14. D. Tanner, P. G. Andersson, L. Tedenborg, P. Somfai, *Tetrahedron* **50**, 9135 (1994).

15. D. Tanner, L. Tedenborg, P. Somfai, *Acta Chem. Scand. A* **51**, 1217 (1997).

16. T. E. Nielsen, D. Tanner, *J. Org. Chem.* **67**, 6366 (2002).

17. D. R. Williams, G. S. Cortez, *Tetrahedron Lett.* **39**, 2675 (1998).

18. D. R. Williams, T. A. Brugel, *Org. Lett.* **2**, 1023 (2000).

19. S. Ghosh, F. Rivas, D. Fischer, M. A. González, E. A. Theodorakis, *Org. Lett.* **6**, 941 (2004).

20. G. Hirai, H. Oguri, M. Hirama, *Chem. Lett.* **28**, 141 (1999).

21. S. M. Moharram, G. Hirai, K. Koyama, H. Oguri, M. Hirama, *Tetrahedron Lett.* **41**, 6669 (2000).

22. G. Hirai, H. Oguri, S. M. Moharram, K. Koyama, M. Hirama, *Tetrahedron Lett.* **42**, 5783 (2001).

23. G. Hirai, Y. Koizumi, S. M. Moharram, H. Oguri, M. Hirama, *Org. Lett.* **4**, 1627 (2002).

24. N. Hikage, H. Furukawa, K. Takao, S. Kobayashi, *Tetrahedron Lett.* **39**, 6237 (1998).

25. N. Hikage, H. Furukawa, K. Takao, S. Kobayashi, *Tetrahedron Lett.* **39**, 6241 (1998).

26. N. Hikage, H. Furukawa, K. Takao, S. Kobayashi, *Chem. Pharm. Bull. (Tokyo)* **48**, 1370 (2000).

27. M. Sakai, M. Sasaki, K. Tanino, M. Miyashita, *Tetrahedron Lett.* **43**, 1705 (2002).

28. S. Mutti, C. Daubié, F. Decalogne, R. Fournier, P. Rossi, *Tetrahedron Lett.* **37**, 3125 (1996).

29. E. Nakamura, S. Matsuzawa, Y. Horiguchi, I. Kuwajima, *Tetrahedron Lett.* **27**, 4029 (1986).

30. I. Ojima, T. Kogure, *Organometallics* **1**, 1390 (1982).

31. S. Katsumura, K. Hori, S. Fujiwara, S. Isoe, *Tetrahedron Lett.* **38**, 4625 (1985).

32. T. Ooi, H. Sugimoto, K. Maruoka, *Heterocycles* **54**, 593 (2001).

33. B. M. Trost, Y. Masuyama, *Tetrahedron Lett.* **25**, 173 (1984).

34. The use of deuterium isotope effects in natural product synthesis. See (*39–41*).

35. H. Lebel, E. N. Jacobsen, *Tetrahedron Lett.* **40**, 7303 (1999).

36. Y. Ito, T. Hirao, T. Saegusa, *J. Org. Chem.* **43**, 1011 (1978).

37. Selected physical data, ¹H-NMR and ¹³C-NMR spectra, mass spectra, and CD spectra are provided as supporting material on *Science* Online.

38. The optical rotation of natural norzoanthamine showed [α]²⁴_D −6.2 (*c* 0.23, CHCl₃), contrary to the reported value [α]_D +1.6 (*c* 0.42, CHCl₃) (*1*, *3*).

39. D. L. J. Clive, M. Cantin, A. Khodabocus, X. Kong, Y. Tao, *Tetrahedron* **49**, 7917 (1993).

40. D. L. J. Clive *et al.*, *J. Am. Chem. Soc.* **116**, 11275 (1994).

41. E. Vedejs, J. Little, *J. Am. Chem. Soc.* **124**, 748 (2002).

42. We are grateful to D. Uemura for providing us with natural norzoanthamine. Financial support from the Ministry of Education, Culture, Sports, Science, and Technology, Japan [a Grant-in-Aid for Scientific Research (A) (No. 12304042) and a Grant-in-Aid for Scientific Research on Priority Areas (A) "Exploitation of Multi-Element Cyclic Molecules" (No. 13029003)] is gratefully acknowledged.

Rapid Late Pleistocene Incision of Atlantic Passive-Margin River Gorges

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The direct and secondary effects of rapidly changing climate caused large rivers draining the Atlantic passive margin to incise quickly into bedrock beginning about 35,000 years ago. Measured in samples from bedrock fluvial terraces, 10-beryllium shows that both the Susquehanna and Potomac Rivers incised 10- to 20-meter-deep gorges along steep, convex lower reaches during the last glacial cycle. This short-lived pulse of unusually rapid downcutting ended by 13,000 to 14,000 years ago. The timing and rate of downcutting are similar on the glaciated Susquehanna and unglaciated Potomac Rivers, indicating that regional changes, not simply glacial meltwater, initiated incision.

A fundamental control on the development of landscapes is the rate at which rivers cut through rock. River incision into bedrock translates the effects of climate and tectonics through drainage networks, thus controlling rates of landscape evolution (*1*, *2*). Despite broad interest in understanding the style and timing of landscape change, only a handful of studies have directly measured the rate and timing of fluvial bedrock incision. Most of these studies quantifying bedrock incision rates have been conducted in tectonically active regions (*3–5*); however, the majority of Earth's surface is tectonically quiescent, including passive margins around the globe for which river incision rates are largely unknown. In this report, we used 59 measurements of cosmogenic ¹⁰Be (tables S1 and S2) to quantify the rate and timing of bedrock incision along two of the largest rivers draining the Atlantic passive margin, the Susquehanna (70,200 km²) and the Potomac (29,900 km²) (Fig. 1).

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

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

Similarly, the Potomac River lies more than 100 m below the uplands within a broad outer valley. The river drops nearly 20 m as it passes over Great Falls and through 3-km-long Mather Gorge. The gorge is 75 to 125 m wide (*11*) and confined by a 1-km-wide bedrock terrace (Fig. 2B). This terrace is studded with fluvially rounded outcrops standing decimeters to meters above the bedrock surface. The Potomac Basin remained glacier-free during the Pleistocene (*10*).

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

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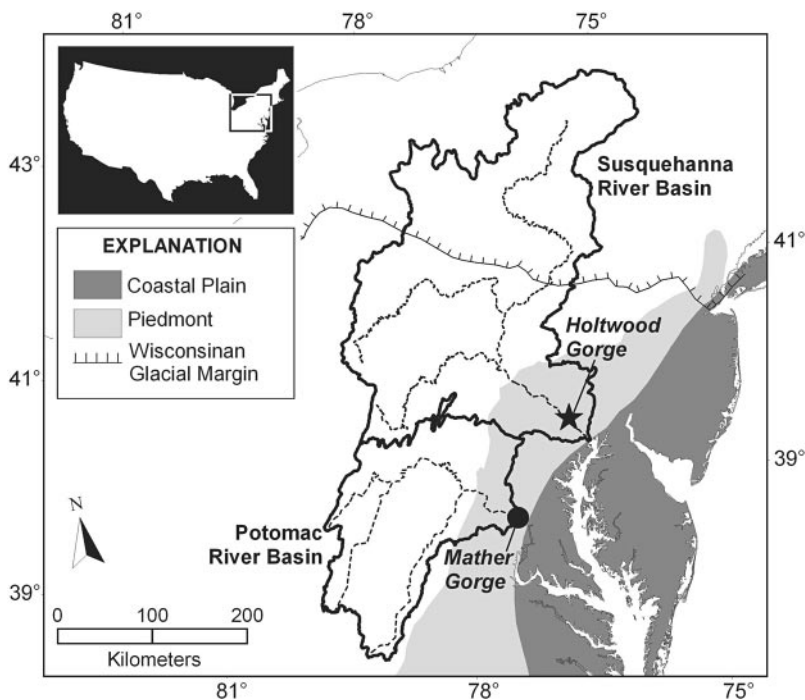*To whom correspondence should be addressed. E-mail: lreusser@uvm.edu

Fig. 1. Map of the Atlantic passive margin and the Susquehanna and Potomac River Basins. Both Holtwood Gorge (black star) and Mather Gorge (black circle) lie near the Appalachian Piedmont/Coastal Plain transition. During the last glacial maximum, ice covered ~40% of the Susquehanna Basin; the Potomac Basin remained free of glacial ice (*10*).

Fig. 2. Bedrock terraces within Holtwood and Mather Gorges, and longitudinal profiles of the lower Susquehanna and Potomac Rivers. (**A**) Terrace levels 1 and 3 in the middle of Holtwood Gorge along the Susquehanna River at low-flow conditions. Level 2 is not preserved at this location. At higher discharges, lower strath is inundated. A person is included in foreground for scale. (**B**) View across Mather Gorge along the Potomac River at high flow (1700 m³/s). Well-defined strath terrace treads on both banks. Scale bar, 2 m. (**C**) Long profile of the lower Susquehanna River (*6*) showing the location of Holtwood Gorge. (**D**) Long profile of the lower Potomac River (*6*) showing the location of Great Falls and Mather Gorge. m asl, meters above sea level.

Rates of downcutting on both rivers markedly increased after 35 thousand years ago (ka), as evidenced by abandonment and exposure of prominent bedrock terraces defining the gorges on both the Susquehanna and Potomac Rivers at 30 ± 6.9 ka ($\pm$SD, $n = 10$) and 33 ± 5.4 ka ($n = 8$), respectively (Fig. 3, A and B). Four samples collected along an elevation transect in the middle of Holtwood Gorge indicate that from >100 to 32 ka, the Susquehanna River incised at <0.2 m/ky. From 32 to 16 ka, the rate of downcutting more than doubled to ~0.5 m/ky, closely matching a rate of ~0.6 m/ky ($r^2 = 0.94$; 31 to 15 ka) calculated with 14 samples along a cross section in the upper Holtwood Gorge (Fig. 4A). The mean exposure age of the lowest terrace suggests that rapid incision ceased on the Susquehanna by 14 ka (Fig. 3A).

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

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

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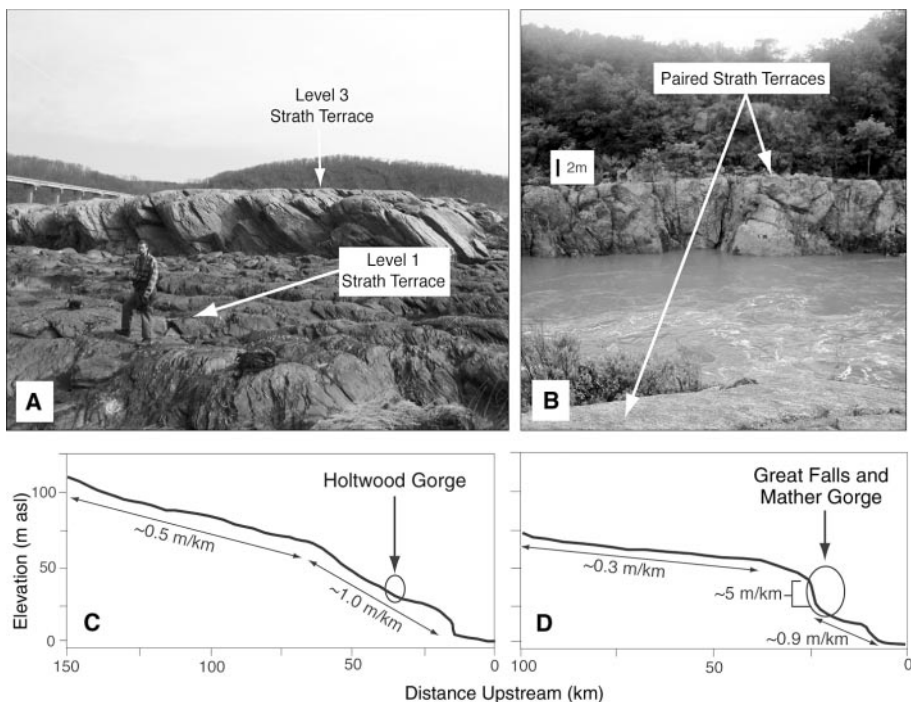
curred at about 32 ka (*17–20*), coincident with initiation of rapid incision along both rivers. If this final sea-level drop was the proximal cause of rapid late Pleistocene gorge incision, then the effect must have translated instantaneously across the already-drained continental shelf and through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

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

Because most bedrock erosion occurs during floods (*24, 25*), increases in flood magnitude and/or frequency could have driven late Pleistocene incision. Although there are no paleodischarge records for these rivers, other data can be used to infer changes in flood frequency and magnitude over time. Good correlation between the Greenland storminess record (Fig. 3D) (*26*) and that of northeastern North America over the past 13,000 years (*27*) suggests that the Greenland record is a reasonable proxy for geomorphically effective flood events on the Susquehanna and Potomac Rivers. In addition, cooling climate during the last glacial period, as inferred from the Greenland Ice Sheet Project 2 (GISP2) ice core record (Fig. 3E) (*28–31*), probably changed runoff dynamics within both basins, increasing the number, severity, and duration of snowmelt floods. Over the past ~75 years, such floods represent ~75 and ~65% of the largest 25 discharge events on the Susquehanna and Potomac Rivers, respectively (*32*). The GISP2 records of increased storminess and falling temperatures in the North Atlantic are coincident with the onset of rapid gorge incision ~33 ka. Furthermore, storminess rapidly decreased and temperatures climbed ~15 ka, coincident with the end of rapid incision on both rivers (Fig. 3).

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

Cosmogenic dating appears to implicate climate change as a driver of late Pleistocene passive-margin river incision into rock, yet modeling results suggest that sediment availability is also a critical variable controlling bedrock incision (*1, 34, 35*). Although we have no quantitative record of paleosediment load, there are discontinuous low gravel terraces along the Susquehanna River through Holtwood Gorge (*7*), suggesting a change in sediment dynamics dur-
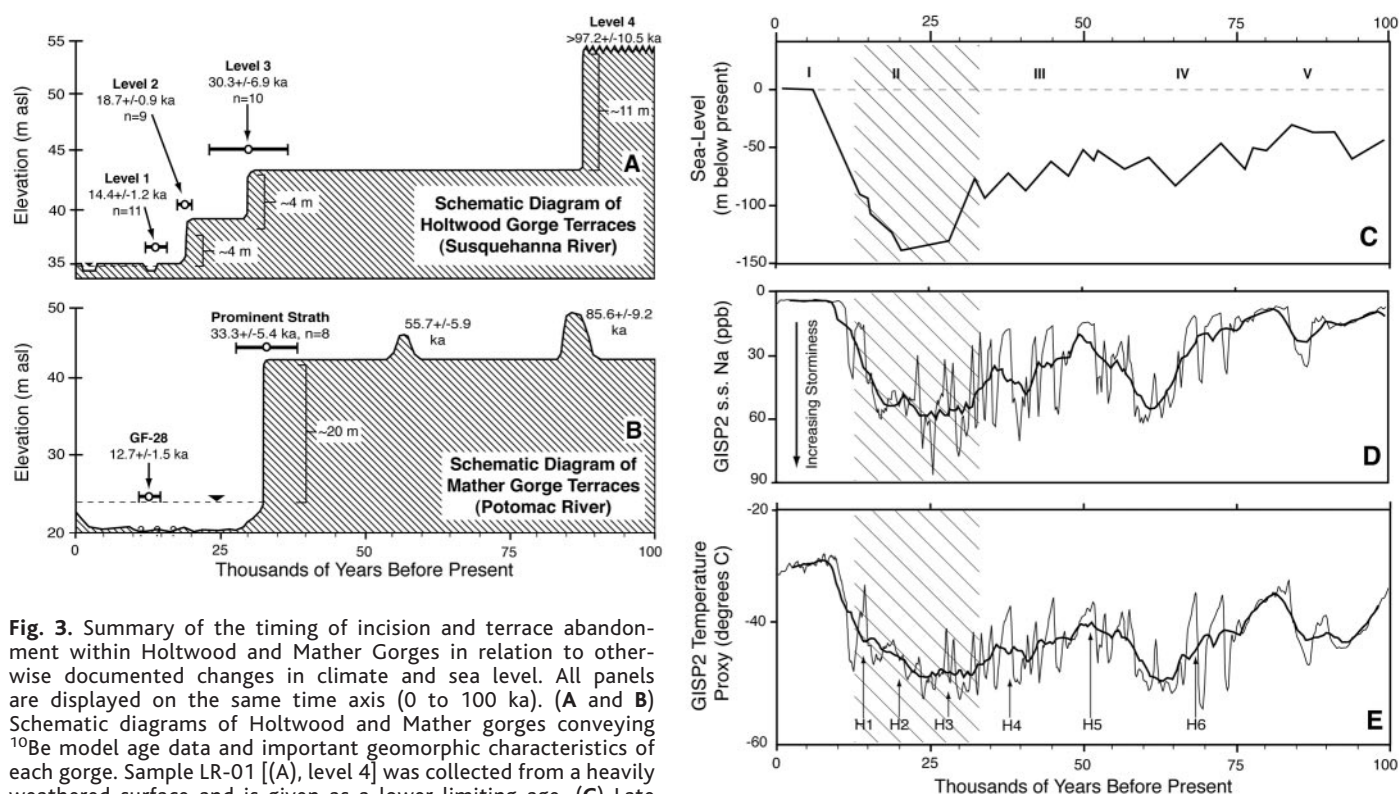

Fig. 3. Summary of the timing of incision and terrace abandonment within Holtwood and Mather Gorges in relation to otherwise documented changes in climate and sea level. All panels are displayed on the same time axis (0 to 100 ka). (**A** and **B**) Schematic diagrams of Holtwood and Mather gorges conveying [10]Be model age data and important geomorphic characteristics of each gorge. Sample LR-01 [(A), level 4] was collected from a heavily weathered surface and is given as a lower limiting age. (**C**) Late Pleistocene sea-level record derived from Huon Peninsula (*18*). Roman numerals are oxygen isotope stages. (**D**) GISP2 sea salt (s.s.) Na record (*26*) resampled to a 50-year interval with Analyseries (*36*), and smoothed with a 10-point (thin line) and 100-point moving window average (bold line). ppb, parts per billion. (**E**) Paleotemperature estimates inferred from the GISP2 ice core record (*28*), resampled to a 50-year interval with Analyseries and smoothed with 10-point (thin line) and 100-point moving window (bold line). Heinrich events (H1 through H6) are from dating of the Deep-Sea Drilling Project (DSDP) site 609 core (*37*). Hatched areas in (C), (D), and (E) show the episode of rapid incision we measured. m asl, meters above sea level.
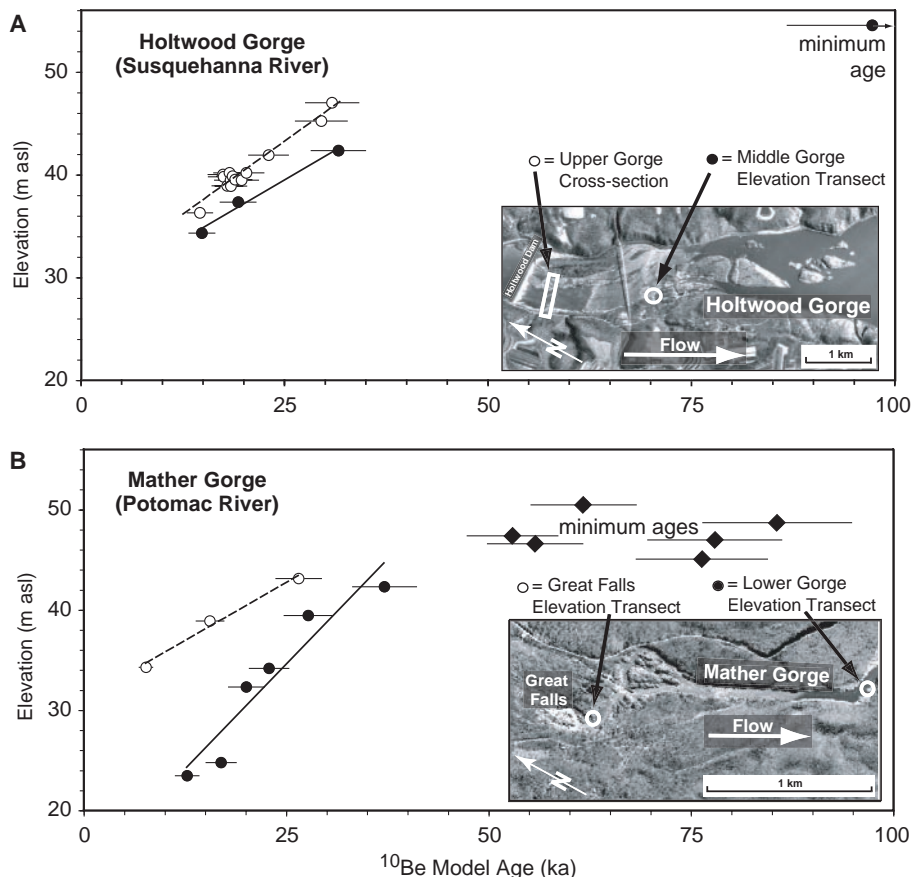
Fig. 4. Plots of incision rates at discrete locations or along cross sections within each gorge. The shift between upstream and downstream transects within both Holtwood (**A**) and Mather (**B**) Gorges is due largely to river gradients. Data points labeled as "minimum ages" are from weathered outcrops and thus provide lower limiting ages. (A) The minimum age sample was collected from a heavily eroded island peak standing >10 m above the prominent level 3 terrace. (B) The minimum age samples (black diamonds) were collected from bedrock knobs standing decimeters to meters above the prominent strath surface. White arrows indicate flow direction. Error bars indicate one standard deviation fully propagated age uncertainty. m asl, meters above sea level.

ing the Pleistocene. A change in the relationship between flow and sediment load could have removed bed armoring, allowing incision, or increased tool loading, promoting abrasion (*34, 35*). Rapid excavation of alluvial fills in response to falling sea level could have exposed broad straths previously blanketed with sediment, thus allowing the initiation of rapid incision.

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

clear when we better understand the complex interactions between land-level change, river hydraulics, sediment dynamics, and bedrock erosion.

References and Notes

1. K. Tinkler, E. Wohl, Eds., *Rivers over Rock: Fluvial Processes in Bedrock Channels* (Am. Geophys. Union, Washington, DC, 1998).
2. K. Whipple, G. Hancock, R. Anderson, *Geol. Soc. Am. Bull.* **112**, 490 (2000).
3. D. Burbank *et al.*, *Nature* **379**, 505 (1996).
4. J. Leland, M. Reid, D. Burbank, R. Finkel, M. Caffee, *Earth Planet. Sci. Lett.* **154**, 93 (1998).
5. K. Hartshorn, N. Hovius, W. B. Dade, R. Slingerland, *Science* **297**, 2036 (2002).
6. J. Reed Jr., *Geology* **9**, 445 (1981).
7. F. Pazzaglia, T. Gardner, *Geomorphology* **8**, 83 (1993).
8. E. Zen, *U.S. Geol. Survey Open-File Rep. 97–480* (1997).
9. D. Merritts, K. Vincent, E. Wohl, *J. Geophys. Res.* **99**, 14031 (1994).
10. D. Braun, in *U.S. Geol. Survey Open-File Report 94–434*, D. D. Braun, E. J. Ciolksz, J. D. Inners, J. B. Epstein, Eds. (1994), pp. 1–20.
11. E. Zen, *U.S. Geol. Survey Open-File Report 97–60* (1997).
12. Materials and methods are available as supporting material on *Science* Online.
13. We used the Hydrologic Engineering Centers River Analysis System (HEC-RAS) (www.hec.usace.army.mil) to estimate cosmic radiation absorbed by outcrop-covering floodwaters in Holtwood Gorge (Susquehanna River) through time (*12*) (fig. S1).
14. P. Bierman *et al.*, in *Beryllium: Mineralogy, Petrology, and Geochemistry, Reviews in Mineralogy*, E. Grew, Ed. (Mineralogical Society of America, Washington, DC, 2003), vol. 50, pp. 147–196.
15. D. Granger, J. Kirchner, R. Finkel, *Geology* **25**, 107 (1997).
16. J. Reed Jr., R. Sigafoos, G. W. Fisher, *The River and the Rocks; the Geologic Story of Great Falls and the Potomac River Gorge* (U.S. Geol. Survey, Reston, VA, 1980), p. 75.
17. N. Shackleton, *Quat. Sci. Rev.* **6**, 183 (1987).
18. K. Lambeck, J. Chappell, *Science* **292**, 679 (2001).
19. Uncertainties on the order of 10% for dating of sea-level changes and [10]Be age modeling, production rates, and exposure history (*20*) preclude confident assertion of whether sea level dropped before or after incision rates increased.
20. D. Clark, P. Bierman, P. Larsen, *Quat. Res.* **44**, 367 (1995).
21. J. Pelletier, personal communication.
22. B. Douglas, R. Peltier, *Phys. Today* **March**, 35 (2002).
23. I. Winograd, *Quat. Res.* **56**, 299 (2001).
24. N. Snyder, K. Whipple, G. Tucker, D. Merritts, *J. Geophys. Res.* **108**, 2117, 10.1029/2001JB001655 (2003).
25. G. Tucker, *Earth Surface Processes and Landforms* **29**, 185 (2004).
26. P. Mayewski *et al.*, *J. Geophys. Res.* **102**, 26345 (1997).
27. A. Noren, P. Bierman, E. Steig, A. Lini, J. Southon, *Nature* **419**, 821 (2002).
28. K. Cuffey, G. Clow, *J. Geophys. Res.* **102**, 26383 (1997).
29. Oscillations in pollen spectra from Florida and the Southern Appalachians (*30, 31*) correlate well with GISP2 paleotemperatures, indicating that high-latitude temperature changes translated to the Susquehanna and Potomac Basins.
30. E. Grimm, G. Jacobson, A. Dieffenbacher-Krall, H. Almquist, abstract 45-8 presented at the *XVI INQUA Congress*, Reno, NV, 23 to 31 July 2003.
31. R. Litwin, B. Morgan, L. S. Eaton, paper presented at the *NE/SE Geol. Soc. Am. Regional Meeting Abstracts with Programs*, Tyson's Corner, VA, 25 to 27 March 2004.
32. We downloaded daily discharge records from http://waterdata.usgs.gov/nwis/rt. For the Susquehanna River, we used flow data from October, 1931 to present recorded at the Marietta, PA, gauging station (USGS 01576000). For the Potomac River, we used flow data from March, 1930 to present recorded at the Little Falls Pump Station, MD (USGS 01646500).
33. D. Braun, in *53rd Annual Field Conference of Pennsylvania Geologists*, J. Inners, Ed. (PA Geol. Survey, Harrisburg, PA, 1988), pp. 3–25.
34. L. Sklar, W. Dietrich, *Geology* **29**, 1087 (2001).
35. G. Hancock, R. Anderson, *Geol. Soc. Am. Bull.* **114**, 1131 (2002).
36. Analyseries is available at http://www1.ncdc.noaa.gov/pub/data/paleo/softlib/analyseries.
37. G. Bond *et al.*, *Nature* **360**, 245 (1992).
38. Funded by NSF grant EAR0003447 (P.R.B.) and Department of Energy contract no. W-7405-Eng-48 under the auspices of the Laboratory Directed Research and Development (LDRD). R. Alley, I. Winograd, F. Pazzaglia, H. Markewich, K. Whipple, A. Noren, and three anonymous referees reviewed the manuscript. E. Butler provided field assistance.