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).

Water Inundation Modeling:

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).

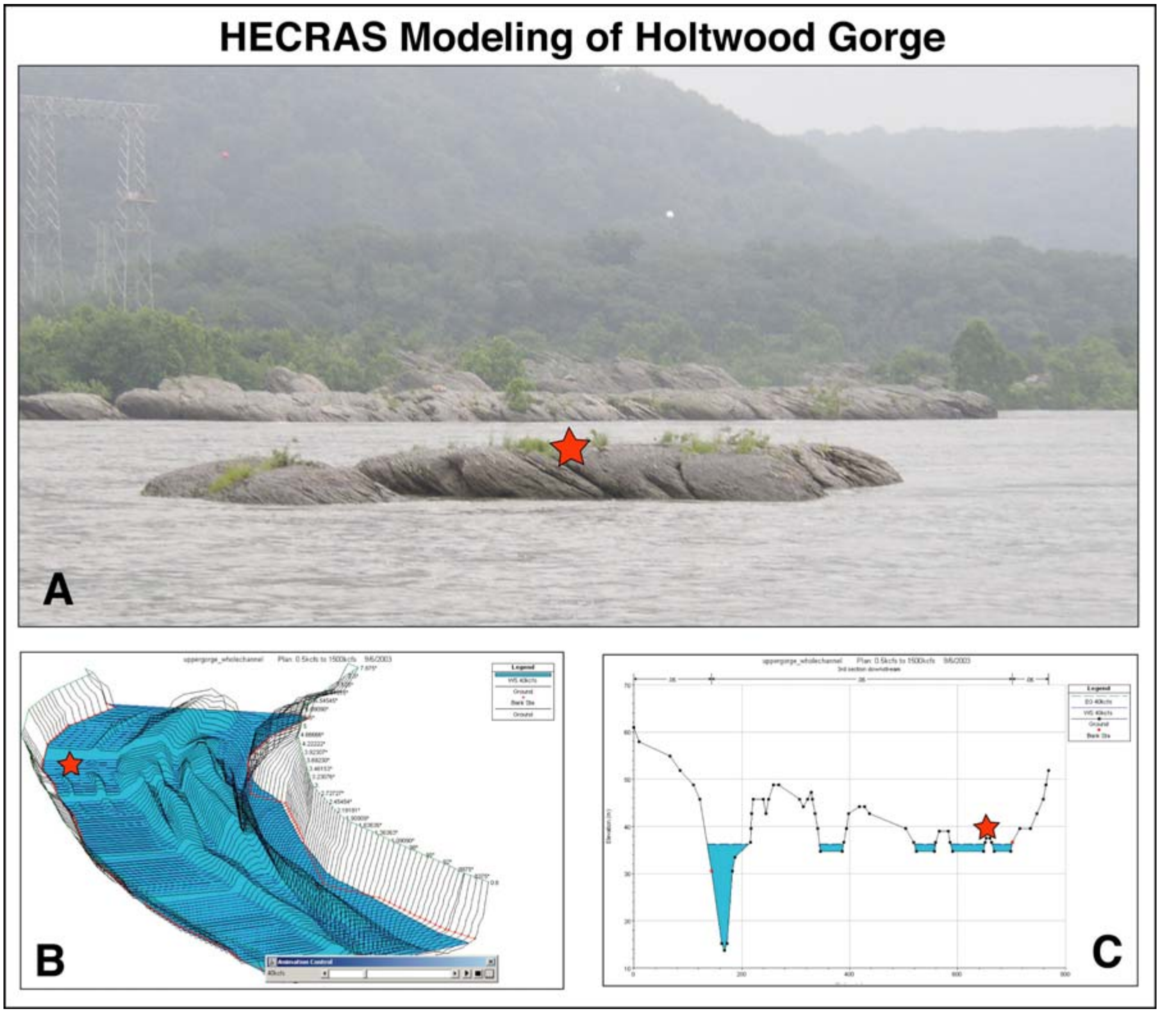

Figure S1: Example of a calibration photo used to constrain water depths for the HECRAS model within Holtwood Gorge at known discharges. Photo (**A**) was taken from the western shore of the Susquehanna River in the upper gorge at a discharge of ~40 kcfs. River flow is from left to right (NW to SE). 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 S1: 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 S2: 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.

References Cited in Supporting Online Material:

S1. E. Zen, *Open File Report* **97-60** (U. S. Geological Suvey, Reston, VA, 1997).
S2. P. Bierman, M. Caffee, *Am. J. of Sci.* **301**, 326 (2001).
S3. C. Lal, *Earth Surface Processes and Landforms* **104**, 424 (1991).
S4. A. Dunne, C. Elmore, P. Muzikar, *Geomorphology* **27**, 3 (1999)