appears that changing climate, acting through a variety of primary and secondary effects, initiated and maintained rapid rates of vertical 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 glaciated Susquehanna River and the unglaciated 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 meltwater, were responsible for this pulse of incision (Bierman and others, 2004; 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, fluctuations in water and sediment discharge, growth of the Laurentide Ice Sheet, and passage of the resulting glacial forebulge. Climate itself, by altering the hydrology of both watersheds, also could have caused incision along these passive margin rivers. Below is a discussion of these climate-related boundary conditions and the capacity of each to have influenced rates of incision along the middle Atlantic seaboard during the late Pleistocene.

Sea level: In many instances, river incision through bedrock appears to be accomplished by headcutting in response to base-level drops (for example, 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 Chappell, 2001). The initiation of rapid incision within Holtwood Gorge, as indicated by the abandonment of the level 3 terrace at ~36 ka (fig. 17A) 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, and probably unsteady 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 and rapid late Pleistocene vertical incision rates remains uncertain.

The glacial forebulge: 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 Peltier, 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 (personal communication, Jon Pelletier, 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 <50 percent 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.

Basin hydrology and sediment dynamics: Incision through bedrock, especially in heavily fractured bedrock reaches such as Holtwood Gorge, is accomplished most efficiently by hydraulic plucking of joint blocks (Whipple and others, 2000). Aided by extensive potholing (for example, Thompson, 1990), the majority of channel bed lowering in Holtwood Gorge appears to have occurred in such a manner. Because this style of erosion requires stream power far greater than what the Susquehanna River typically generates under modern hydrologic conditions, it seems logical that discharges were more frequently greater during the carving of the gorge.

Increases in the frequency and magnitude of flood events capable of exceeding thresholds for rock detachment 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, 1991a, 1991b; Hancock and others, 1998; Whipple and Tucker, 1999; Tucker and Brass, 2000; Tucker and Whipple, 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.

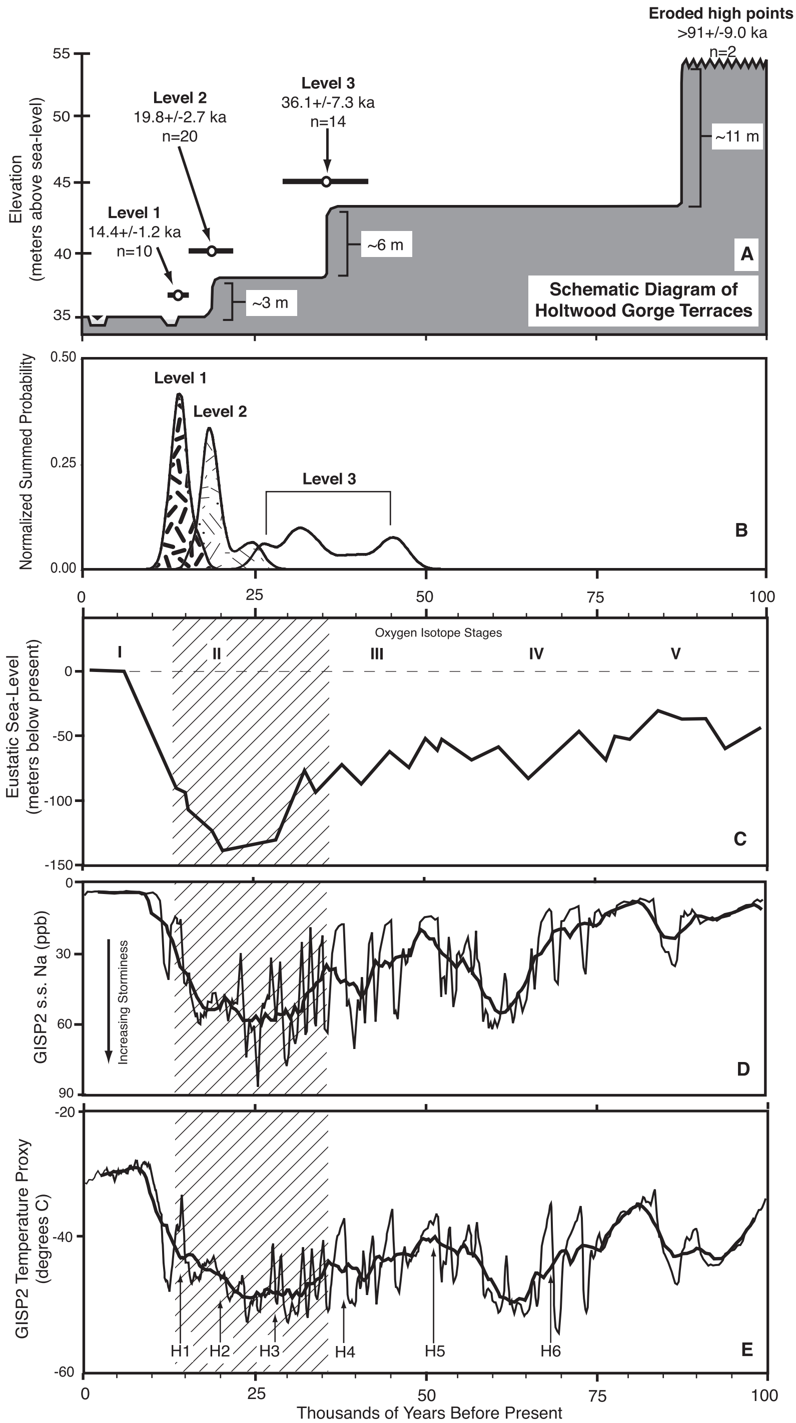


Fig. 17. Summary of the timing of incision and terrace abandonment within Holtwood Gorge in relation to otherwise documented changes in climate and sea level. All panels are displayed on the same time axis (0 to 100 ka). (A) Schematic diagram of Holtwood conveying ^{10}Be model age data and important geomorphic characteristics of the gorge. The mean age of two samples collected from heavily weathered surface is given

Acting in concert with the flood hydrology for the Susquehanna River, changes in sediment dynamics likely played a role during the episode of rapid incision measured with ^{10}Be. 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 rock (Gardner, 1983; Sklar and Dietrich, 1998, 2001; Hancock and Anderson, 2002). While today, very little sediment exists in Holtwood Gorge, and the sediment flux through the Susquehanna system as a whole is well under capacity (Pazzaglia and others, 1998), discontinuous low strath terraces mantled with several meters of alluvium are common not far upstream (Pazzaglia and Gardner, 1993; Engel and others, 1996), suggesting that sediment did indeed flux through the Susquehanna channel during the carving of the gorge. If, prior to the initiation of rapid incision at ~36 ka, Holtwood Gorge was choked with sediment, rates of vertical incision were probably slow because the channel floor was insulated from erosion. This model suggests that around ~36 ka, evidenced by the abandonment age of the highest well preserved terrace, the Susquehanna River re-encountered the channel bed and began to incise rapidly into bedrock. Because most incision in Holtwood Gorge appears to have been accomplished by plucking, changes in the water and sediment discharge down the Susquehanna River ~36 ka could have quickly excavated alluvial fills thus re-exposing the channel floor to erosion during extreme discharge events.

Because records of past discharge levels 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 storminess at high latitudes through the late Pleistocene (Mayewski and others, 1994). A marked increase in storminess, beginning at ~35 ka and lasting until ~10 ka, correlates well with the initiation and cessation of incision within Holtwood Gorge (fig. 17D), as indicated by the overall abandonment age of the level 3 terrace (~36 ka) and the mean age of the youngest terrace (~14 ka). Good correlation between the GISP2 s.s. Na record and records of past storminess 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 δ^{18}O record (fig. 17E) (Cuffey and Clow, 1997), presumably altered runoff dynamics within the Susquehanna basin. Oscillations in pollen spectra from Florida and the southern Appalachians (Grimm and others, 1993, 2003; Litwin and others, 2004) correlate well with GISP2 temperatures, indicating that high-latitude temperature changes also affected the mid-Atlantic region.

Cooling climate, in combination with a steep temperature gradient along the nearby ice front could have concentrated annual discharge into a fewer number of larger events and/or promoted increased extratropical cyclonic activity caused by large-scale frontal convergence near the ice margin (Hirschboeck, 1991). A stormier

as a lower limiting age. (B) Normalized cumulative probability curves for each of the three prominent terrace levels. (C) Late Pleistocene sea-level record derived from Huon Peninsula (Lambeck and Chappell, 2001). Roman numerals are oxygen isotope stages. (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). (E) Temperature 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.

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. In addition, antecedent land-surface conditions, such as frozen ground or increased snow depth, may have influenced the flood hydrology of the Susquehanna River (Hirschboeck, 1991). Colder temperatures near the glacial margin could have affected the frequency of ice jams and increased the magnitude of subsequent outburst flooding. In fact, over the past ~75 years of record, nearly 75 percent of the largest 25 discharge events on the Susquehanna River occurred as snowmelt floods, rain on snow events, or ice jam related flooding. (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 increased flooding, caused by cold and unstable climatic conditions during the last glacial cycle, was capable of instigating and maintaining the pulse of incision 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 high magnitude/low frequency flood events (Baker, 1974; Wohl, 1993; Wohl and others, 1994; Baker and Kale, 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 increased flooding as the first-order driver of incision during the late Pleistocene.

Effects of drainage basin glaciation: Our dating does not altogether discount the effects of drainage basin glaciation. Following the initial acceleration in incision rate ~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 River (Braun, 1988; Mix, 1992; 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, 2004; Reusser and others, 2004). The Potomac Basin lies >100 km south of the Wisconsinan glacial margin (fig. 1), suggesting that while climate-induced flooding during the last glacial cycle appears to have been the first-order driver of incision for both rivers, glaciation and increased meltwater and/or sediment discharge during deglaciation within the Susquehanna Basin were also capable of affecting rates of bedrock incision.

IMPLICATIONS

Prolonged bedrock incision of the lower Susquehanna River commenced in the middle Miocene (15–20 My) (Pazzaglia and Gardner, 1994a, 1994b). Since that time, downstream reaches of the Susquehanna, and other rivers draining the Atlantic margin, have remained oversteepened, despite ongoing incision into bedrock that has generated 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 fall resulting from slow isostatic compensation to erosion, flexural upwarping of the Appalachian Piedmont caused by offshore deposition (Pazzaglia and Gardner, 1994a), and protracted eustatic sea-level fall beginning in the middle Miocene (Haq and others, 1987; Pazzaglia and others, 1998).

The persistence of steep river gradients along the lower reaches of the Susquehanna primes the river for incision by increasing stream power needed to remove rock. Short-term, late Pleistocene incision rates derived from ^{10}Be exposure ages are more than an order of magnitude faster than estimated long-term rates of downcutting. 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 compel these rivers to cut rapidly into bedrock.

Extensive cosmogenic dating has constrained the timing and rate of bedrock incision along the largest river draining the U.S. Atlantic passive margin. While dates alone can not explain fully why, or by what processes, this incision occurred, they offer compelling evidence that episodes of bedrock incision are tied to glacial cycles and trends in global climate. These findings and the method we employ are not limited to the Susquehanna River, or to passive margins in general, but provide valuable insights into the nature of bedrock channel incision across a wide range of settings around the globe. Comprehending when, where, and why rivers incise has important implications for the connectivity of terrains and the evolution of landscapes.

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