Late Pleistocene Bedrock Channel Incision of the Lower Susquehanna River: Holtwood Gorge, Pennsylvania

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Introduction:

Bedrock channel systems are critical for understanding landscape evolution because they communicate boundary conditions, such as fluctuations in base level and/or land level, climate change, and tectonics across landscapes (e.g., Whipple et al., 2000). However, until recently, quantifying the timing, rate, and spatial pattern of bedrock fluvial incision has not been possible. The measurement of cosmogenic nuclides, produced in situ, now allows dating of bedrock erosional surfaces, such as fluvially sculpted strath-terraces (Hancock et al., 1998; Lal, 1991; Lal and Peters, 1967). We have used ^{10}Be to decipher the spatial and temporal pattern by which the largest river draining the east coast of North America, the Susquehanna, erodes through rock (Figure 1). Flights of bedrock terraces preserved within Holtwood gorge offer a unique opportunity to investigate quantitatively the history of fluvially sculpted surfaces, prerequisite to understanding when, how, and why rivers incise hundreds of meters through rock.

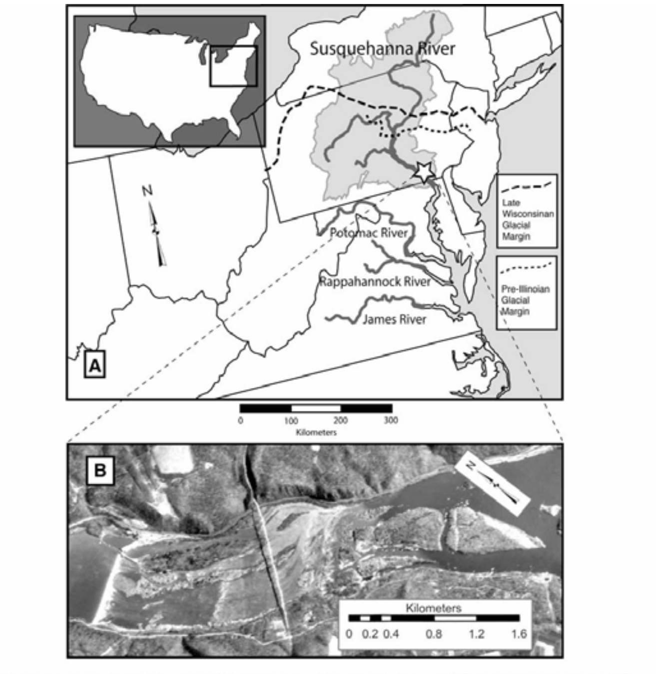

Figure 1. Location map of the Susquehanna River field area. **(A)** General layout of the US Atlantic passive margin with the locations of the James, Rappahannock, Potomac and Susquehanna Rivers. The Susquehanna River basin originates in central New York State and drains into Chesapeake Bay. Mapped glacial margins show that approximately 50 percent of the basin was glaciated during the Late Quaternary. **(B)** Section of a Digital Orthoquad (DOQ) showing the extent of Holtwood Gorge below Holtwood Dam along the lower reaches of the Susquehanna River as it flows to the southeast.

Most previous cosmogenic research considering river-eroded rock has focused on tectonically active settings where modern rock and surface uplift is accompanied by rapid rates of river incision (Burbank et al., 1996; Hancock et al., 1998; Leland et al., 1994; Leland et al., 1998; Pratt et al., 2002). In contrast, little work considers river incision into bedrock in passive settings (Bierman et al., 2003; Granger et al., 1997). Many rivers draining the North American passive margin (the Susquehanna, Potomac, Rappahannock and James) have incised deep into bedrock as they cross the fall zone, separating the Appalachian Piedmont from the Coastal Plain (Harbor et al., 2001; Pazzaglia and Gardner, 1993; Pazzaglia et al., 1998). Well-preserved fluvially sculpted bedrock forms, ubiquitous quartz, and the accessibility afforded by Holtwood Dam make Holtwood Gorge an ideal location to utilize cosmogenic dating techniques.

Setting of the Susquehanna River and Holtwood Gorge:

Similar to other rivers draining the central Appalachians, the Susquehanna narrows and the channel deepens in its lower reaches as it crosses the fall zone, separating the Piedmont from the Coastal Plain (Pazzaglia et al., 1998). At the fall zone, the Susquehanna passes through a series of cataract-gorge-terrace systems, most of which are presently flooded by hydroelectric dam reservoirs. Holtwood Gorge, the largest and most spectacular gorge along the lower Susquehanna, has escaped such flooding because it is located immediately downstream from Holtwood Dam.

Four distinct levels of bedrock terraces are preserved along the sides of Holtwood gorge and as isolated bedrock islands (dissected straths) within the gorge (Figure 2). With the exception of occasional ‘tails’ of sediment extending from the downstream end of several mid-channel islands, Holtwood Gorge is largely devoid of sediment; thus long-term burial of outcrops by fluvial sediments appears unlikely.

The uppermost strath (level 4) is preserved primarily on the western bank of the river and as island tops in the lower gorge. It consists of heavily weathered accordant summits. Because definitively fluvial forms are not preserved on this surface, it is uncertain whether these summits still represent fluvially sculpted rock. Intermediate levels (2 & 3) still preserve fluvially sculptured forms and are littered with upstream dipping potholes. The level 2 terrace can be correlated nearly 5 km downstream from the dam. The lowest strath (level 1) stretches over the western two thirds of the upper gorge, and is visible and accessible only at times of low flow when Holtwood Dam is not releasing water over its spillway. It can be correlated between 2 and 3 kilometers downstream from the dam depending on the pool elevation of Conowingo reservoir, which backs up into Holtwood Gorge. Although remarkably planar at large spatial scales (kilometers), the level 1 strath appears ‘rough’ at smaller scales (meters to tens of meters) in comparison to the rounded and streamline morphology of terraces higher above the river bed.

The northern half of the Susquehanna basin has been repeatedly glaciated; the southern half, in which Holtwood Gorge is located, remained free of ice although outwash and glacial meltwater flowed down the river, probably punctuated by a series of outburst floods. Rounded boulders of varying lithologies and up to several meters in diameter can be found perched on level 2 and 3 bedrock surfaces. Some boulders are presumed to have originated at least 50 km upstream as flood-transported clasts during deglaciation (Kochel and Parris, 2000). Radiocarbon dating constrains the Late Wisconsin glacial advance between 17 to 22 ^{14}C ky in Pennsylvania, with a maximum extent at about 20 ky (Braun, 1988; Sevon and Fleeger, 1999).

Sampling Methods and Results:

Field mapping and high-precision GPS surveying within Holtwood Gorge were used to identify four levels of bedrock strath terraces. We collected bedrock samples in longitudinal transects along each terrace level in order to detect age variance in the

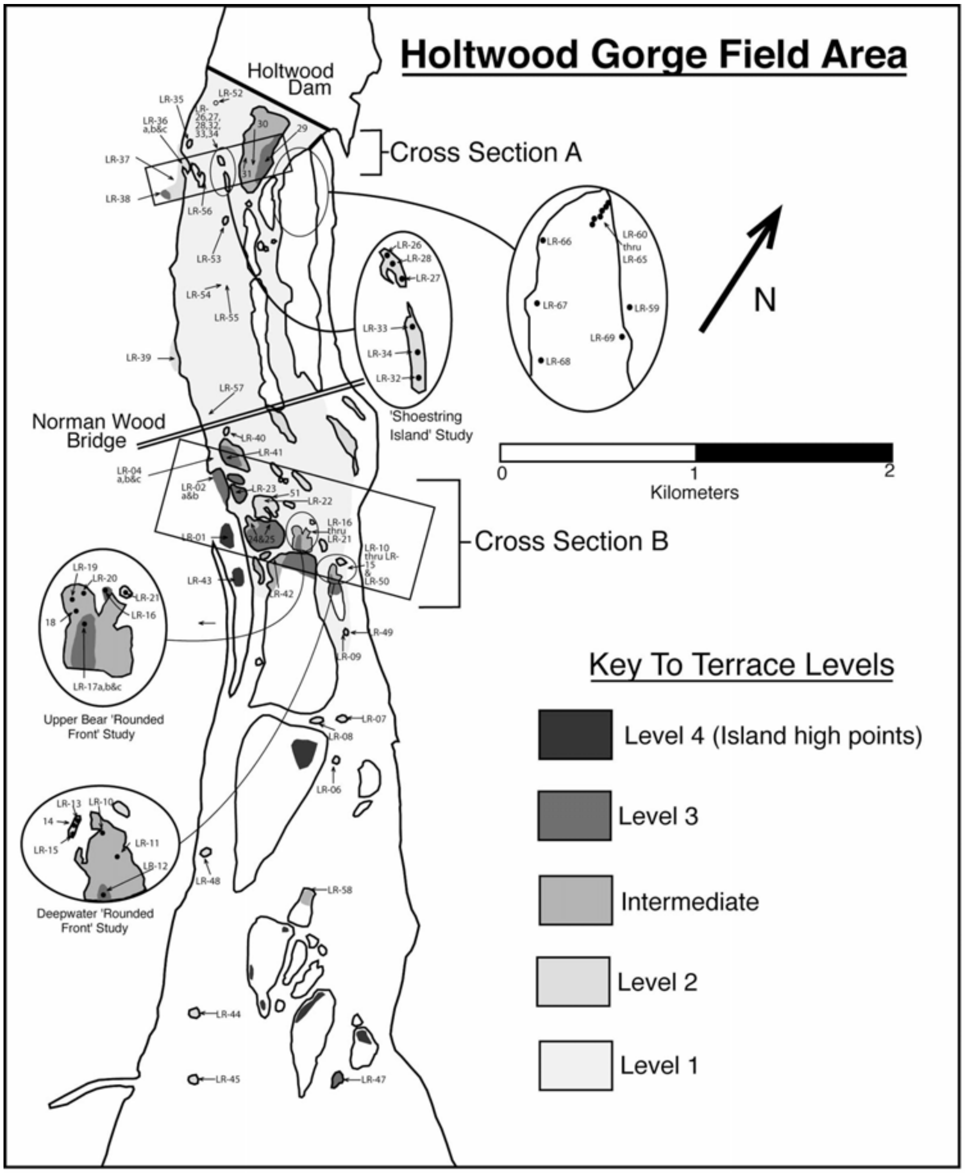

Figure 2: Field map of the Holtwood Gorge field area. Map displays all sample site locations, prominent cross sections, and the terrace level assigned to bedrock surfaces in the gorge.

downstream direction (longitudinal rates of incision). At sites on both the level 1 and 2 terraces, we collected 3 samples within 10 to 15 meters of one another to test spatial variability of ^{10}Be activity on single bedrock surfaces. In order to calculate vertical rates of incision, we collected samples in vertical transects along several cross sections in the gorge.

^{10}Be analysis of 47 samples reveals that flights of bedrock strath terraces preserved within Holtwood Gorge are Late Pleistocene features, and that the Susquehanna River has incised more than 20 m in the past ~100 ky and >8 m in the past 30 ky. Within Holtwood Gorge, model exposure ages increase with elevation above the modern river bed. The lowest terraces, levels 1 and 2, are on average 0.25 and 3 meters above the modern channel. They yield, respectively, mean model exposure ages of 14.5+/-1.3 ky (n=11) and 19.9+/-3.4 ky (n=24). A single sample from the level 3 terrace (8.5 m above the channel) yields an age of 31.6+/-3.3 ky. A heavily weathered and eroded high point, standing ~20 meters above the modern channel yields a lower limiting age of ≥97.2+/-10.5 ky (Figure 3). Model ages for samples collected between the level 2 and 3 terraces range from 17.6+/-1.9 ky to 35.7+/-3.8 ky. In gereral, model ages increase with elevation above the riverbed for these intermediate elevation samples.

^{10}Be activities for clusters of three samples 10 to 15 meters apart on both the level 1 and 2 terraces are in tight agreement (<10%, 1 sigma), suggesting that single samples are representative of the entire outcrop from which they are collected. Mean model ages for samples collected in downstream transects along the level 1 and 2 terraces are distinguishable (t=-5.93, p<0.0005). However, the two terraces display different patterns of longitudinal exposure age variance. There is no relationship between model age and distance for 2 km downstream along the lower level 1 terrace. In contrast, model ages steadily decrease in the upstream direction along the higher level 2 terrace suggesting a longitudinal incision rate of ~1.5 ky/km over a distance of 5 km.

Timing and Spatial Patterning of Erosion:

Model ages along the level 2 terrace coincide with marine oxygen isotope stage (MIS) 2 and a ~150 m drop in sea level during the last glacial maximum (~20 ky; Braun, 1988), implicating global ice volumes related to climate cycles as the drivers of incision (Figure 3). Decreasing ages upstream suggest that this terrace is a time-transgressive surface, sequentially abandoned as the river incised toward level 1 by knickpoint retreat. Deglaciation outburst flooding down the Susquehanna River, as suggested by Kochel and Parris (2000) probably lowered the channel bed further, ceasing approximately 14 kya (mean age of the lowest level). The rapid removal of slabs of rock by quarrying during such events could explain the lack of an age gradient along the level 1 terrace. The rough surface texture of the level 1 terrace in contrast to the more rounded morphology of surfaces higher above the riverbed suggests that different erosional mechanisms were active

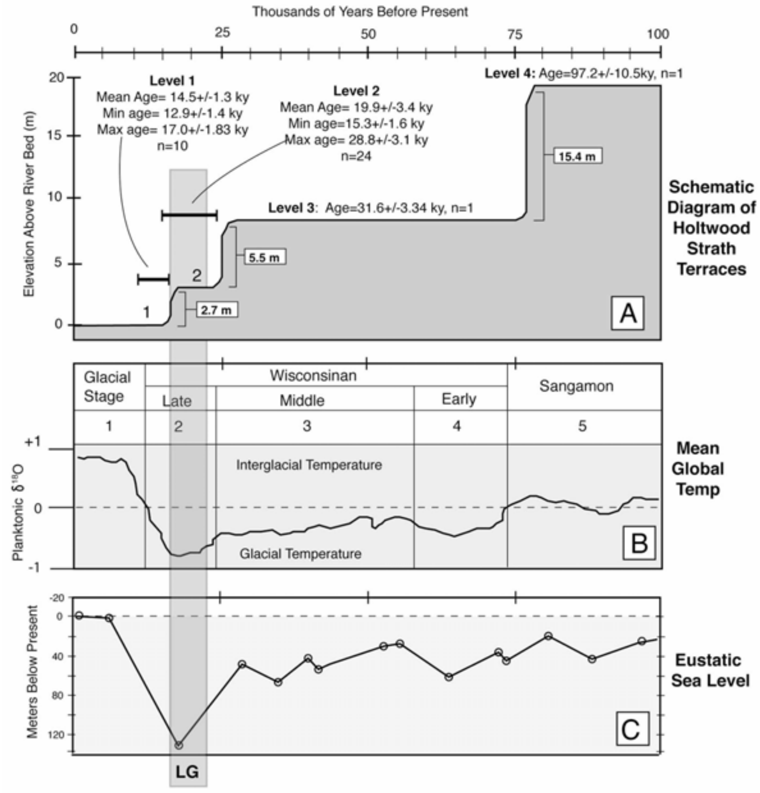

Figure 3: Summary of the spatial and temporal patterning of erosion within Holtwood Gorge. Parts A, B & C are displayed on the same axis of time in order to allow for correlation. (A) A graphical representation of the age range and meam elevation above the modern river bed for each of the strath terrace levels. (B) Mean global temperature inferred from the deap-sea oxygen isotope record (Linsley, 1996 & Ridge, 1992). Numbers indicate oxygen isotope stages. (C) Eustatic sea level curve for the Late Pleistocene. Curve constructed from estimates from the Huon Peninsula (Chappell, et.al., 1996). 'LG' indicates the time span of the last glacial max in Pennsylvania (17-22 ky: Braun, 1988).

in different parts of the channel during extreme discharge events. While large amounts of rock were removed from the channel bottom via block quarrying as the bed lowered toward level 1, the sides of the channel and isolated bedrock islands appear to have been synchronously sculpted through abraision by entrained sediment.

Rates of vertical incision dramatically decrease with elevation above the modern riverbed. Incision between the lowest two levels in Holtwood gorge occurred at a rate of ~0.79 m/ky, while incision between the highest terrace levels in the gorge appears to have been much slower (~0.2 m/ky). The timing and increased rate of vertical incision between the level 1 and 2 terraces within Holtwood gorge is similar to rates calculated within Mather Gorge along the Potomac River, MD between 35 ky and 6 ky (~0.7 m/ky; Bierman et al., 2002), further supporting global climate change as the first-order driver of incision. Increased stream power, related to elevated discharge and/or sediment load during deglaciation (e.g. Leland et al., 1998) is a plausible explanation for the initial abandonment of the level 2 terrace in Holtwood Gorge.

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