6. The Incision History of a Passive Margin River, the Potomac Near Great Falls

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Introduction

This field trip focuses on the emerging significance of complex geomorphic processes that have operated in a passive margin setting in the mid-Atlantic region (fig. 1A). The application of cosmogenic exposure dating to understanding the responses of rivers to Quaternary tectonic, eustatic, and climatic variations is providing unprecedented information about landscape histories. This trip presents new information about the response of the Potomac River to regional variability in sea level and climate over the late Pleistocene and Holocene. We present a regional framework, field observations of the morphology of the Potomac River gorge below Great Falls (fig. 1B), and data on the age relations of strath terraces associated with the Potomac River gorge.

Acknowledgments

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Regional Framework: The Complexity of Passive Margin Settings

Passive margins, the trailing edges of continental plates, are geomorphically complex. Despite the absence of active tectonics, passive margins exhibit features such as great escarpments (Matmon and others, 2002; Bank and others, 2001), river gorges, and marine terraces (Flint, 1940; Cooke, 1952). New analytical techniques, such as fission track thermochronology (Naeser and others, 2001) and cosmogenic isotope exposure dating (Bierman and others, 2002) are providing insights into the processes that control passive margin evolution. Passive margins exhibit both stable and active features. Recent analyses of great escarpments (Matmon and others, 2002) provide evidence that "…the locations of great escarpments bordering passive margins are exceptionally stable and are probably determined by crustal structure." By contrast, this trip will focus on active rock erosion in the Potomac River gorge, particularly the formation processes and ages of strath terraces and knickpoints. Fluvially eroded straths and knickpoints provide direct evidence for river channel adjustments to climate, discharge, and crustal motion. They form one set of datable surfaces that will help unravel the complexities of passive margins.

Geologic Setting

The geomorphology of the Potomac River valley as it enters the Coastal Plain is a complex series of terraces and channels. The terrace morphology between Great Falls and the Coastal Plain is distinct and mappable, but the age is not well understood. Investigations of bedrock strath terraces (Zen, 1997a,b; Bierman and others, 2002) and fill terraces show that there has been significant modification of the

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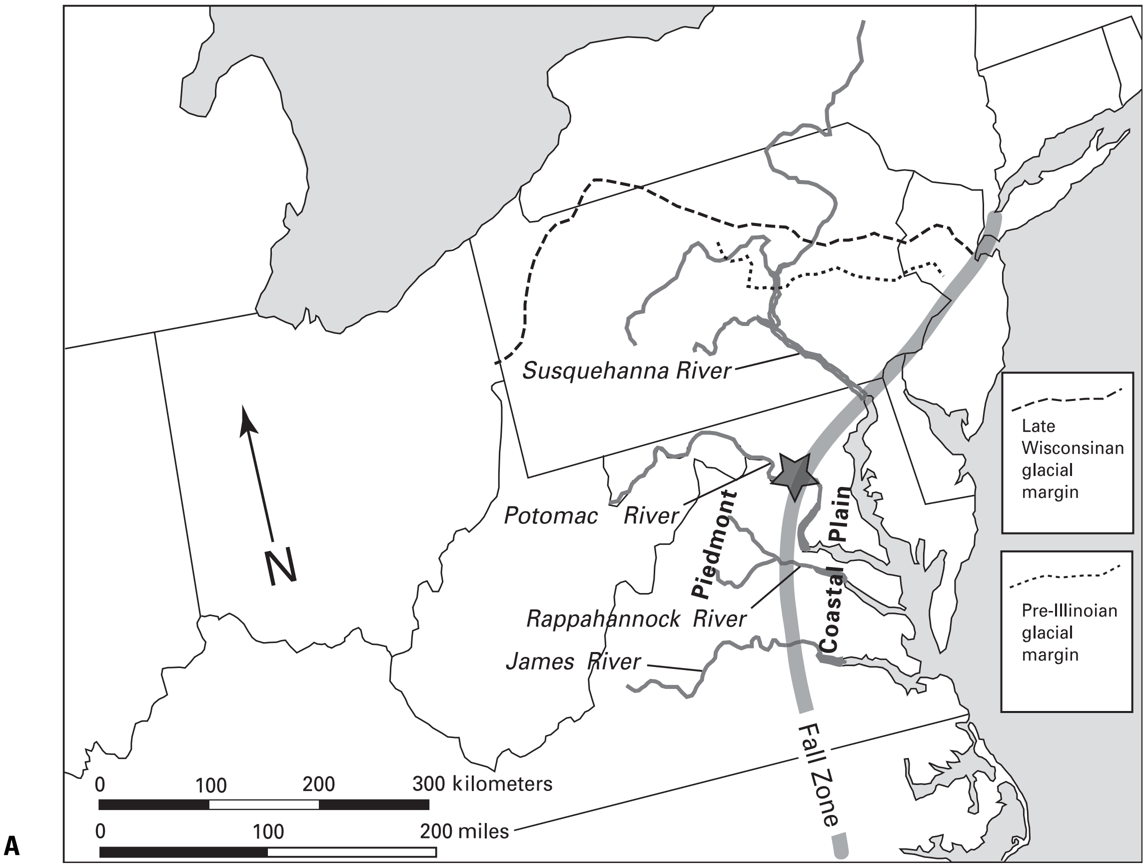
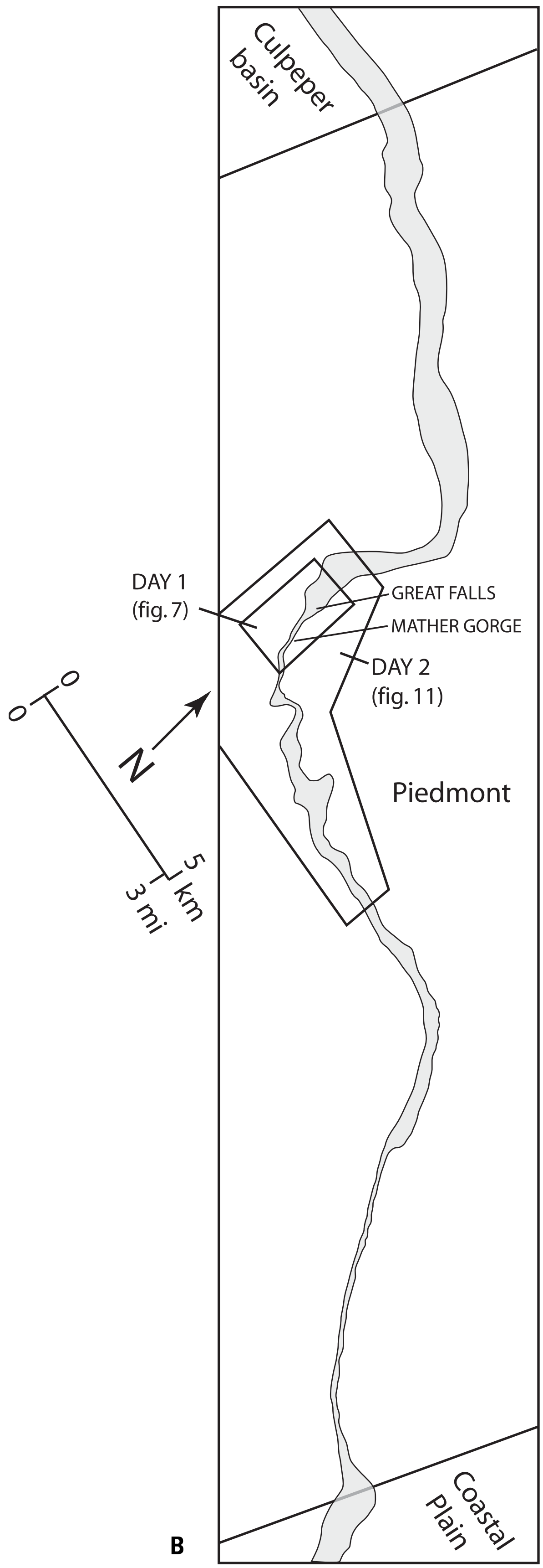


Figure 1. A, Index map of the Eastern United States showing the location of the field trip (star) near Great Falls of the Potomac River. Regional features include the Fall Zone, separating the Piedmont and Coastal Plain provinces, and the Pleistocene glacial borders north of the Potomac River drainage basin. B (facing page), Location map of the Potomac River in the vicinity of Great Falls, showing the areas to be visited on Days 1 and 2 of this field trip.

Potomac River valley and tributaries to the Potomac over the past half-million years. The stratigraphy of upland sedimentary deposits on the Piedmont (Fleming and others, 1994) indicates that the Potomac River has incised into a Miocene-to-Pliocene landscape of fluvial to nearshore marine deposits. The ages assigned to upland gravel deposits (Fleming and others, 1994) are based on correlation with downdip Coastal Plain units. There is no direct dating of fluvial gravels that underlie the highest elevations, but Tertiary ages are consistent with rates of topographic inversion resulting from bedrock weathering, saprolite formation, and soil erosion (Pavich and others, 1985). The fluvial incision and topographic inversion relative to upland gravels is attributed primarily to eustatic sea-level drop since the Miocene.

There is direct evidence along the Atlantic Coast for higher than present sea level in the late Tertiary to the last interglacial period (MIS 5). The basal elevations of fluvial gravels and sands adjacent to the Potomac River suggest significant downcutting of the river since late Tertiary time, perhaps over the last 5 Ma. A series of fill terraces can be mapped below the highest level at Tysons Corner, Va. (fig. 2). The fluvial gravel deposit at Tysons Corner is possibly older than 5 Ma based on identification of late Tertiary-age fossils (A.J. Froelich, USGS, oral commun., 1980). These gravels may be age-equivalent to the Bryn Mawr Gravels mapped by Pazzaglia (1993) in the upper Chesapeake Bay area.

There are many fluvial features that invite more detailed analysis and explanation. Prominent features include the bedrock channel and strath terraces of the Potomac River near Great Falls. Lacking tectonic forcing, except for possible forebulge uplift (Douglas and Peltier, 2002), it is likely that climatic and sea-level variations have played major roles in the modification of this landscape during the late Quaternary. There are no numerical age measurements for the upland sedimentary units, but new age data for the Potomac River bedrock strath terraces (Bierman and others, 2002) are presented here. One of the major observations from the new data is that rates of bedrock gorge cutting can be very rapid; the fluvial incision relative to remnant fluvial gravel deposits may have occupied a small fraction of the total time since the Miocene (~5 Ma). This highlights the need for improved age-control on the youngest of the sedimentary units in order to understand the dynamics of transgressive deposition and regressive erosion during eustatic cycles.



B

Day 1

The Potomac River Gorge Below Great Falls: Field Observations and Inferred Processes of Excavation

Introduction

The Potomac River flows across the Piedmont physiographic province between Blockhouse Point, Maryland (opposite the Fairfax-Loudoun County boundary), and tidewater at Georgetown, Washington, D.C., a distance of about 35 river kilometers. About one-third of the way across the Piedmont, the river makes a sudden drop of about 50 ft (feet) (15 m (meters)) in a distance of 500 ft (150 m), through a series of cascades collectively called the Great Falls of the Potomac, and enters Mather Gorge. This gorge, excavated out of thoroughly fractured Neoproterozoic and Early Cambrian metamorphic rocks, consists of several rectilinear segments. The gorge extends for about 3 km (kilometers) (1.9 miles (mi)), then makes a sharp turn to the left below a rock promontory in which Black Pond is nestled. Beyond the nearby Sherwin Island, the valley opens up somewhat. Remnants of bedrock straths (in other words, abandoned channels) are recognized all the way to tidewater (Zen, 1997a; Southworth and others, 2000). The gorge is as narrow as 30 m (100 ft) at its entrance; the most scenic part, between the entrance and Sandy Landing, is 70 m (230 ft) wide and as much as 30 m (100 ft) deep to water level.

At low flow, Great Falls consists of three channels: Maryland Falls, The Streamers, and The Spout (fig. 3). Each channel has 10- to 15-ft (3–5 m)-high cataracts separated by pool reaches. Maryland Falls and The Streamers have three cataracts each, and The Spout has four. The Great Falls Water Intake Dam is located between 0.6 and 1 mi (1 and 1.6 km) above the Falls, and provides engineering data on the 3,300-ft (1-km)-wide channel. The dam has a recorded elevation of 150.5 ft (45.9 m) above sea level (asl). As its height varies between 6 ft (2 m) near the ends and a maximum of 10 ft (3 m) (Hahn, 1992, p. 46), the channel is flat to 1.5 parts per thousand except for some protruding rock islands. Below Great Falls, the remnants of this channel form a strath that is readily traceable to Plummers Island just inside the Capital Beltway American Legion Bridge, 5.6 mi (9 km) downstream, and it might exist all the way to Key Bridge at the original Fall Line at tidewater (Zen, 1997a).

Below the Water Intake Dam, the modern river has four knickpoints: Great Falls (top, ~140 ft (43 m) above sea level), Yellow Falls (top, ~ 68 ft (21 m) above sea level), Stubblefield Falls (top, ~ 57 ft (17 m) above sea level), and

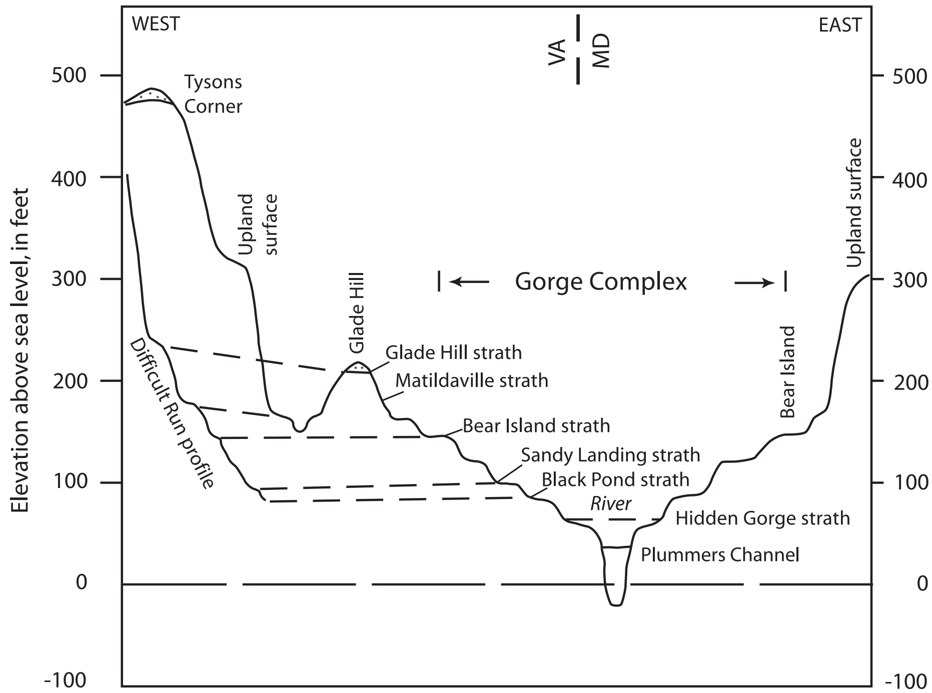


Figure 2. Synoptic and schematic cross section of the nested straths (Zen, 1997a). Elevations are appropriate for the entrance to Mather Gorge. Also shown are the upland surface and the Miocene-Pliocene fluvial deposit sequence found at Tysons Corner. Elevations of features are approximate. The profile of Difficult Run, a tributary entering the river near the end of Mather Gorge, is schematic except for the elevations of the knickpoints; these have been adjusted for the effect of longitudinal declinations of the straths. Horizontal distance not to scale.

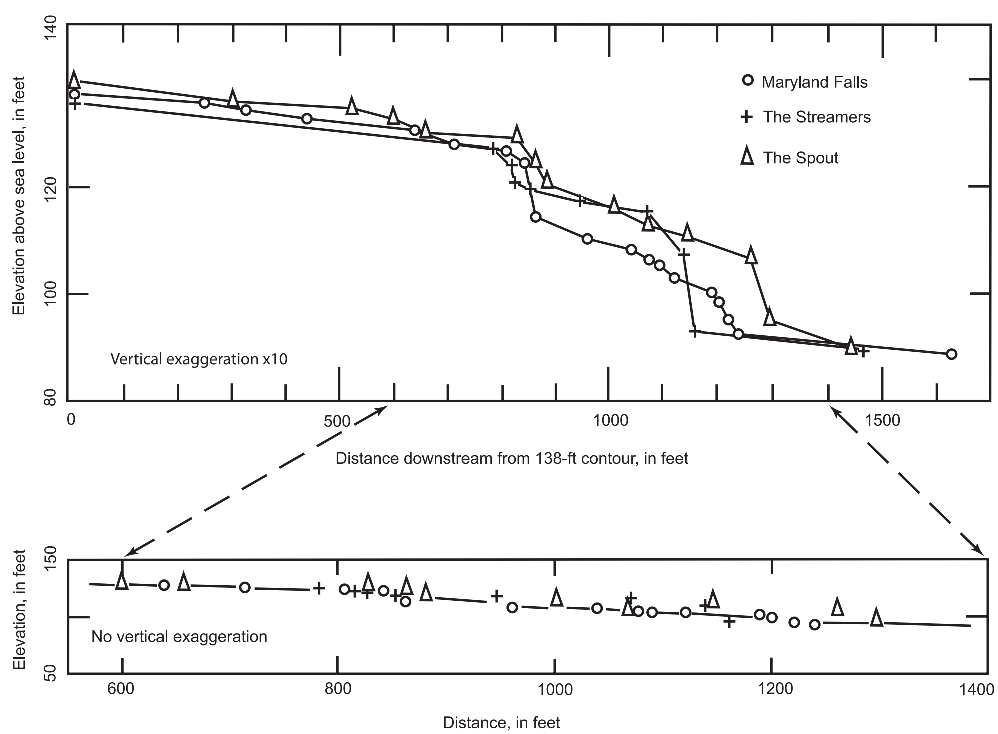


Figure 3. Longitudinal profile of Potomac River water surface at Great Falls (Zen, 1997a). From east to west, the three strands are Maryland Falls, The Streamers, and The spout. Upper profile, vertical exaggeration 10x. Lower profile, expanded view of the main drop, no vertical exaggeration.

Little Falls (top, ~ 40 ft (12 m) above sea level). Tidewater is the lowest base-level. The bedrock gradient between Blockhouse Point and the Water Intake Dam is 0.07 percent (Zen, 1997b); within the gorge complex and between knick-points it is typically about 0.06 percent. I have used this “default” gradient to reconstruct the paleochannels.

As the bounding knickpoints retreat, a given channel reach is constantly being eroded at the lower terminus but also extended by erosion at the higher terminus (fig. 4). The record of a strath, thus, is diachronous; it is, in general, younger at its upper end, and the contiguous straths are nested within one another.

Between Great Falls and Sherwin Island, the gorge system contains many channels at different levels. Several, including one that separates Olmsted Island from the mainland (the “fishladder channel”) by-pass Great Falls, have their own cascades, and are active today. Some others become active only during floods; yet others serve no modern river function even during the highest recorded flood levels.

Straths of the Potomac Gorge

Evidence for straths of the Potomac River gorge complex (Zen, 1997a) includes three large data sets: (1) “concordant summits,” which are surfaces of former channel floors; (2) “rock benches,” which are similar features preserved as erosional remnants of limited areal extent, mostly on sides of younger straths; (3) “channels and ponds” incised into earlier straths and their associated scour ponds (the outlet sill levels are recorded); and two small data sets: (4) the levels of aligned lateral potholes (Zen and Prestegaard, 1994); and (5) outlet sills of plunge pools. All these recorded features show evidence of wear by running water (for example, flutes, sculptured *p*-forms, and potholes); fig. 5A plots stratth elevations against measured river distances.

Using a default gradient of 0.06 percent to connect the datapoints and to guide the reconstruction of the other straths (fig. 5B), seven tiered straths are recognized within the Potomac River gorge complex. For ease of reference, these straths are here informally given geographic names (highest/oldest first); the elevations shown are the actual or projected elevations asl at or near the entrance to Mather Gorge.

1. Glade Hill level:	200 ft (61 m)
2. Matildaville level:	155 ft (47 m)
3. Bear Island level:	140 ft (43 m)
4. Sandy Landing level:	115 ft (35 m)
5. Black Pond level:	95 ft (29 m)
6. Hidden Gorge level:	77 ft (23 m)
7. Plummers Channel level:	53 ft (16 m) (observed, not projected).

As Mather Gorge is incised into what is the modern river channel above Great Falls, the level of that channel becomes the Bear Island strath below Great Falls, dry except during decadal floods. This strath forms much of Great Falls Park in

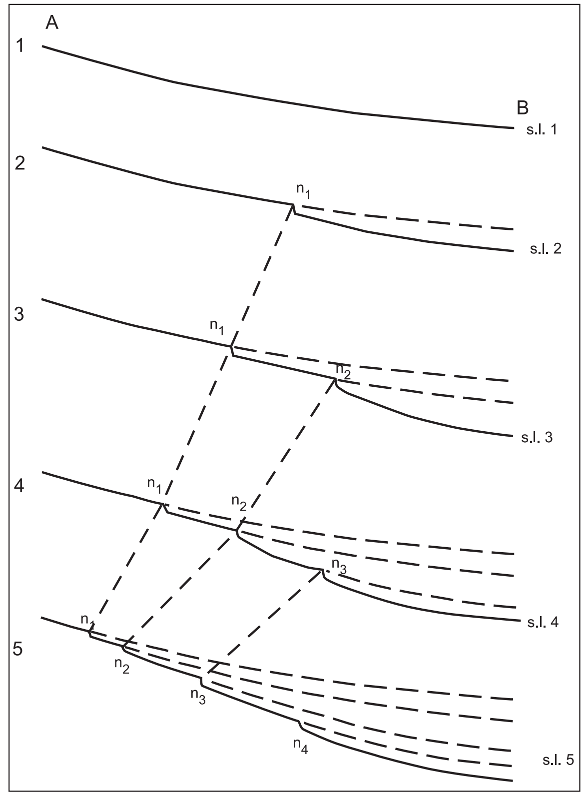


Figure 4. Schematic interpretation of formation of straths through retreat of knickpoints. The knickpoints between points A and B, designated n_1, n_2, and so forth, move upstream with the passage of time, indicated by 1, 2, and so forth, in response to successive drops in sea level (s.l. 1, s.l. 2, and so forth). As a result, the younger and lower straths become entrenched within the older straths.

Virginia, as well as the high points of Olmsted Island, Rocky Island, Bear Island, and Sherwin Island in the Chesapeake and Ohio Canal National Historical Park in Maryland. A diagrammatic cross section of the nested straths is shown in figure 2. Added here are the upland surface at about 350 ft (107 m) asl and the presumed Miocene-Pliocene fluvial deposit at 450 ft (137 m) asl at Tysons Corner, Va., interpreted as the oldest record of the paleo-Potomac River (Zen, 1997b).

The best record of the highest strath, the Glade Hill (fig. 6), is a fluvial boulder bed resting directly on unweathered schist on the flat top of Glade Hill at 200 ft (61 m) asl (Stop 1). The well-rounded boulders are varieties of quartzite. The nearest source of similar quartzite is the west limb of the Blue Ridge anticlinorium (Nickelsen, 1956; Southworth and Brezinski, 1996) at Harpers Ferry, W. Va. Geomorphic features, mostly knickpoints on entrenched tributaries, allowed extension of this level between Glade Hill and Harpers Ferry (Zen, 1997b).

The next lower strath, Matildaville (fig. 6), forms a rock bench near the ruins of that hamlet in Great Falls Park (Stop 4). This strath can be traced as far as the Water Intake Dam as waterworn summits of rock islands rising above the Bear

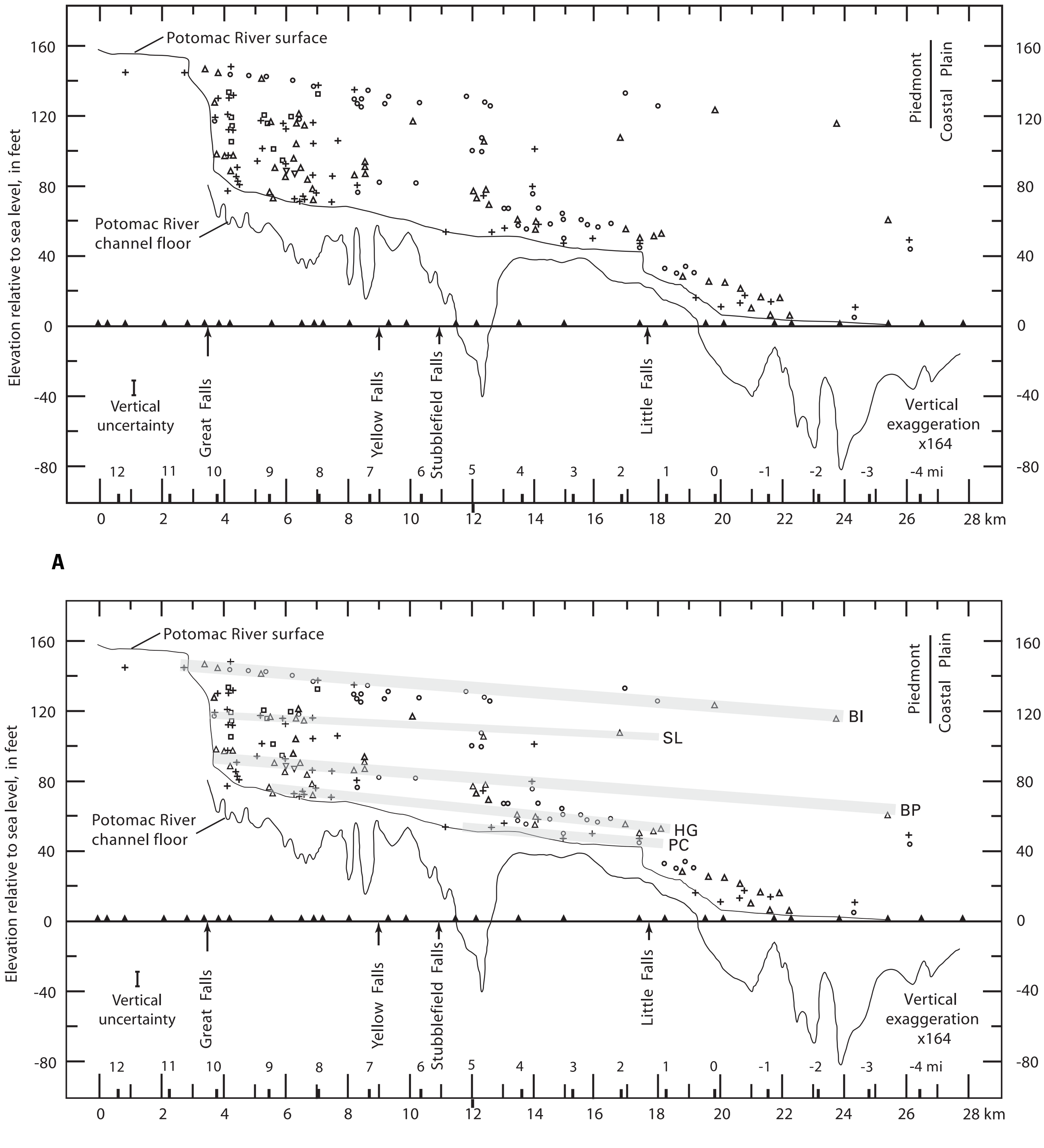


Figure 5. Composite record of strath elevations along the Potomac River gorge complex, Great Falls to tidewater. Kilometer scale is measured from Gladys Island. Miles scale is measured from Chain Bridge, as originally used by Reed and others (1980). Vertical uncertainty refers to the uncertainty in location of individual outcrops during mapping. A, Data: circles, rock summits; crosses, channels and scour ponds; up-pointing triangles, rock benches; down-pointing triangles, outlets of plunge pools; squares, lateral potholes. Profile of channel floor based on sounding by J.C. Reed, Jr. (written commun., 1993). B, Interpretation of data as strath levels (Zen, 1997a), not including Glade Hill and Matildaville straths that are higher than the Bear Island level. BI, Bear Island; SL, Sandy Landing; BP, Black Pond; HG, Hidden Gorge; PC, Plummers Channel.

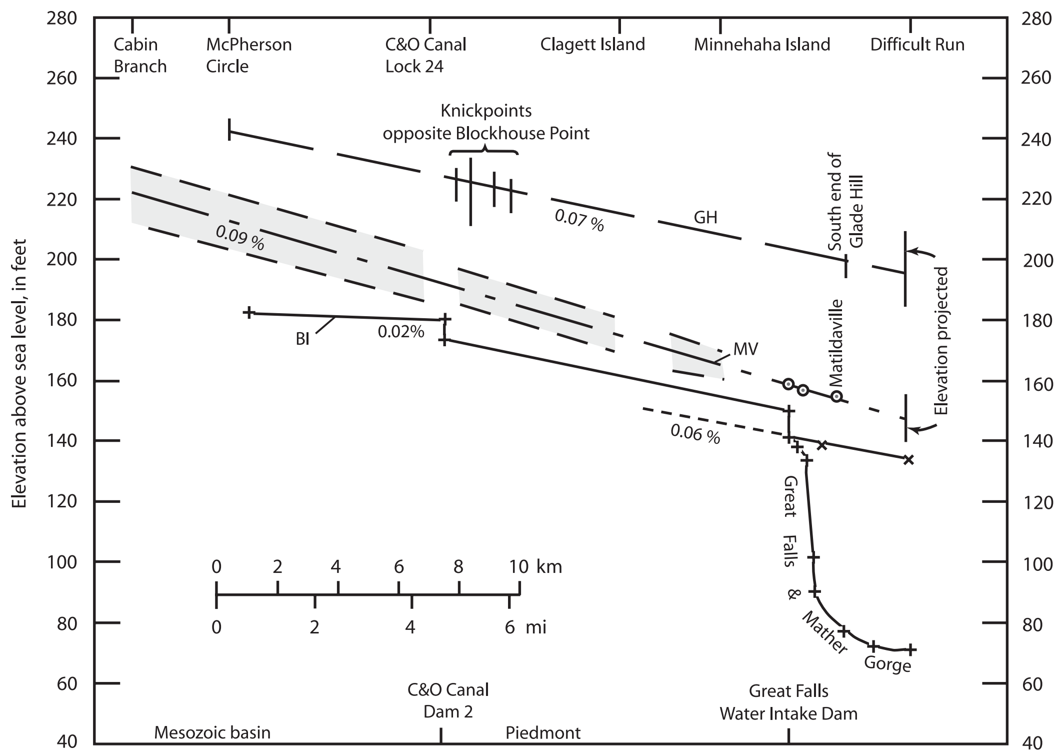


Figure 6. Comparison of the profiles for Glade Hill (GH), Matildaville (MV) (screened area represents vertical uncertainty), and Bear Island (BI) straths with the modern river channel. Solid lines designate BI and the modern river channel above the Great Falls Water Intake Dam. Projection of modern river channel is indicated by dashed line. Circled points and vertical bars show selected data (Zen, 1997b). The elevations at Difficult Run are projected (Zen, 1997a). The BI profile drops 6 ft at the dam because below this point the elevations refer to the rock floor but above this point they refer to the water surface. +, water surface elevations; x, channel floor elevations. Distances are measured along the river. Vertical exaggeration 328x.

Island level, as well as lateral potholes on the sides of waterworn outcrops. Upriver from the dam and as far as the western edge of the Piedmont, it is recognized as waterworn islands, *p*-forms, and sharp erosional benches where spurs of Piedmont hills are trimmed (Zen, 1997b). These benches can be recognized even in the early Mesozoic Culpeper basin as far as the mouth of Cabin Branch near the site of Edwards Ferry, Md.

The Glade Hill strath has an inferred gradient of 0.07 percent between Glade Hill and Harpers Ferry. This result is consistent with hydraulic demands for moving the boulders to Glade Hill (Zen, 1997a). The Matildaville strath has an inferred steeper gradient of 0.09 percent (fig. 6); this higher value may explain its disappearance upstream of Cabin Branch. Curiously, neither strath seems to show lower gradients within the early Mesozoic Culpeper basin, across which the modern gradient is 0.02 (fig. 6; Zen, 1997a).

Modes of Gorge Excavation

Abrasion, quarrying, and drilling are among the possible modes of excavation for the Potomac River gorge (see also Tinkler and Wohl, 1998a,b).

Abrasion

The importance of abrasion is attested by the abundance of *p*-forms, flutes, and water-rounded rock surfaces. Abrasion should be especially powerful at knickpoints (Hancock and others, 1998) where flow is vigorous; yet abrasion, by itself, could not account for the excavation of Mather Gorge, particularly in view of the age constraints discussed on Day 2. Abrasion is likely important in molding the fractured albeit initially flat rock surfaces as seen below the Water Intake Dam into the breadloaf shapes of the Bear Island strath.

Quarrying

The ability of flood discharge to loosen blocks of rocks at the lips of knickpoints might be the key step in the *en bloc* removal, or quarrying, process and could be the major cause of excavation of Mather Gorge (Zen, 1997a; see also Seidl and Dietrich, 1992; Tinkler and Wohl, 1998a). Block loosening could be by hydraulic impact or by gravity and thawing and freezing during more quiescent periods. The efficacy of freezing and thawing depends on annual temperatures, and if river flow continues during cold seasons the process might only marginally affect the main channel. Hancock and others (1998) mentioned hydraulic wedging; for that to promote block removal, however, the wedged material must first be removed by a flood.

In fractured bedrock channels such as the Potomac, another process might be at work. At the lip of a knickpoint, the pressure exerted at the top of a rock is the normal component of the water column (ignoring the atmospheric pressure!). At the under surface of the fracture-bounded block, the upward pressure is augmented by the height of the intermediate water column but this difference does no work. If, however, the fracture is part of a hydraulically connected fracture system, then the upward pressure could be sensitive to hydrological events elsewhere. Specifically, just below the Water Intake Dam, within the very flat bedrock channel, during periods of low flow water pours vigorously into the steeply dipping fractures. A connectivity of hydraulic signals within the fractures just below the channel floor seems plausible. In filled fractures, such signals would propagate at the speed of sound, about 1.5 km/second in water. Slight as the effect must be, it would push the rock slab upward, unopposed, during the entire period of waxing flood.

The distance between the Water Intake Dam and the top of Great Falls varies between 1 and 1.5 km (0.6–0.9 mi). During an onset of flooding, the crest passes downriver at about 2 m/s (meters/second) (E-an Zen, unpub. data), and so a pressure change due to increased water depth at the top of the rock block would take above 500 to 700 seconds to travel the distance between the dam and the lip of Great Falls. However, the same change transmitted through the fracture system would take only about 1 second (albeit probably attenuated by leakage). For about 10 minutes, the pulse of flood would exert small but unopposed upward pressure on the underside of the rock block. By extension, during waxing flood there could be sustained unbalanced upward thrust lasting hours to days. Could this hydraulic jacking loosen a block and ready it for eventual tumbling over the knickpoint within the main channels?

The process of quarrying is episodic. It occurs only during floods that had adequate power. Further, a given point along the river remains immune to quarrying except during the upriver passage of a knickpoint. Yet another possible source of episodicity is that excavation probably was most effective during glacial periods with greater runoff relative to seepage into the ground. Today, the Great Falls-Mather Gorge system might be only marginally active, awaiting the next cold epoch.

The rate of knickpoint retreat is not likely to be constant and also differs for different knickpoints. Thus, cataracts could bunch and transiently create large declivities (for example, the modern Great Falls; for past records, see Zen, 1997a), or disperse into "rapids" such as at Yellow Falls and Stubblefield Falls.

Drilling

"Drilling" is a subset of the abrasion process but merits separate discussion because of its importance. As here used, the term refers to erosion caused by local turbulence, including formation of both vertical and lateral potholes (Zen and Prestegaard, 1994; see also Hancock and others, 1998, p. 40). Vertical potholes form on the channel floor but lateral potholes form in response to flow separation at rock obstacles. Formation of lateral potholes can be quite rapid: a few centimeters per year or more (Gregory, 1950; Putzer, 1971; Vivian, 1970; Bloom, 1998, p. 205; see Zen, 1997a). Because the vortex forming a lateral pothole is produced by a physical obstacle and not by chance encounter with a free vortex, vortices will form at the same sites when the flood reaches an appropriate level.

Coalescence of lateral potholes thus could widen the channel between knickpoints. A plausible example of such a process is a field of lateral potholes, some as high as 2 m (7 ft), along the Billy Goat Trail on the Bear Island side of Mather Gorge, formed when the Sandy Landing strath was the active channel (Stop 2).

Neither quarrying nor drilling automatically leads to bedrock channels that have the inferred strath gradients. This is troublesome because during floods, the water surface gradient in the upper reaches of Mather Gorge is as much as 0.6 percent (E-an Zen, unpub. data), several times that of the straths. Some other process must have intervened to "ream out" the longitudinal profile to those of the straths. How and why this occurred remains a puzzle; hydraulic jacking down to the level of the base of the knickpoint-defining cascades might be one mechanism.

Shoestring Channels on the Potomac: Modern and Ancient

The modern channel as well as paleochannels of the Potomac River contain records of multiple channels stacked in time and space. Particularly intriguing are "shoestring channels" (Zen, 1997a) that are straight or smoothly arcuate in plan view, narrow, have a nearly constant width (typically 15 m; 50 ft), and a shallow depth. A modern shoestring channel that may provide a conceptual template is the channel bounding Cabin John Island, entirely in alluvial cover, having a length of 0.5 km (0.3 mi), a sinuosity less than 1.1, and a length/width aspect ratio of 40. Its upstream end is arcuate. By comparison, a 0.6-km (0.4-mi)-long active shoestring channel incised in bedrock, also ending headward in an arcuate reach, bounds the east side of Plummers Island. It has a sinuosity of 1.05 and a length/width aspect ratio of 40.

Networks of shoestring channels of similar length and aspect ratios are preserved on several straths; some are active during floods. Examples include the heads of Vaso Island, Sherwin Island, incised channels at the south end of Bear Island, and the complex, multi-tiered network of channels around Rocky Island (Zen, 1997a). At Rocky Island, both straight and arcuate channels, the latter mimicking a meander, had formed in an alternating time sequence, crossing and beheading one another. Comparison of the configurations of these channels suggests that the bedrock shoestring channels might be imprinted from preexisting alluvial channels. If so, we might infer that during quiescent periods, the Potomac channel and straths were veneered with alluvium. Floods would remove this material to expose the rock floor to erosion. We see these latter records, but miss the alluvial parts of the story (see also Howard, 1998, p. 307). Inheritance from vanished alluvial regimes might have played a major role in the alignment of modern channels, including Mather Gorge itself.

An illustrative shoestring channel near Lock 12 of the Chesapeake and Ohio Canal opposite Plummers Island is an oxbow having a sinuosity of 2.4 (defining nearly three-quarters of a circle), about 15 ft (5 m) deep and 25 ft (8 m) wide, cut into the Hidden Gorge strath. Its configuration seems to require an origin through superimposition from an alluvial mantle where meander loops could develop. Thus, comparison of the alluvial and bedrock channels suggests their common origin.

Is the Gorge Erosion Still Active?

The age of the Potomac River gorge complex, including Mather Gorge, is being measured by the cosmogenic nuclide method and the results are a major focus of Day 2. We now know that for the upper reaches of Mather Gorge, the Bear Island strath became substantially dry by about 35 ka (Bierman and others, 2002) implying an average gorge incision rate of about 2.5 ft/1000 yr (0.8 m/1000 yr) (the modern submerged gorge floor has sill elevations at about 70 ft (21 m) asl between deeps; J.C. Reed, Jr., USGS, oral commun., 1993). The young date suggests that gorge incision and knickpoint retreat at Great Falls are active, but do the hydraulics of the recorded floods support this idea?

We can estimate the water gradient during floods near the entrance to Mather Gorge. For the largest recorded flood, that of 1936, a minimum estimate of the gradient, based on data in Grover (1937), is 0.3 percent; for the January 1996 flood Zen measured a gradient of 0.6 percent near the marker post (this may be anomalous; see discussion for Stop 9) but 0.3 percent along Mather Gorge. In what follows, I used a gradient of 0.3 percent. For the 1996 flood, I estimated a flow speed of 15±3 ft/s (5±1 m/s) at the entrance to Mather Gorge 46 hours after the peak; and a flow speed of 9±1.5 ft/s (3±0.5 m/s) at Sandy Landing. Leopold and others (1964) cited a value of 22 ft/s (6.7 m/s) at Little Falls Gauge Station for the 1936 flood but this seems improbable; the average speed of passage of the crest of that flood between Great Falls and Little Falls was 6 ft/s (2 m/s), the same as what Zen obtained for the 1996 flood by dividing the discharge, Q, by an accurately constructed cross section area of the channel across Mather Gorge.

These parameters lead to an estimated unit stream power within the main channel of about 2 to 3 kilowatts per square meter (kW/m2) (Williams, 1983). Extrapolation from Williams (1983) suggests that blocks as much as 6 ft (2 m) in diameter could be moved. This estimate is consistent with the preserved evidence of movement of 1-m (3-ft) blocks at Stop 8. As a dimension of 1 m is comparable to the spacings of fractures and joints in the bedrock near Great Falls, the headward retreat of Great Falls and the resulting extension of Mather Gorge could occur during decadal floods even though the evidence for the process is largely hidden from our view.

The Little Falls gauge record goes back only to 1930. However, in May 1994 the Great Falls Park posted notes on some post-1773 floods, including those post-1930, that rose “above drought level” below Great Falls. Comparison between these values and the flood levels recorded on that marker post (which has a base elevation of 146 ft (44 m) asl; Stop 9) shows that “drought level” is 65 ft (20 m) asl. Calculated pre-1930 flood records are shown in table 1.

If the tabulations are reliable, then a striking feature is that since 1773 only the 1785 and 1889 floods have topped the Bear Island strath. Even if the itemized 19th-century floods were all underestimates, there were fewer 19th-century floods of comparable magnitude. This deficit is compatible with the climate record since 1730 based on a tree-ring study at Point of Rocks (Cook and Jacoby, 1983). However, the extant post-1773 flood records are consistent with the idea that headward migration of Mather Gorge through knickpoint retreat is still episodically active. The modern process, however, may be slower than its counterpart during the glacial intervals and, with our short historical and hydrological records, humans would hardly notice the landscape modifications caused by knickpoint retreat at Great Falls.

Day 1 Trip Route and Stop Descriptions (fig. 7)

Leaving the McLean Hilton, turn left on Jones Branch Drive.

Turn right (north) on International Drive/Spring Hill Road.

Proceed about 0.5 mi, then turn left (west) onto Old Dominion Drive.

Continue on Old Dominion Drive (west) about 3 mi.

Enter Great Falls Park.

Pass the park entrance and park in the farthest parking area about 0.5 mi past the guard station.

Table 1. Major floods at Great Falls since 1773.
[Abbreviations are as follows: ft, feet; m, meters; asl; above sea level)]

Date	Flood height above "drought level," in ft	Known/calculated elevation above sea level, in ft	Discharge, in 1000 ft^3/s (1000 m^3/s) at Little Falls
Sept. 1996	—	146	314 (8.89)
Jan. 1996	—	148	347 (9.82)
Nov. 1985	82	147	317 (8.98)
June 1972	87	151	359 (10.16)
Oct. 1942	90	155	447 (12.66)
Apr. 1937	85	150	347 (9.82)
Mar. 1936	91	156	484 (13.70)
Mar. 1924	>65	139[1]	
1889	>73	>138[2]	
1877	70	135	
1870	≥60	≥125	
1857	≥60	≥125	
1852	64	129	
1847	≥58	≥123	
1785	≥80	≥145	
1773	≥75	≥138	

[1]This is the level based on the photographic record at Lock 17 on the C&O Canal (National Park Service, 1991, p. 59). Lock 17 is directly across from the lower observation platform (140 ft (43 m) asl) in Great Falls Park.

[2]Notes on the U.S. Geological Survey's Little Falls Gauge Station (01646500) webpage say that the "flood of June 2, 1889, was approximately the same magnitude as that of March 19, 1936."

Stop 1. Lower observation platform.

The horizontal line at the upstream end of the visible river is the Water Intake Dam, built on a flat bedrock channel floor. Below Great Falls, this floor forms the principal rock benches visible to the right. It is hummocky as a result of subsequent erosion, mainly along fractures. Great Falls is a series of cataracts, each 10 to 15 ft (3–5 m) high, separated by pools (fig. 3). Immediately below the observation platform on the Maryland side (if water level permits viewing) is a large rock bench with a sharp peak at about 100 ft (30 m) asl. The base of this peak, at about 95 ft (29 m) asl, is ringed by lateral potholes; it was a rock obstacle when the channel was at the Black Pond level (here at 95 ft; 29 m). Another preserved bench of this strath is downriver, on the Virginia side, across from the fishladder. Looking at Rocky Island, its top is the Bear Island strath (here at 140 ft; 43 m). The transverse, arcuate channel at its north (left) side has a rock sill at 77 ft (24 m) (the Hidden Gorge strath). Hidden Gorge is an erosion channel that at high water bisects Rocky Island; it is a wetland area during periods of low to medium flow.

Walk along footpath that parallels the ruins of the Patowmack Canal, to the edge of the clearing.
Cross small wooden bridge to right.
Take the Carriage Road to the right of the building to follow the base of Glade Hill.

The swamp to the right occupies a former channel of the Bear Island strath. Milton (1989) reports that bedrock is a few feet below the muck surface; this is confirmed by Lee (1993) using a portable seismograph. The bedrock here is about 140 ft (43 m) asl, confirming that the valley is a part of the Bear Island strath. The upper end of the valley is partly filled by colluvium, which prevented even the 1936 flood to enter; nor could it have backed up beyond the abandoned quarry (en route to Stop 3) from Sandy Landing (see also Milton, 1989). This wetland area thus is fed by rainwater and seepage. The Carriage Road follows a regional sewer interceptor (from whence cometh the odor in warm weather).

Stop 2. Glade Hill.

Ascend at the point opposite a weir in the swampy valley. Notice outcrops of fresh schist to about 200 ft (61 m) (top elevation, 210 ft; 64 m), as well as scattered boulders of quartzite. The hill is flat-topped; it has no saprolite or streams running off its side. It is set within the incised upland whose top is about 350 ft (107 m). Glade Hill is not a Piedmont hill; instead, it is the oldest recognized strath of the Potomac River (Glade Hill level; see also Reed and others, 1980) preserved through topographic inversion. It is capped by a boulder bar in the former channel.

The boulders are various types of quartzite that can be

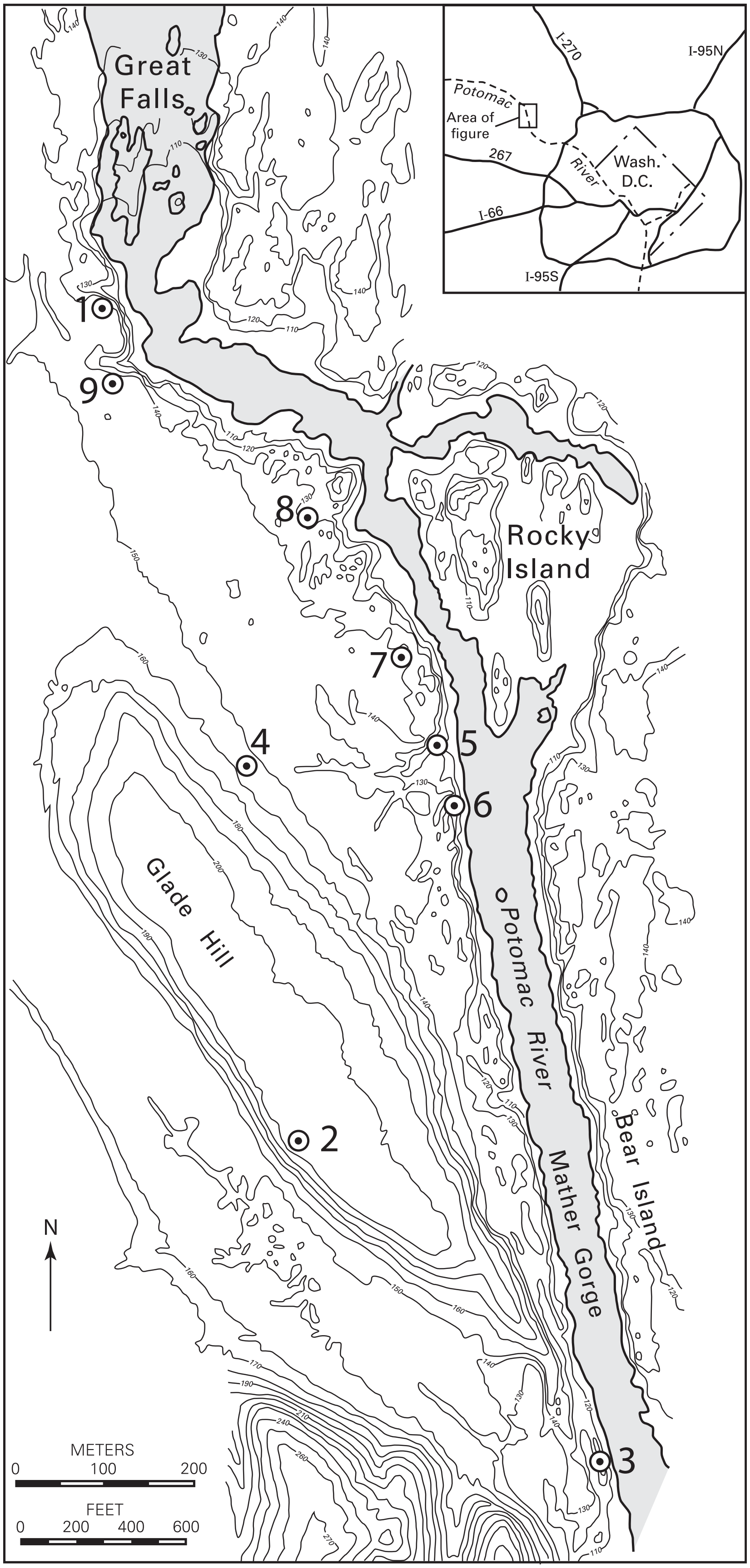


Figure 7. Day 1 field trip stops. Inset shows location of figure area in regional setting. Topographic contours in feet.

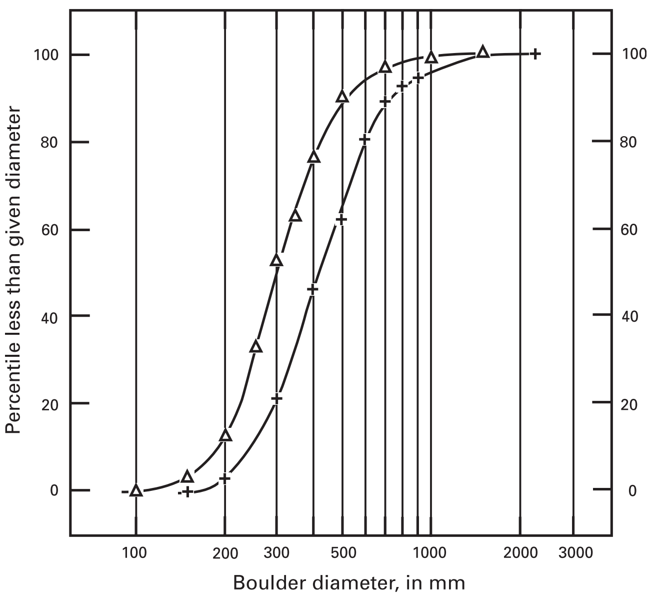


Figure 8. The Glade Hill boulder count, showing both the maximum (crosses) and median (triangles) diameters for all located unbroken boulders. n = 280. The lines are interpolations of the actual points. See Zen (1997a) for data and discussions.

matched with the Lower Cambrian Weverton Formation on the west flank of the Blue Ridge province, exposed along the Potomac River just below Harpers Ferry, 45 mi (72 km) (river distance) away. The absence of clasts of Piedmont rocks (and extreme rarity of Mesozoic rocks from the intervening Culpeper basin) makes it unlikely that these boulders were transported incrementally; one or a few large floods must have brought them here in brief, but violent, flood events.

We do not know the paleowidth of the Glade Hill strath. It could have been as wide as 1,800 ft (600 m), which is the maximum possible width for the 200-ft (61-m) level, or as narrow as Glade Hill, about 300 ft (100 m). Zen (1997b) estimated the Glade Hill channel gradient, as far west as Harpers Ferry, at about 0.07 percent. As the hydraulic conditions have allowed transport of boulders as much as 2-1/4 m (~7 ft) across all the way from Harpers Ferry, but stopped them here, we can place some constraints on the flood magnitude on a per-unit width basis by means of the unit stream-power relations (Williams, 1983). Such a flood would require about twice the discharge of the 1936 flood. The regression data of Hoyt and Langbein (1955, p. 20) and of Zawada (1997) both suggest that for the Potomac River having a drainage area down to this point of about 10,000 square miles (mi^2) (26,000 square kilometers (km^2)), a maximum flood discharge of 1 million cubic feet per second (ft^3/s), or twice that of March 1936, is reasonable; if the paleochannel was as wide as the modern one, the discharge per unit width would also be double the modern value. I speculate that the boulders originated from a debris apron between Maryland Heights and Loudoun Heights near Harpers Ferry (see Southworth and Brezinski, 1996, fig. 26), mobilized by exceptional, possibly climate-triggered, floods.

Some of the boulders contain still recognizable feldspar grains in arkosic layers. The frequency distribution of the median and maximum diameters of all the unbroken boulders (n = 280) is consistent with a single population; the largest boulders have maximum diameters exceeding 2 m (7 ft) (fig. 8; data in Zen, 1997a; assumes the unobserved boulder dimensions were the shortest). A large boulder of vein quartz might be from the Piedmont but large bodies of vein quartz are abundant in the rocks near Loudoun Heights (see Southworth and Brezinski, 1996, fig. 23).

Follow first the ridgeline south, then the bridle trail back to the swamp valley.
The original hilltop beyond the bridle trail has been destroyed by quarry operation, and the sharp ridgeline is an artifact.
Follow trail to Sandy Landing.

Stop 3. Sandy Landing.

The large, water-polished and *p*-form-rich rock bench is part of the Sandy Landing strath; here it crowds the edge of the Bear Island strath. View of large (~ 2 m; 7 ft) lateral potholes across the river, likewise part of the Sandy Landing strath. The small hanging valley diagonally entering Mather Gorge is another Sandy Landing channel, but its elevation near the gorge has been reamed by downcutting to lower base levels. The Sandy Landing strath is quite wide near the southern end of Bear Island; there it is incised by later channels. We will discuss the straight section of Mather Gorge at Stop 6.

Follow the blue-blaze River Trail back north.

Stop 3A. (optional).

A lateral pothole along the narrow rock bench, which is the edge of the Bear Island strath (Mather Gorge cuts diagonally across the Bear Island alignment). Notice the small-scale waterworn configuration within the pothole: the quartz-rich layers stand out against the mica-rich layers. From the left edge of the pothole, a small muscovite-bearing pegmatite was sampled in the late 1970s for age determination. The model Rb-Sr "age" of the muscovite, 469±12 Ma assuming an initial strontium ratio of 0.707, was taken to be the age of the peak metamorphism and anatexis of the schist (Fisher, 1970; Muth and others, 1979). The sampled spot is beginning to be colonized by crustose lichens after about a quarter century; 10 years ago, the chipped surface was still shiny.

Stop 3B. (optional; Reed and others, 1980, p. 31).

A well-preserved vertical pothole, bottom not exposed. In the Great Falls area, the depth/width aspect ratio of vertical potholes rarely exceeds 1.5; frictional energy loss probably controlled the erosional reach (see Alexander, 1932). Two well-preserved vertical potholes (one 0.2 m (0.7 ft) and the other 1 m (3 ft) across at the bottom) have double basins separated by a water-sculpted ridge. Could it be that the tip of the vortex was bi-stable (Jonathan Tuthill, oral commun., 2000)?

Follow the path along the canal locks.
Take the path left to ascend toward the ruins of Matildaville.

The footpath roughly follows the alignment of Canal Street. The large building was the Superintendent's House, the glass-and-crockery-littered ground at Stop 4 marks the site of Dickey Inn, which existed until the early 20th century. The foundation with a curious alcove was the spring house (Garrett, 1987).

Stop 4. Matildaville.

This hamlet for canal keepers was sited at 155 ft (47 m) level on the Matildaville level strath. The site was safely above even the 1936 flood. The exposure is waterworn; large lateral potholes, belonging to the 140-ft (43-m) or Bear Island strath, occur at its northeastern base and establish the chronological sequence of the Bear Island and Matildaville straths. A lateral pothole consistent with the Matildaville strath can be seen on the side of a waterworn rock prominence west of the picnic area, near the small parking lot.

Go across the alluvium-filled holding basin of the Patowmack Canal.
Go east on the trail that parallels the basin's outflow channel.
Turn right onto the blue-blaze River Trail.

Stop 5. Trestle over small stream.

This miniature gorge in the small stream which we first crossed at the holding basin seems much too large for a watershed area of about 0.5 km^2 (0.2 mi^2). Milton (1989) suggests that the channel is sited on lamprophyre dikes. I found no dike within the channel; at the channel mouth, dikes are exposed off the side (see photograph in Reed and others, 1980, p. 27). This robust channel is a fossil strand of the Potomac River when the paleo-Great Falls was just upriver from the mouth, abandoned when further knickpoint retreat deprived this stream of its flow. The flat stretch of the channel below the trestle is consistent with its being part of the Sandy Landing strath.

Go south and cross the trestle.
Peel off immediately to the left, and climb up a large rock at the top of the cliffs above Mather Gorge.
Watch out for rock climbers!
Do not fall into the river!

Stop 6. View above Mather Gorge.

Across the river, on the Maryland side of Mather Gorge, at least three lamprophyre dikes, each no thicker than 1 ft (0.3 m), are aligned with the small valley (part of the Sandy Landing strath). These dikes are weathered back from the more resistant schist and follow parallel joints that dip steeply down river. Biotite in dikes just like these, near Stop 1, yielded 363–360±13 Ma by the K-Ar method (Reed and others, 1970), showing that not only had rock deformation and metamorphism ceased, but that some joints had already formed. On the Virginia side, a triplet of lamprophyre dikes are assumed to be the same dikes as those visible on the Maryland side. If true, then projecting their strikes across the 70-m (230-ft)-wide gorge would show a dextral offset of 25 m (82 ft), a point used as evidence (for example, Reed and others, 1980, see photograph on p. 27) that a fault is responsible for this straight 1.4-km (0.9-mi) reach of the gorge (sinuosity <1.01). However, this evidence is permissive, because the dikes might have jumped across preexisting fractures (indeed, the just-mentioned photograph of the dikes shows two of the dikes to pinch out). As the strike of the dikes is visible only for a couple of meters, their straight extension across the gorge is an assumption. No fault could be identified along its expected on-land continuation on Rocky Island. Detailed landform analysis of the Bear Island strath shows no preferred thalweg; yet 25 ft (8 m) lower, the Sandy Landing channel closely followed the Mather Gorge alignment (Stops 3, 5, 6, 8). A fault that did not affect the Bear Island strath would have to become the controlling structure within that short vertical distance.

Another possible cause of the straight gorge is control by fractures. Tormey (1980) reported concentration of fractures in a direction parallel to the gorge. Again, the evidence is permissive because the fractures could be the result of stress release, analogous to the formation of sheeting fractures in quarries (Jahns, 1943). One joint-bounded cliff face just up river shows a lateral pothole at the Sandy Landing level, so at least some of the gorge-parallel joints dated back to when the gorge excavation was just beginning.

The rocks here are mica schists and graywackes metamorphosed in the Ordovician. Sillimanite, andalusite, and large pseudomorphs of cordierite are present, as well as disputed pseudomorphs of kyanite (which may be that of sillimanite; see Hopson, 1964; and Fisher, 1970). The metamorphic pressure was likely in the 2 to 4 kilobar range (lower if the identification of kyanite was invalid). As the granite and pegmatite show that the temperature must have reached 700°C (Stop 3A), the average vertical thermal gradient must have been 60–70°C/km. This is unlikely for an "upstroke" P-T trajectory in a subduction zone; more likely the setting was back-arc extension. These rocks must have been elsewhere during the Taconian deformation.

Return to the River Trail. Recross the trestle bridge.
Go past the bronze plaque marked Mather Gorge Overlook to a large rock outcrop on the left about 500 ft (150 m) beyond the plaque.

Stop 7. Lateral pothole.

Three aligned potholes on a large rock obstacle within the Bear Island strath. The pothole farthest upriver (north) is about 4 m (13 ft) from the rock's prow (Zen and Prestegaard, 1994, figs. 3, 4). Note that the potholes are not nucleated on fractures. Note the overhanging alcove, the shallow and simple basin, and the downstream inclination of the potholes. The plans of these potholes are far from circular; they terminate sharply in the downstream direction but taper on the upstream side. The waterworn sloping downstream edges of the potholes are integral parts of the architecture. They are not broken edges of former vertical potholes.

Lateral potholes form where vortices are created by flow separation at rock obstacles. The process can be observed during floods on many rivers, including the Mather Gorge reach (see also Zen and Prestegaard, 1994, p. 50). The overhangs mark levels of water-air intersection during "average" eroding floods. The asymmetry results from the tip of the eroding vortex being anchored in the pothole but the top being swept downstream by the current; in the absence of other indications, they can give the paleoflow direction.

The processes of removal of rock material during pothole drilling include hydraulic impact, cavitation, and blasting by suspended load. The interiors of the potholes show strong material control (see also Stop 3A): millimeter-thick quartz-rich layers stand out in relief, and the ridges smoothly grade into recessed unweathered mica-rich layers. The millimeter-scale selectivity rules out large "grinders" as the principal agent of erosion (see Alexander, 1932; see Wentworth, 1924). Large grinders found in fossil potholes may have choked the hydrodynamic process, contrary to the intuitive inference.

Reliable data on the rates of pothole formation are scanty. The available data from natural settings, however, yield consistent values on the order of 1 in (2–3 cm) per yr (Gregory, 1950; Putzer, 1971; Bloom, 1998). A pothole of the size seen here could be formed within a human lifespan. The interior of the potholes on high level straths are commonly coated with colonies of crustose lichens whose enlargement rate is a fraction of a mm per yr (Lawrey and Hale, 1977). Their presence shows that the occasional inundations during decadal floods do not modify the potholes.

Continue on the River Trail to where the gravel path splits near the edge of the open area.
Take the right split for about 70 ft (20 m).
Go right on an unimproved trail for 100 ft (30 m).
Opposite a low rock on the right, bear left on an obscure path toward the river, emerging in the open area above an abandoned plunge pool.

Stop 8. Plunge pool of a fossil cascade.

The outlet is at 115 ft (35 m), part of the river's Sandy Landing strath. The cascade formed when the paleo-Great Falls was near the head of Rocky Island, subsequent to its residence near Stop 5. The top of this fossil falls is about 130 ft (40 m) asl, incised about 10 ft (3 m) into the Bear Island level.

During the waning stage of the January 1996 flood, the river current damaged and bent every tree within the amphitheater; their direction of bend described a large clockwise gyre (looking down) that persisted for some hours. A rampart fronting the reshaped debris apron was about 9 ft (3 m) high and sloped 20° towards the pond. This rampart was formed of blocks of local schist mixed with blocks of concrete and a few blocks of sandstone. The blocks were as much as 2 m (7 ft) across and showed a tendency for the long dimension to be aligned with the strike of the rampart. The top of the reshaped apron consisted of sand draped over the blocks, introduced at a later and lower stage from a side channel, as well as artifacts, such as a 10-ft (3-m) section of 2-in (5-cm) diameter iron pipe, the working end of a rusted manual lawnmower, and other objects whose shapes provide little or no hydrodynamic lift. These may have been "lags" from earlier events. One block of concrete, 42 by 27 by 8 in (1.1 by 0.7 by 0.2 m), bent a standing iron fence post (a piece of old detritus) and rested in its crook, demonstrating that blocks of this size were moved by the flood, which at this point should have generated unit stream power of about 1 KW (Williams, 1983).

Return to the River Trail and onto the picnic ground.

Stop 9. Flood marker post.

The water levels for six post-1930 floods are shown on figure 9. These, plus a seventh flood that just touched the base of the post, together yielded a regression relation between these local elevations and Q values recorded at the Little Falls Gauge Station (Bob Ridky, USGS, oral commun., 2002). The Little Falls Q value needed to first dissect the Bear Island level (here at about 140 ft (43 m) asl) into islets, then to completely inundate it, is about 220,000 to 230,000 ft^3/s (6,200-6,5000 m^3/s) In addition to the seven post-1930 floods (and probably two others in 1785 and 1889) that inundated Bear Island and other parts of the "flood plain," four high flows since 1930 (dated Aug. 1955, Oct. 1977, Feb. 1979, Feb. 1984) exceeded 200,000 ft^3/s and were nearly brimful to the Bear Island strath. These floods must have moved blocks more than 1 m (3 ft) across (as attested by the record at Stop 8) but we cannot see the results. The location of the marker post, just downstream from the transverse rock wall athwart the main flow down the falls, however, cautions us that superelevation could have caused reproducible but anomalous flood levels as well as water-surface slopes here.

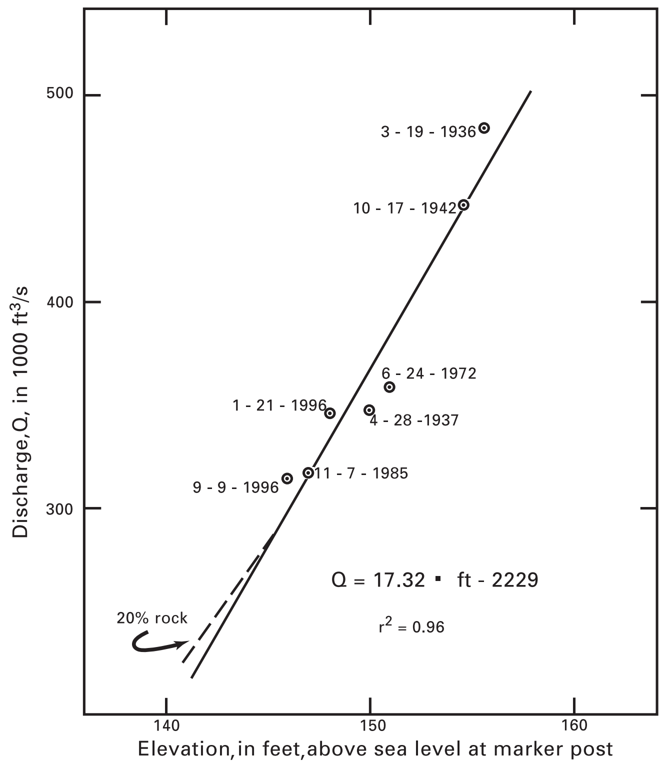


Figure 9. Regression of the seven post-1930 flood levels, in feet asl, at the marker post near the scenic overlook at Great Falls Park against the discharge, Q in 1000 cubic feet per second (1000 ft^3/s), as recorded at the Little Falls Gauge Station. Dashed line shows the relation that would obtain if 20 percent of the space between 140 ft and 146 ft were occupied by rocks.

End of Day 1.

Day 2

Cosmogenic Dating of Strath Surfaces of the Potomac River near Great Falls

Introduction

Resolving the age of bare bedrock strath terraces bordering the Potomac River and other rivers draining the central Appalachian Mountains (fig. 1A) is key to understanding the nature of bedrock channel incision along the Atlantic passive margin. Until recently, direct dating of such erosional surfaces has not been possible. Over the past decade, the development and application of surface exposure dating methods (Bierman, 1994; Gosse and Phillips, 2001), particularly the application of in situ produced cosmogenic nuclides such as ^{10}Be, now allows dating of exposed bedrock surfaces, including bare-rock strath terraces.

This field trip presents data that we have gathered over the last 4 years from terraces along the Potomac River. We have taken a similar approach to studying terraces of the Susquehanna River (Reusser and others, 2003). We will visit sample sites near the Potomac River and discuss how the data collected and analyzed so far help us to understand better the timing and spatial pattern of channel incision upstream, within, and downstream of Great Falls and Mather Gorge. The fundamental geomorphology of the gorge/falls/strath-terrace complex is discussed in detail in Day 1 of this guidebook.

Background Information—Cosmogenic nuclides and terrace dating

Cosmogenic nuclides, produced in rock and soil near and on the Earth's surface, have seen increasing use in geomorphic studies since their first applications in the late 1980s (Craig and Poreda, 1986; Kurz, 1986; Nishiizumi and others, 1986; Phillips and others, 1986). Although the use of such nuclides for dating was first suggested almost half a century ago (Davis and Schaeffer, 1955), widespread application happened only after the more recent development of accelerator mass spectrometry (Elmore and Phillips, 1987). Hundreds of studies have now been published that rely, at least in part, on such nuclides either for age estimates or for estimating rates of surface processes. Reviews pertinent to both the cosmogenic literature and cosmogenic techniques are provided by several authors: Bierman and Nichols (2004); Bierman (1994); Bierman and others (2003); Gosse and Phillips (2001); Kurz and Brooke (1994); Zreda and Phillips, (1998).

Cosmogenic nuclides have not been widely applied to bedrock exposed by fluvial erosion. To date, most cosmogenic dating of strath terraces has been done along rivers draining active margins (Hancock and others, 1998; Leland and others, 1998; Pratt and others, 2002) and only a handful of analyses have been published. Some work has been done on rock exposed in channels to estimate rates of bedrock lowering and knickpoint retreat (Hancock and others, 1998; Seidl and others, 1997), and alluvial terraces have been dated in several locations (Burbank and others, 1996; Hancock and

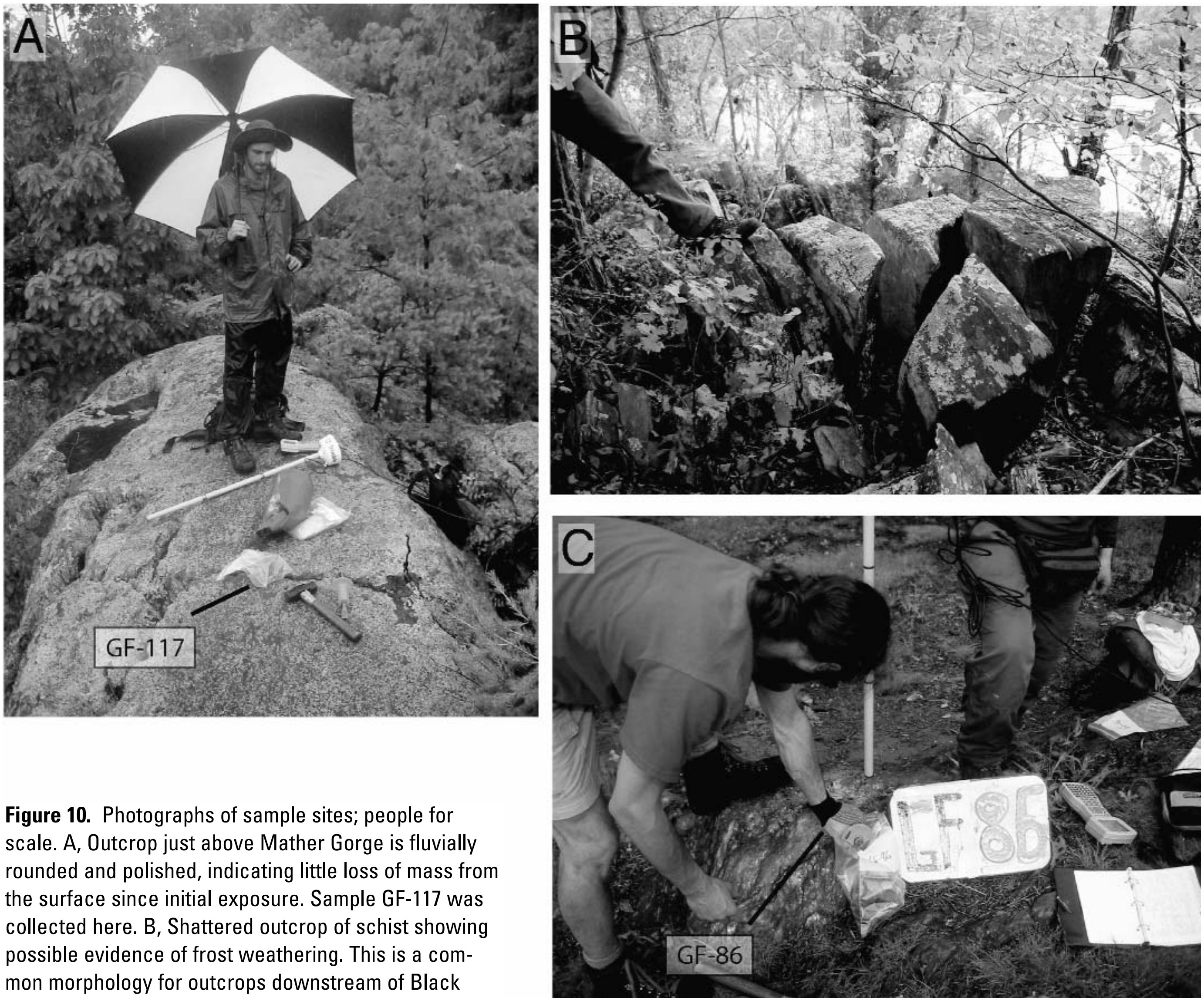


Figure 10. Photographs of sample sites; people for scale. A, Outcrop just above Mather Gorge is fluvially rounded and polished, indicating little loss of mass from the surface since initial exposure. Sample GF-117 was collected here. B, Shattered outcrop of schist showing possible evidence of frost weathering. This is a common morphology for outcrops downstream of Black Pond. Sample GF-75 was collected near here. C, Outcrop from which sample GF-86 was collected is covered for the most part by fine-grained sediment. Fine-grained red soil is exposed behind the outcrop, which stands only 20 cm (8 in) above the ground surface.

others, 1999; Repka and others, 1997; Schildgen and others, 2002). In some cases, alluvial terrace dating has used a technique that accounts explicitly for inheritance of nuclides from prior periods of exposure upstream (Anderson and others, 1996). Cosmogenic data are just starting to be collected for bedrock terraces bounding passive margin rivers, such as the Potomac (Bierman and others, 2003; Bierman and others, 2002; Reusser and others, 2003).

The basic premise of the cosmogenic method is the accumulation of nuclides over time in response to cosmic-ray dosing, the result primarily of neutrons splitting target atoms in minerals (Lal and Peters, 1967). Measuring nuclide concentration is now a relatively straightforward but time consuming procedure. Interpreting measured nuclide concentrations provides the greatest challenge in many situations. Nuclide concentrations can be interpreted confidently as exposure ages only if several conditions are met: rapid exposure of rock from a depth of several meters, no cover by soil, sediment, or water since initial exposure, and no erosion of the rock surface. Violations of these conditions can result in age overestimates (inheritance; Colgan and others, 2003) or age underestimates (stripping of soil or erosion of rock; see Bierman and Gillespie, 1991).

Field observations suggest that most samples collected from bedrock surfaces along the Potomac River meet the requisite conditions for dating. All but a few sampled outcrops preserve intact fluvial forms (sculpting, potholes, and polish), implying little erosion since abandonment (fig. 10A). Several samples collected from below mean low water have nuclide concentrations equivalent to only several thousand years of continuous surface exposure suggesting that most nuclides measured in currently exposed outcrops resulted from subaerial cosmic-ray dosing rather than from exposure under river water (Bierman and others, 2003). For 3 km (2 mi) downstream of Great Falls, most outcrops we sampled stand greater than 1 m (3 ft) above their surrounding rock or soil; thus, we conclude the likelihood of extended burial by soil or overbank sediments is low. However, 3 km (2 mi) downstream of Great Falls there is a dramatic change in the appearance of the most prominent strath terrace surface. Here and farther downstream, most outcrops are heavily weathered both chemically and by what appears to be frost shattering (fig. 10B); these downstream outcrops are much more deeply immersed in alluvium and may well have been covered at sometime in the past (fig. 10C). Thus, model dates on most downstream outcrops are likely minima.

Calculations, made for the Susquehanna River, suggest that occasional inundation of sampled outcrops by floodwaters probably has little effect (an error at the percent level) on model ages except for samples within 1 m (3 ft) of mean river level. Large flows are so rare and short-lived that their waters intercept few neutrons and thus have little effect on cosmogenic model age estimates; common flows in today's channel geometry do not raise river stage enough to submerge many sampled outcrops. Prior to or at the beginning of incision, outcrops which today are inundated only every decade were likely flooded multiple times each year. The vertical incision rates we calculate are sufficiently rapid (0.5 to 0.8 m/1000 yr) that annual water cover and neutron absorption would rapidly be reduced for outcrops within the gorge just several thousand years after incision begins. However, for samples collected from outcrops on the broad strath terrace, incision rates were presumably much lower as the strath was being beveled; thus, inundation of outcrops by floodwaters likely absorbed some neutrons. Of course, we have no way of estimating flows in the past when climate was different nor can we know paleochannel geometry. In any case, the effect of floodwater absorption of neutrons would be to reduce the model ages we report.

Sampling and Analysis Strategy

Our sampling strategy is designed to provide age estimates for exposed bedrock surfaces at different elevations along the Potomac River from above Great Falls to Plummers Island at the I-495 American Legion Bridge, 6.25 mi (10 km) downstream (fig. 11). Samples collected along the length of the most prominent morphological feature, a broad bedrock strath called the Bear Island level by Zen (1997a) dominate the sample population. Examining sample age, as a function of distance downstream, allows us to speculate about the timing and horizontal rate of incision along the river (fig. 12). At eight places along the river, we collected vertical transects of samples, which allow us to estimate rates of vertical incision. Two of those transects are shown in figure 13.

We collected samples, using a hammer and chisel, from the best-preserved outcrops we could identify in the field. Such identification was based on the presence of water-polished rock, potholes, fluvially shaped and streamlined outcrops, and the absence of surface weathering. If quartz veins were present, we sampled them; otherwise, we sampled schist. Sample elevation was measured using a global positioning system (GPS). At open-sky sample sites, differential GPS (Trimble 4400) provided centimeter-scale precision. Under tree cover, a Trimble ProXR using Coast Guard beacon correction provided elevations with 1- to 2-m precision. We processed samples at the University of Vermont using standard methods (Bierman and Caffee, 2001). Isotope ratios were measured at Livermore National Laboratory and model exposure ages were calculated by using an integrated ^{10}Be production rate of 5.2 atoms g^{-1} y^{-1} adjusted for the elevation and latitude of the sample sites considering the neutron-only corrections provided by Lal (1991).

Field Observations

We have identified three morphologically distinct sections of the Potomac River separated by the present and a proposed paleo knickpoint in the 10-km (6-mi) reach that extends from just above Great Falls to Plummers Island. Three sections are separated by the current knick zone (Great Falls) and what we interpret as the paleo knick zone (Black Pond).A brief description of the two knick zones and three morphologically distinct sections follows.

1. The Potomac River above the knick zone: Above Great Falls, the river occupies a wide channel in which water-rounded rock crops out in isolated knobs mostly within the river but also along the shore. Soil-mantled slopes extend nearly to the channel margin in most places; there are restricted areas of overbank deposition in other locations. Little bare rock is exposed except at and near the channel margins. We view this section of the river as a modern analog of the paleo-Potomac River downstream, before significant incision of the channel. If the river were to incise significantly above Great Falls, sections of the present-day channel bottom would become terrace surfaces and the in-channel rock outcrops here would become isolated high knobs.

2. The current knick zone (Great Falls): At Great Falls, the river has incised deeply, leaving waterworn, fluvially rounded outcrops high and dry above the modern channel. The water moves through Great Falls in distinct channels rather than moving over a single waterfall; this pattern of erosion isolates a series of high points in the knick zone that are above the water level (and thus continually exposed to cosmic

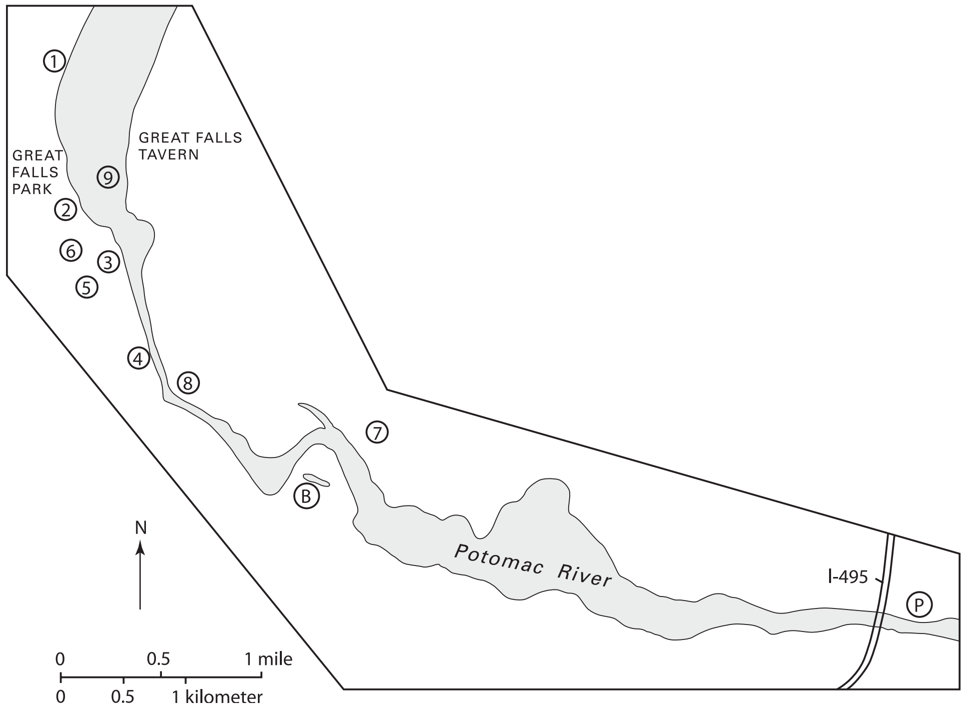


Figure 11. Day 2 field trip stops and location of sample sites. Black Pond, B, is the site of paleo-Great Falls; P, Plummers Island.

radiation) at most river stages (fig. 14). Conversely, at the base of the channels, there is outcropping rock that sees little if any cosmic-ray dosing. As one approaches the falls from upstream, the river has begun to incise about 1 km (0.6 mi) before the falls, leaving increasing amounts of rock and a greater vertical extent of rock exposed in the channel and along its margins than farther upstream.

3. The young terrace landscape: Immediately downstream of Great Falls and adjacent to Mather Gorge on both the Maryland and Virginia banks of the river is a wide strath terrace of fresh bedrock, mantled by thin sediment in places. This surface extends 3 km (2 mi) on the Virginia bank from Great Falls to Cow Hoof Rock. Bedrock forms on what we term the young terrace landscape are well rounded and water sculpted; most appear fresh and only lightly weathered. The majority of our samples have been collected on and below this surface. Many of these samples were collected near the edge of the terrace overlooking the gorge where very little sediment covers the bedrock.

4. The last paleo-falls (pre-Great Falls) knick zone (Black Pond): The area surrounding Black Pond on the Virginia bank is one of transition where the riverside landscape of the Potomac changes dramatically, suggesting that this was the location of a long-lasting stand of a paleo-Great Falls, occupied until the Potomac began incising Mather Gorge. Upstream of the Black Pond area, the young terrace landscape is dominated by exposed, fresh rock outcrops, the result of this downcutting. Downstream, the old terrace landscape is soil mantled; outcrops are isolated and usually heavily weathered. The morphology upstream of Black Pond is similar to the present-day Great Falls. There are isolated high points separated by deep channels (fig. 15). Channel bottoms, meters above the waters of the Potomac, are cluttered with boulders. The Black Pond area has been left high and isolated by incision of the Potomac River. The upstream end of this peninsula is bare rock, water polished, and fluvially rounded from the tops of the highest isolated knobs to the base of the now-abandoned channels. The highest outcrops likely stood above all but the highest flows while the channels were usually submerged; rock on these high points is more weathered than rock at the channel bottoms, implying a longer period of exposure. On the uplands south and east of Black Pond, rock exposed on the uplands becomes extremely weathered 200 m (650 ft) downstream and 10 m (33 ft) in elevation.

5. The old terrace landscape: Downstream of Black Pond, the wide strath terrace continues on the Maryland side to the American Legion Bridge, but little rock crops out—a dramatic change from the young terrace landscape upstream where rock outcrops dominate the terrace surface. Most rock on what we term old terrace landscape is buried by a thick (up to 5 m (16 ft) in stream cuts) cover of red, fine-grained sediment that could be overbank material or loess. There are two exceptions—just below and just above the American Legion Bridge are Plummers Island and an unnamed island, respectively. Both are isolated bedrock hills and both have little to no fine-grained sediment cover and an assortment of fluvial forms (heavily weathered) extending to their summits (fig. 16). The outcrops on the old terrace landscape were

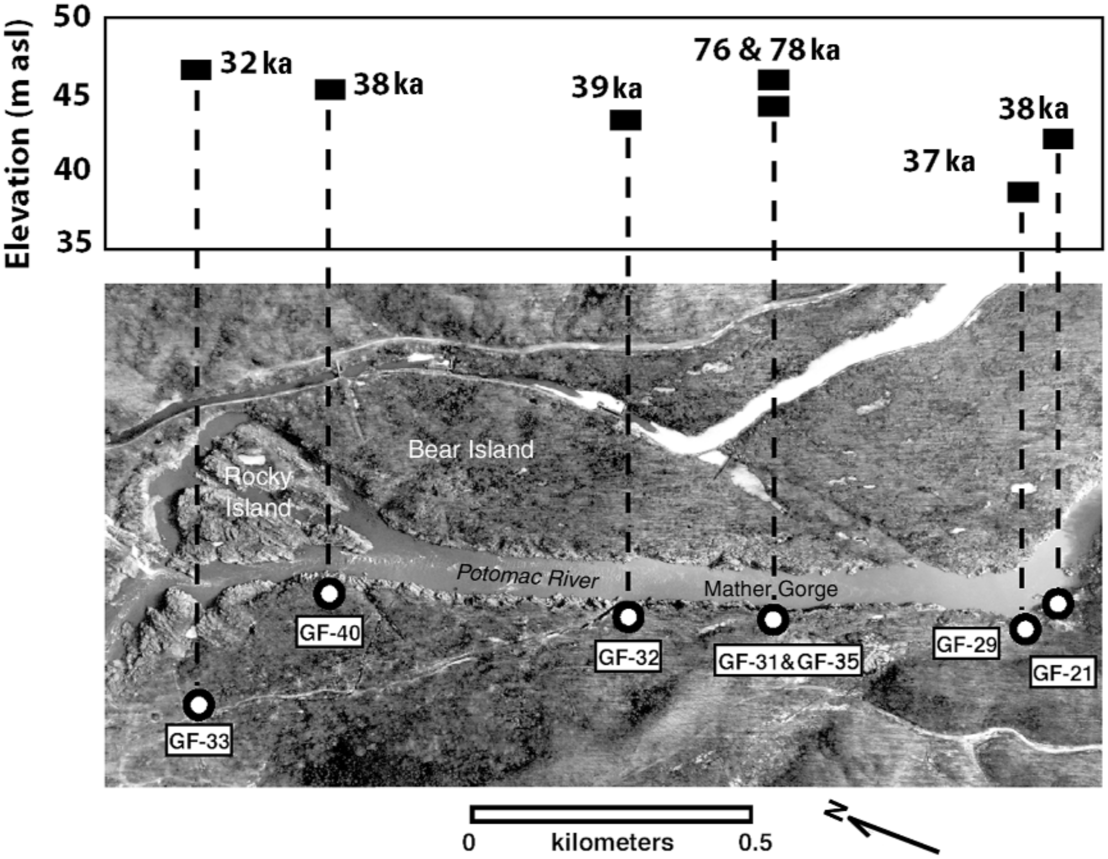


Figure 12. Samples collected from the Bear Island surface along the Virginia side of the Potomac River show no trend of age with distance downstream. m asl, meters above sea level.

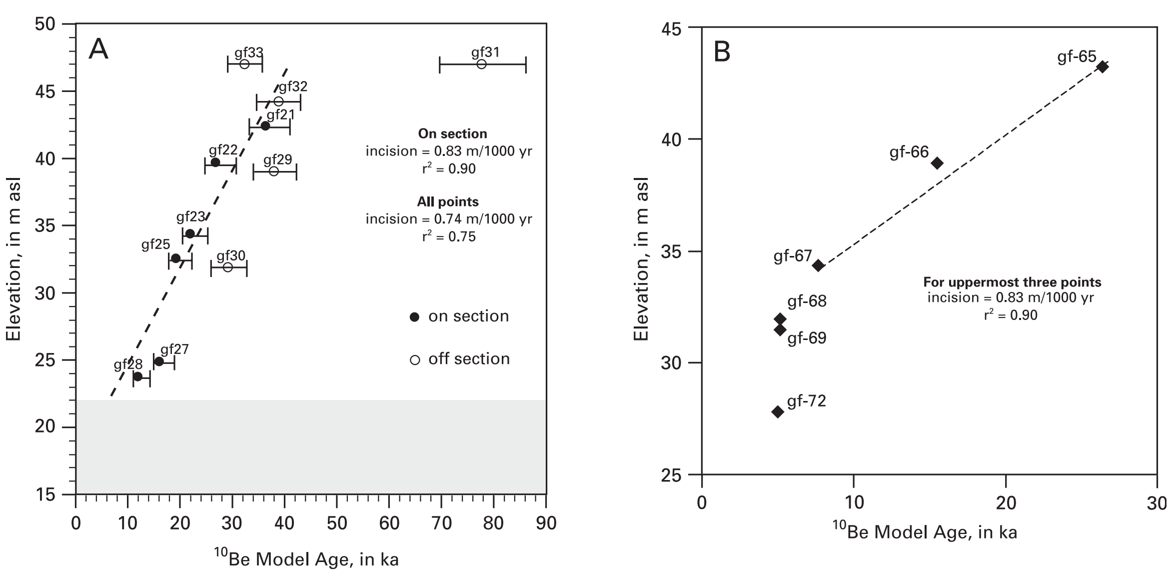


Figure 13. The model age of samples collected along vertical transects is related to elevation above the river channel. This relation can be used to estimate effective vertical incision rates at several places. A, Transect at Cow Hoof Rock. B, Transect at the Maryland viewing platform (Stop 9). "On section" are samples collected on the Cow Hoof Rock vertical transect. "Off section" are samples not collected on that transect but at other locations along and below the 140-ft strath.

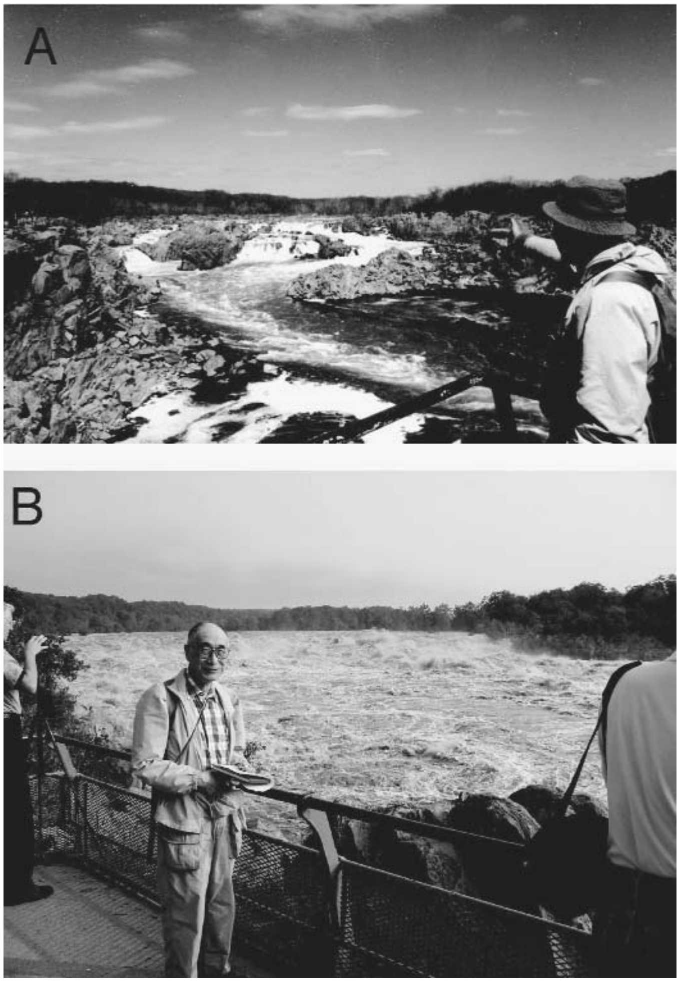


Figure 14. High points in the channel remain exposed to cosmic radiation during all but the largest floods. A, Photograph of Great Falls from downstream viewing platform on the Virginia side during low-flow conditions. B, Photograph of Great Falls from same viewpoint during high-flow conditions after Hurricane Isabel, September 2003 (flow ~165,000 cubic feet per second).

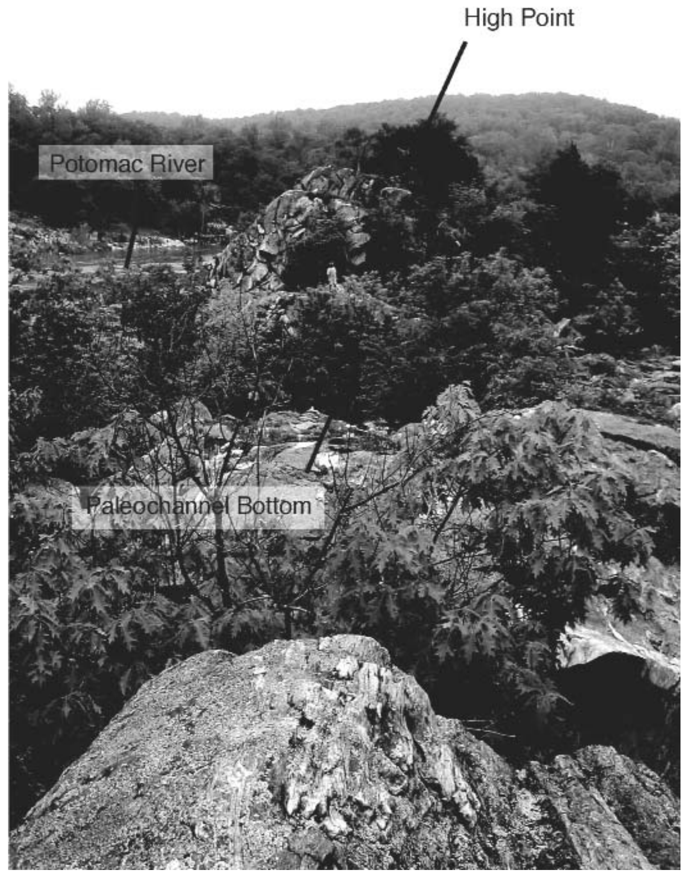


Figure 15. At Black Pond, paleochannels are exposed including the high points and the channel bottoms. Photograph taken from a high point looking toward another high point. Main channel of present-day river is in distance. Looking toward Maryland from the Virginia side of the river. Person for scale in upper center of photo.

heavily weathered, pitted, and shattered (fig. 10B). In many places, trees are growing through cleaved rock. Most outcrops are at most a few meters above the soil and were exposed at the terrace margin or near drainages. All sampled outcrops preserved at least a suggestion of fluvial erosion. Some have degraded potholes nearby; others appear rounded or streamlined by water.

Day 2 Trip Route and Stop Descriptions (fig. 11)

Leaving the McLean Hilton, turn left on Jones Branch Drive.

Turn right (north) on International Drive/Spring Hill Road.

Proceed about 0.5 mi, then turn left (west) onto Old Dominion Drive.

Continue on Old Dominion Drive (west) about 3 mi and enter Great Falls Park.

Pass the park entrance and park in the farthest parking area about 0.5 mi past the guard station.

Stop 1. The Potomac River upstream of Great Falls.

This stop illustrates the broad channel morphology of the river prior to major incision that has modified that morphology downstream. Note the isolated islands of rock exposed in the channel here and along the channel margin. Rock exposed on these islands is dosed by cosmic radiation; however, rock exposed on the channel bottom is largely shielded from cosmic rays by water.

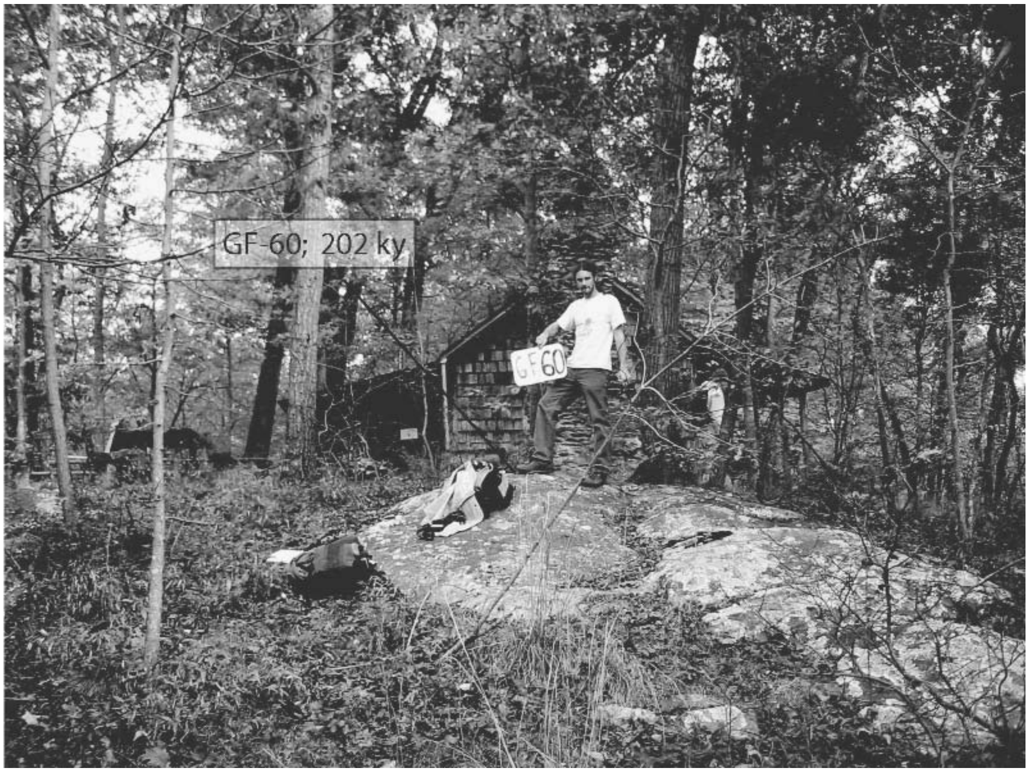


Figure 16. Sample GF-60 was collected from this outcrop at the top of Plummers Island. The outcrop is smooth and includes a remnant of a pothole suggesting that erosion has been minimal.

Find the trail head at the upstream end of the parking lot.

Walk along the gravel trail by the river until the Great Falls aqueduct dam is reached.

Go past the dam to examine the channel morphology (considering that the dam ponds water about 1.5 m (5 ft) higher than the natural river level). About 1 km (0.6 mi) farther upstream, we collected two samples from outcrops adjacent to the channel (fig. 17A). The lower outcrop (GF-53) gave a ^{10}Be model age of 31 ka. The outcrop about 1 m (3 ft) higher (GF-54) gave a slightly older model age (33 ka). Both ages suggest that incision between 35 and 30 ka was not limited to Mather Gorge but extended upstream past Great Falls, albeit to a much lesser depth.

Return to just downstream of the dam site to examine the vertical transect of samples GF-55 to GF-58. We collected four samples here at different elevations (fig. 17B). Ages range from 22 to 38 ka. The ages of the upper three samples, which span an elevation range of 4 m (13 ft), are very similar (38, 35, and 36 ka in decreasing elevation). Such similar ages imply rapid incision occurring about 35 ka, very similar to the age at which Mather Gorge begins to incise several kilometers downstream. The lowest sample (GF-58) gives a model age of 22 ka. Because this lowest sample sat just 10 cm above the water level the day we sampled (flow = 11,000 ft^3/s), the model age for this sample is a minimum estimate, the result of shielding by water during floods. Because the discharge the day we sampled was nearly two times median flow, the impact of flood-induced neutron absorption is likely to be minimal, even here.

The lowermost two samples were completely covered by floodwaters of Hurricane Isabel, for which the Little Falls gauge, 14 km (9 mi) downstream, recorded a peak discharge of 167,000 ft^3/s. This flood represented the 28th highest daily maximum flow in 73 years (yr) of record, a 2.6-yr recurrence in the partial duration series and the 13th largest annual flow, a 5.7-yr recurrence in the annual maximum series. For more information on flood flows, see the discharge values in table 1 (Day 1).

To view Great Falls and several sample sites near the falls, walk past the Visitor Center.

Take the footpath to the most upstream overlook platform.

Stop 2. Great Falls overlook.

When standing on the overlook, look back at the outcrop in the woods (fig. 18A; GF-37) which gave ^{10}Be model ages of 25.9 ka and 25.5 ka (two laboratory replicates), suggesting that significant incision here, at Great Falls, took place prior to the last glacial maximum.

Across the river is Olmsted Island and the viewing plat-

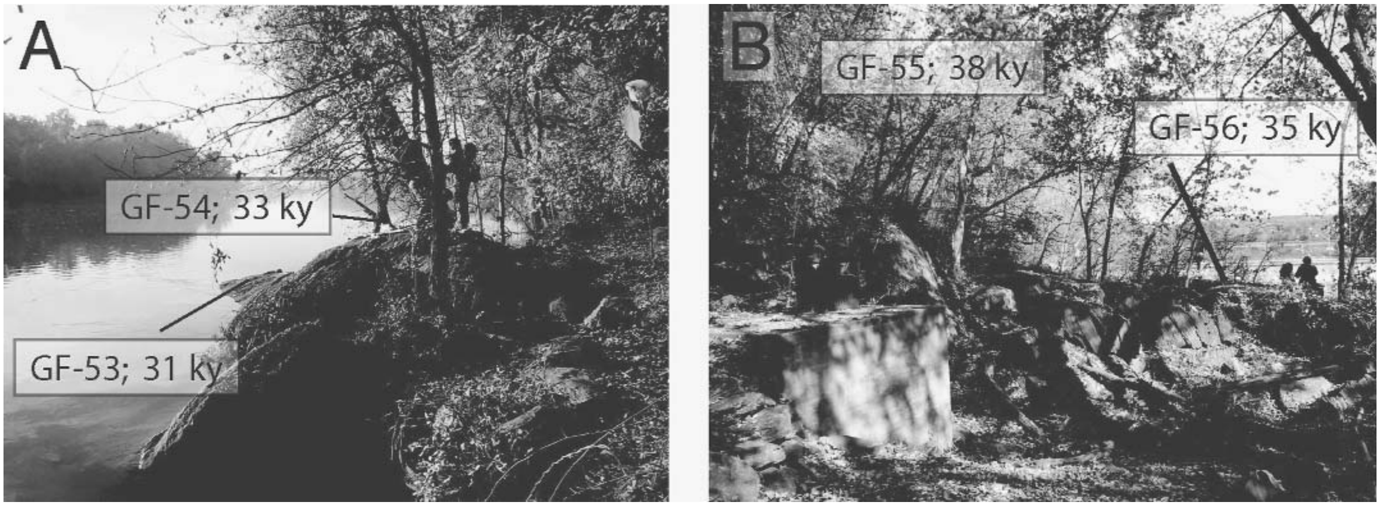


Figure 17. Sample sites upstream of Great Falls at Stop 1 (Day 2). A, Samples GF-53 and GF-54 were collected from fluvially rounded and polished outcrops along the Virginia side of the river upstream of the aqueduct dam. B, Samples GF-55 and GF-56 were collected as the two highest samples of a four-sample transect downstream of the aqueduct dam.

form. Upstream of the viewing platform, in the woods, we sampled one of the highest outcrops on Olmsted Island (GF 46). The outcrop was hard, fresh, and fluvially eroded (fig. 18B). It gave a model ^{10}Be age of 30 ka. Downstream of the viewing platform on the Maryland side of the river channel, we collected a vertical transect of eight samples (GF-65–GF-72) from the highest point (fig. 18C) to the water's edge at low flow, a span of 15.4 m (50.5 ft) elevation. The uppermost sample (GF-65) on the Maryland side has an age of 27 ka, similar to the exposure age of the outcrop here. Several samples lower on the vertical transect have shorter model exposure ages ranging from 16 to 5 ka, the latter age common to three samples collected within 2 m (7 ft) of flow at 11,000 ft^3/s (fig. 13) implying very rapid incision of greater than 4 m (13 ft) in the mid-to-late Holocene. The apparent incision rate reflected by this profile is about 50 cm/1000 yr between 27 and 12 ka, increasing to nearly 100 cm/1000 yr during the middle Holocene.

This age similarity, for samples collected from rock surfaces bordering Great Falls, suggests that the falls we see today began to take on their modern character at this location between 25 and 30 ka. Since that time, the falls have deepened and steepened but there is no cosmogenic dating evidence for steady, ongoing knickpoint retreat.

To explore the channel of the Potomac River prior to the last glacial maximum, walk downstream from Stop 2.

Pass the grassy picnic areas, to the River Trail through the woods that parallels the river's edge.

Along this trail, which winds along the terrace margin, are many bedrock outcrops, many of which preserve evidence of fluvial rounding and erosion. There is significant relief on this surface with some outcrops standing several meters above the general terrace level. By analogy to the modern river, we suggest that these same higher outcrops stood above the most common flows of the river when the Bear Island level was the bottom of the river channel.

Stop 3. The Dominant Strath Terrace: the Bear Island level.

This is the largest and most continuous strath terrace of the Potomac River near Great Falls, encompassing both the less-extensive Matildaville level and the more-extensive Bear Island level of Zen (1997a). This broad, composite surface ranges in elevation from 140 ft (43 m) to 155 ft (47 m) asl at Great Falls and dips gently downstream. Exposure ages on this strath are multi-modal with a cluster of four ages between 86 and 62 ka on high, isolated, and weathered outcrops; two ages for adjacent high outcrops at 53 and 55 ka; and another cluster of five ages from 39 to 32 ka on lower, better-preserved rock surfaces. We interpret the older ages on higher surfaces as minimum limits for an initial period of channel-bottom erosion (>75,000 yr) that lowered but did not dissect the terrace. The younger ages, which cluster between 32 and 39 ka with no clear pattern upstream or downstream, indicate the timing of terrace abandonment and the rapid incision of Mather Gorge starting about 38 ka. The age-clustering represents the time at which the Potomac River incised a narrow channel (Mather Gorge) of sufficient depth to carry the most common flows. When this occurred, the Bear Island level was abandoned. What was once the broad, inundated channel bottom was then left exposed more or less continuously to cosmic radiation.

Sample site GF-33 is found just after the trail enters the woods (fig. 19A). This is a lightly weathered outcrop of schist that stands about 1 m (3 ft) above the soil around it.

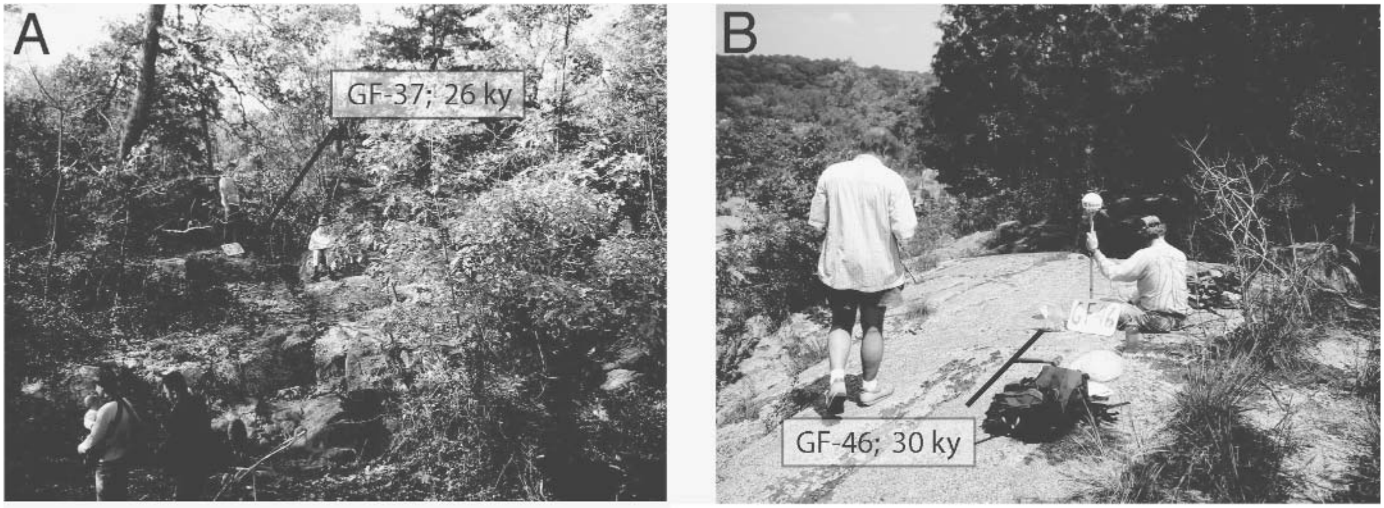


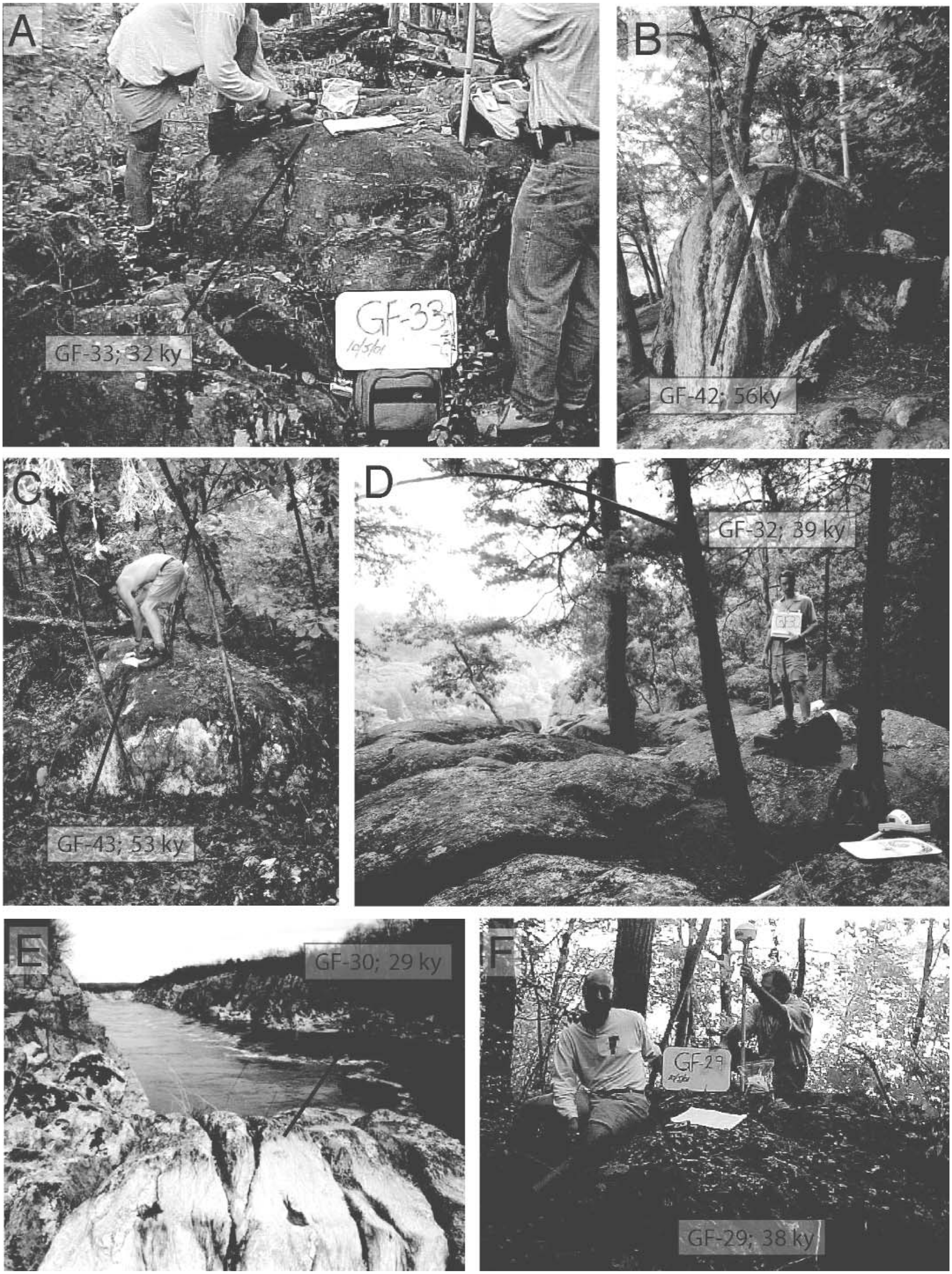
Figure 18. Sample sites just above Great Falls. A, Sample site GF-37 adjacent to the upstream Great Falls viewing platform on the Virginia side of the river. B, Sample site GF-46 upstream of the walking trail on Olmsted Island. C, Sample site GF-65, highest elevation sample on the vertical transect downstream of the viewing platform on the Maryland side of the river just below Great Falls.

The model ^{10}Be age is 32 ka. Farther down the trail, sample GF-40 has a model exposure age of 38 ka. Samples GF-42 and -43 (figs. 19B, C) have very similar exposure ages of 56 and 53 ka respectively, with the slightly higher outcrop having the slightly older age. GF-32 (fig. 19D), collected from a broad expanse of bare rock just above the walls of Mather Gorge, gives a model ^{10}Be exposure age of 39 ka. Farther downstream, sample GF-30 (fig. 19E) was collected from an outcrop topographically lower than the others, and it has a model ^{10}Be exposure age of 29 ka consistent with exposure after incision of the Bear Island level strath had already begun. This sample site was just inundated by the flood resulting from Hurricane Isabel in September 2003, whereas all other sample sites on the Bear Island level were not. Farther downstream, samples GF-29 (fig. 19F) and GF-21, have model exposure ages of 38 and 37 ka, respectively.

Proceed uphill from GF-21 to an abandoned quarry.

Stop 4. Older, Higher Outcrops—Paleo Islands?

Climbing to the top of the quarry wall, we will examine several outcrops that form another, albeit short, vertical transect. The highest of these outcrops, from which sample GF-31 was collected, is quite weathered, suggesting that it has been exposed longer than the other lower outcrops surrounding it. This field observation is confirmed by ^{10}Be measurements, which suggest that the two higher outcrops (GF-31 and GF-35, within 1 or 2 m (0.35–0.6 ft) of elevation and above the general Bear Island level) record 76,000 and 78,000 yr of exposure, respectively. Nearby, the outcrop from which GF-36 was collected is 7 m (23 ft) lower than the older outcrops, several meters below the general Bear Island level, and records an age of only 23 ka. This young age makes sense as this outcrop could only have been exposed after the incision of Mather Gorge had begun.


A
GF-33; 32 ky
GF-33
B
GF-42; 56ky
C
GF-43; 53 ky
D
GF-32; 39 ky
E
GF-30; 29 ky
F
GF-29
GF-29; 38 ky

Stop 5. Glade Hill Boulder Bed.

From the abandoned quarry, we will walk back to the parking area along the service road. Just before the service road opens into the field with picnic tables, it ascends the upstream end of Glade Hill. Here, we will turn off the trail and climb Glade Hill, which stands above the Bear Island level and was clearly an island during fluvial erosion of the Bear Island and Matildaville levels more than 90,000 ka. Glade Hill is underlain by schist, outcrops of which can be seen as we walk up the hill. However, the top of the hill is mantled by a boulder bed that is overlain by fine-grained, reddened material, probably loess. These bouldery deposits are unique in the vicinity of Great Falls and Mather Gorge.

On top of the hill are large boulders of far-traveled quartzite (discussed in detail at Stop 2, Day 1). Both ^{10}Be and ^{26}Al have been measured in one of these boulders. The ^{26}Al and ^{10}Be model ages are both high (253 and 228 ka, respectively), but they are discordant suggesting either measurement error or a complex history of exposure either before or during burial (Bierman and others, 2003). There is no unique inverse solution to the measured nuclide activities; therefore, we discuss several end-member interpretations below, the calculations for which are based on the production rate estimates of Bierman and others (1996) and Stone (2000). Because the sample was taken from a quartzite boulder fluvially transported to its current location on a high terrace above the Potomac River, there is the added complexity of considering where the boulder received some or all of its cosmic-ray dosing. With only one sample from this deposit, its history remains uncertain.

The simplest and shortest duration scenarios involve a period of exposure followed by deep burial, as explained in Bierman and others (1999). Another possible scenario begins with the boulder accumulating initial nuclide activity upstream, either by a period of surface exposure or from slow, steady erosion on the basin hill slopes, before being deposited in the boulder bar. Because we do not know the elevation at which such dosing might have occurred, we can set only an upper limit for the duration of this initial exposure period, considering the elevation and corresponding nuclide production at the site where the boulder was sampled. Because the sample site must be equal or lower in elevation than where the dosing occurred, the calculated production rates are also lower limits.

Initial boulder exposure of $\leq$280,000 yr or erosion at >2.2 m/m.y. are consistent with a two-step model in which the boulder is then buried for a period ranging from 170,000 yr in the exposure case or 70,000 yr in the erosion case, before being rapidly exposed and then sampled. Such burial might have been caused by the loess that currently covers the boulder bed in places; perhaps, the boulder we sampled was exposed as the loess was eroded in response to Holocene-Pleistocene climate change. These exposure-prior-to-delivery scenarios suggest that the boulder bed was deposited between 70 and 170 ka. Conversely, we could assume that the boulder arrived on the bar with a negligible inventory of cosmogenic nuclides; such a scenario might imply that it was delivered to the Potomac channel by rock fall and rapidly moved downstream. Once deposited, the boulder might have been irradiated before being deeply buried by loess and recently re-exposed; if this were the case, then the boulder was deposited about 450 ka (280±170 ka).

From Glade Hill, go down the hill and toward the picnic area.

Stop 6. More Older, Higher Outcrops.

At the downstream end of the picnic area, one can examine several outcrops in the woods that also stand several meters above the Bear Island level. The outcrops are weathered but still preserve fluvial forms. Samples GF-38 and GF-39 were collected from these outcrops and give ages of 86 and 62 ka, respectively (fig. 20). Considering the possible loss of mass from the surface of these outcrops by erosion, their ages are similar to those visited at Stop 4 and suggest a minor period of incision that left these higher outcrops exposed. The date of incision is uncertain, but likely it was prior to 76 ka and if erosion has been minimal, not much earlier than 86 ka.

Return to the parking area. (As you return to the parking lot, restrooms are on the lower floor level of the Visitor Center and at the upstream (north) end of Glade Hill.)
From the parking area, drive to Old Dominion Drive (1 mi).
Turn left (south) on Georgetown Pike for 4 mi.
Enter I-495 northbound.
Cross the American Legion Bridge; stay in right lane.
Take the Clara Barton Parkway exit (right lane) at the far end of the bridge.
Immediately bear left on exit ramp toward Carderock.
Follow Clara Barton Parkway until it ends.
Turn left onto MacArthur Boulevard.

Figure 19 (facing page). Sample sites on the Bear Island strath terrace surface, downstream of Great Falls. A, GF-33 was collected from an isolated outcrop less than 1 m (3 ft) high. B, GF-42 was collected from a tall outcrop within 10 m (33 ft) of GF-43. C, GF-43 was collected from a shorter outcrop adjacent to GF-42. D, GF-32 was collected from a broad expanse of rock. E, GF-30 is topographically lower than the other pictured samples and overlooks Mather Gorge. This outcrop was submerged during the peak flooding of Hurricane Isabel (~165,000 ft^3/s). F, GF-29 was collected from an isolated outcrop of rock farther downstream than the other samples.

Figure 20. Panoramic photograph of sample sites GF-38 and GF-39 on the Bear Island surface. Both outcrops are weathered and are separated by about 30 m (100 ft).

Go 1 mi to the Old Anglers Inn (on your right).
Turn left into one of the dirt parking lots.
Lunch is by the C&O Canal, a several minute walk from the parking lot. There are usually porta-potties near the parking lot.

Stop 7. The Old Terrace Surface.

Here, we examine the highly weathered outcrops and the mature, reddened soils of the old terrace surface. Outcrops are few and far between. Bedrock is shattered and shows significant physical, granular weathering. Such shattering may be the result of tree roots that wedge outcrops apart or the effect of freeze-thaw processes more active during glacial times than under present climate conditions. Most bedrock outcrops along this section of terrace are isolated knobs standing just above the blanket of fine-grained material that covers the terrace. The fine-grained material is very red, clay rich, and can be several meters deep. It is best observed where tree throws have exposed the soil. The presence of this sedimentary cover smoothes the surface and makes smooth, flat, easily walked trails.

Although we are walking on the Bear Island level at an elevation just below Stops 1 through 6, and just several kilometers downstream, the character of the surface has changed dramatically. We are now just downstream of Black Pond, the area we interpret as the paleo-Great Falls. Upstream of Black Pond, the Bear Island level is dominated by outcrops that are largely intact, exposed, and lightly weathered. Downstream of Black Pond, outcrops are few, deeply weathered, and mantled with reddened soil. We interpret this change in geomorphic character as an indication of surface age; thus, the Bear Island level is time transgressive. Upstream the surface is young; downstream the surface is old. We believe this change in character reflects the episodic nature of knickpoint retreat along the Potomac River; in other words, the knick zone is stable for thousands to tens of thousands of years and then moves rapidly upstream presumably in response to some external forcing such as climate and (or) land-level change relative to base level.

Sample site GF-73 (fig. 21) is a weathered, but still fluvially rounded, outcrop just above a cliff on the Potomac River. As of November 2003, no isotopic data are available for GF-73, nor for the samples farther downstream along this surface. However, we do have data for a single sample (GF-60, fig. 16) collected from the top of Plummers Island, just below the American Legion Bridge, 4 km (2.5 mi) downstream. The age for this sample is greater than 202 ka, supporting the geomorphically based inference that at least some surfaces downstream of Black Pond are much older than those upstream of the pond. This age also implies very low rates of erosion for metadiamictite ($\leq$3 m/m.y.) despite the humid climate of northern Virginia.

If time allows, walk upstream along the C&O Canal towpath.
Turn off on the “escape” trail about halfway along Widewater, the area where the canal widens significantly and occupies an abandoned channel of the paleo-Potomac (Southworth and others, 2001).

Stop 8. Cow Hoof Rock View (optional).

At this stop, we will examine the Cow Hoof Rock vertical transect from afar and note the dramatic change in the landscape (rock outcrops predominate and soil cover is minimal) just 1 km (0.6 mi) upstream of Stop 7. At Cow Hoof Rock, vertical incision from the time of initiation of Mather Gorge (GF-21, 37 ka) until about 13 ka (GF-28), proceeded at about 80 cm/1000 yr (fig. 13). This rate is lower than incision rates estimated in tectonically active areas (Burbank and others, 1996; Leland and others, 1998), similar to rates estimated over the same timeframe on the Susquehanna River, 100 km (62 mi) north (Reusser and others, 2003), and higher than those estimated for the Rocky Mountains (Schildgen and others, 2002).

Retrace route to the parking area opposite the Old Anglers Inn.
Drive 2 mi north on MacArthur Boulevard to the C&O Canal National Historical Park.
Park in parking lot adjacent to Great Falls Tavern.
From the parking area upriver from the tavern, walk downstream along the towpath to the bridge leading across an incised rock channel to Olmsted Island.

Figure 21. Sample GF-73 was collected from a low outcrop alongside the Billy Goat trail downstream of the Old Anglers Inn. It is weathered and stands just proud of the fine-grained sediment covering the Bear Island surface in this locale. No age data were available at the time this guide was written.

Stop 9. Great Falls Overlook, the Maryland view.

Along the path and under the bridges, note the series of bedrock channels separated by bedrock islands elongated in the direction of river flow. The channels are dry at low flow, allowing one to see a series of small knickpoints within the channels. At higher flows, water begins to fill these channels, isolating and eventually flooding the islands (fig. 22). The rock surfaces on these islands are water polished and rounded. Two samples from Olmsted Island give ages of 30 ka (GF-46, upstream of path) and 27 ka (GF-65, downstream of path).

The end of the trail is an overlook of Great Falls. This is the main channel of the Potomac River and carries most of the flow. The width and depth of the main channel suggest that the smaller, ephemeral channels are inactive except during the highest flows and will likely carry less flow over time as the main stem Potomac continues to incise and the falls retreat. It is interesting to note that these small channels (and their knick zones) occur at approximately the same point in the channel of the Potomac as the larger Great Falls. Maybe this spatial coincidence means that most of the erosion is done by flows so large that all islands are covered and the entire Great Falls area acts as one channel, instead of what we see today under lower flow conditions?

At Black Pond (the area we interpret as the paleo-Great Falls), the geometry is similar with isolated high points and incised channels but the abandoned channels are subaerially exposed. There, the main channel of the Potomac is on the Maryland side of the river and the channel-island complex is on the Virginia side (fig. 15).

Conclusions

Fieldwork along the Potomac River, in conjunction with many measurements of cosmogenic nuclides in samples collected from fluvially eroded surfaces, suggests that:

(1) The most distinct bedrock strath terrace bordering the Potomac River downstream of Great Falls is a time transgressive feature. Between Black Pond and Great Falls, this terrace surface, the Bear Island level, was first exposed about 38 ka, coincident with the onset of the latest Laurentide ice advance. Downstream of Black Pond, the same terrace surface is considerably older.

(2) Terrace formation and knick zone retreat appear to be episodic with long stillstands and rapid periods of retreat.

Figure 22. View looking upstream of one channel cutting Olmstead Island. Photograph was taken from Park Service walkway bridge at flow of 60,000 cubic feet per second (ft^3/s). This channel is dry at low flow and was bank full at ~165,000 ft^3/s.

Both field and cosmogenic data argue against steady knick zone retreat over time.

(3) Great Falls first formed between 25 and 30 ka as indicated by the exposure ages of several samples collected just above the knick zone.

(4) Two vertical transects of samples suggest that Mather Gorge was steadily incised at a rate between 0.5 and 0.8 m/1000 yr over much of the late Pleistocene.

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