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New constraints on the late Cenozoic incision history of the New River, Virginia

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Abstract

The New River crosses three physiogeologic provinces of the ancient, tectonically quiescent Appalachian orogen and is ideally situated to record variability in fluvial erosion rates over the late Cenozoic. Active erosion features on resistant bedrock that floors the river at prominent knickpoints demonstrate that the river is currently incising toward base level. However, thick sequences of alluvial fill and fluvial terraces cut into this fill record an incision history for the river that includes several periods of stalled downcutting and aggradation. We used cosmogenic ^{10}Be exposure dating, aided by mapping and sedimentological examination of terrace deposits, to constrain the timing of events in this history. ^{10}Be concentration depth profiles were used to help account for variables such as cosmogenic inheritance and terrace bioturbation. Fill-cut and strath terraces at elevations 10, 20, and 50 m above the modern river yield model cosmogenic exposure ages of 130, ~600, and 600–950 ka, respectively, but uncertainties on these ages are not well constrained. These results provide the first direct constraint on the history of alluvial aggradation and incision events recorded by New River terrace deposits. The exposure ages yield a long-term average incision rate of 43 m/my, which is comparable to rates measured elsewhere in the Appalachians. During specific intervals over the last 1 Ma, however, the New River's incision rate reached ~100 m/my. Modern erosion rates on bedrock at a prominent knickpoint are between ~28 and ~87 m/my, in good agreement with rates calculated between terrace abandonment events and significantly faster than ~2 m/my rates of surface erosion from ancient terrace remnants. Fluctuations between aggradation and rapid incision operate on timescales of $10^4 - 10^5$ year, similar to those of late Cenozoic climate variations, though uncertainties in model ages preclude direct correlation of these fluctuations to specific climate change events. These second-order fluctuations appear within a longer-term signal of dominant aggradation (until ~2 Ma) followed by dominant incision. A similar signal is observed on other Appalachian rivers and may be the result of sediment supply fluctuations driven by the increased frequency of climate changes in the late Cenozoic.

Keywords: Appalachians; Fluvial terraces; Cosmogenic dating; Landscape evolution

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1. Introduction

Even after more than a century of geomorphic study, the spatial and temporal patterns of erosion and exhumation in the Appalachian Mountains are not known in detail. Many studies suggest that erosion from this tectonically inactive landscape averages 20–40 m/my over million-year timescales (Hack, 1965; Pavich et al., 1985; Pavich, 1989; Roden, 1991; Boettcher and Milliken, 1994; Pazzaglia and Gardner, 1994; Matmon et al., 2003; Spotila et al., 2004). However, the shorter-term variability of erosion rates is less well documented. The ubiquity of fluvial terraces throughout the central Appalachians demonstrates variability in the erosional efficacy of river networks through time (Houser, 1980; Colman, 1983; Bartholomew and Mills, 1991; Howard et al., 1995; Mills, 2000; Granger et al., 2001). Since major rivers are the only outlets for sediment removed from the tectonically quiescent landscape, the erosional efficacy of these rivers applies a dominant control over rates of relief production and erosion from the rest of the landscape (e.g., Hack, 1960; Montgomery et al., 2001).

The capacity for erosion and sediment transport of a major river is affected by complex interactions between a large number of external influences, such as climate, bedrock lithology and structure, tectonic activity, sediment supply as determined by rates of hillslope erosion, global base level change, and regional drainage reorganization (e.g., Bull, 1979; Blum and Törnqvist, 2000). Climate variability is a likely driver of many of these forcing factors that affect the behavior of fluvial systems through time (e.g., Zhang et al., 2001). Abundant fluvial deposits throughout the Appalachians provide a record of river downcutting that can be compared to records of climate variability if the duration and detail of the downcutting record can be quantified. For example, thick alluvial deposits abandoned high above modern river levels imply a period of fluvial aggradation followed by subsequent incision (e.g., Granger et al., 2001), but the timing of deposition of this alluvium is not well constrained. Thus, it is unknown whether changes in fluvial regime between aggradation and incision are related to climate change events such as the most recent onset of glacial cyclicity ca. 2–4 Ma (e.g., Shackleton et al., 1984; Maslin et al., 1996).

Many workers have attempted to assign ages to Appalachian river deposits based on relative age indicators, such as degrees of soil development and fluvial terrace morphology (e.g., Colman, 1983; Mills and Wagner, 1985). However, until the past decade, no absolute age data were available by which to calibrate these relative indicators, as most deposits are well beyond the age range of radiocarbon dating techniques. Recent advances in cosmogenic radionuclide (CRN) dating, especially ^{10}Be and ^{26}Al exposure dating, allow ages to be assigned to formerly undatable river deposits such as ancient alluvial terraces (e.g., Hancock et al., 1999; Perg et al., 2001). Even with these newer techniques, exposure dating of old surfaces is challenging. In the humid temperate climate of the Appalachians, numerous weathering and erosion mechanisms degrade potentially datable surfaces, affecting their apparent exposure history (e.g., Mills and Wagner, 1985; Phillips et al., 1998; Hancock et al., 1999; Granger and Smith, 2000). This study applied these cosmogenic techniques, supported by detailed geomorphic observations, to date well-characterized terraces of the New River in SW Virginia.

2. Terraces of the New River in the Virginia Valley and Ridge

The New River is the only major river that drains to the Gulf of Mexico while cutting through the Blue Ridge, Valley and Ridge, and Cumberland (Allegheny) Plateau physiogeologic provinces of the Appalachian Mountains (Fig. 1). Its headwaters lie in the crystalline rocks of the North Carolina Blue Ridge, and it drains ~19,500 km^2 and drops 1360 m in elevation as it passes from North Carolina through Virginia and West Virginia before joining the Ohio River. In the Valley and Ridge province, the river meanders across wide valleys floored with Cambrian and Ordovician carbonate rocks before crossing more tightly folded and uptilted Cambrian through Mississippian sandstones, shales, and carbonate rocks (Fig. 1A). Here, the New River is typically ~2 m deep and floored by mud. The New River's longitudinal profile reflects the drastic changes in lithology that the river crosses, with riffle zones and knickpoints (such as Big Falls) where it crosses the most resistant units (such as

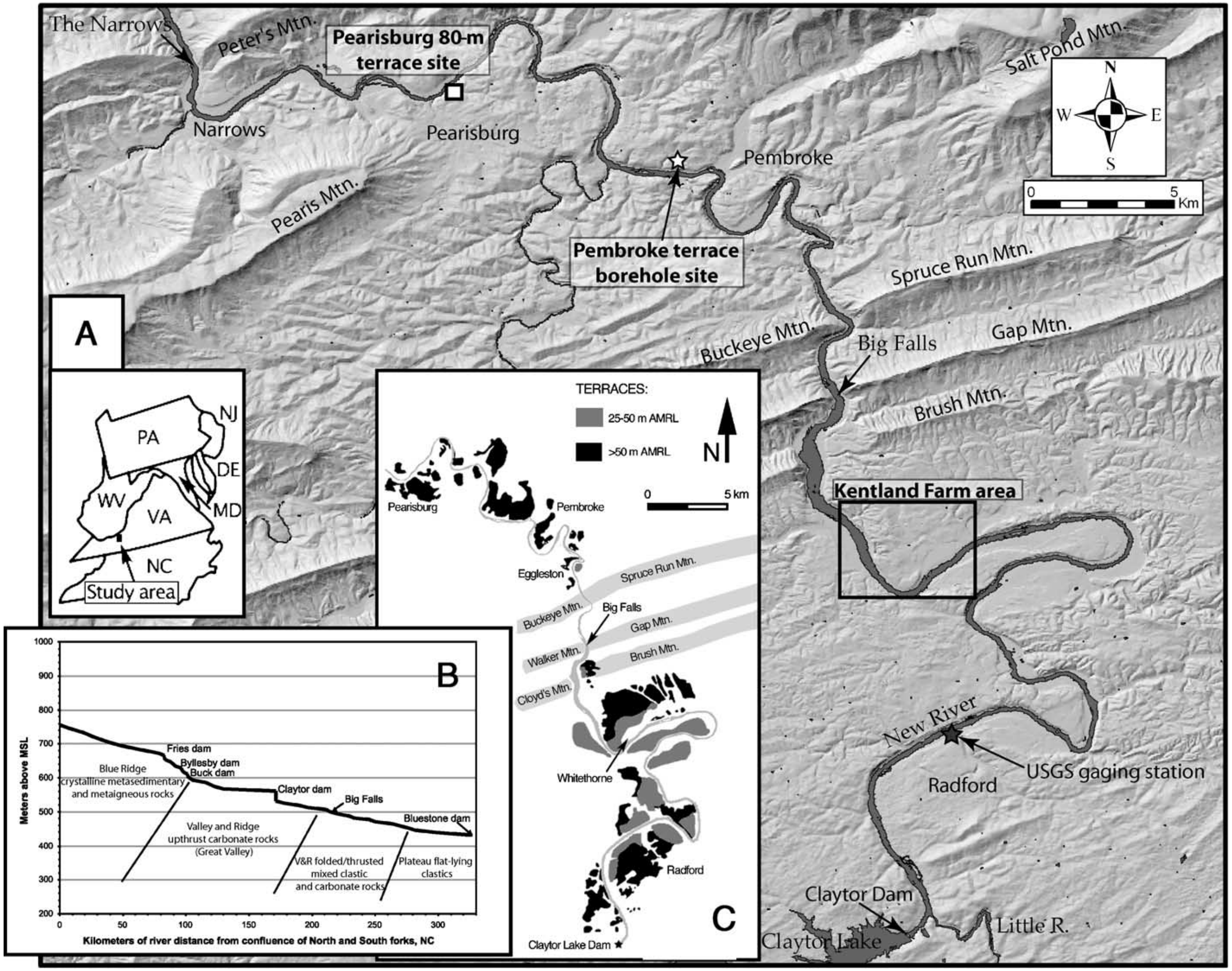

Fig. 1. (A) Topography, important features, and location of sampling sites in the primary study area. Based on USGS 1/3-second National Elevation Dataset. (B) Longitudinal profile of the New River from the confluence of the North and South forks in NC to Bluestone Dam, WV. Note steepening of profile at the transition between the Blue Ridge and Valley and Ridge and irregularities in the Valley and Ridge related to specific lithologies. Vertical exaggeration is ~280×. (C) General distribution of terrace deposits in the study area. Modern floodplain and terraces lower than 25 m AMRL are not shown, but are ubiquitous along the river throughout this area (after Mills, 1986).

the Silurian Tuscarora sandstone) (Fig. 1B). The river is also wider and shallower at these locations. Near the Virginia–West Virginia border, the New River enters the Cumberland Plateau province, where it becomes steeper and has incised into flat-lying Mississippian and Pennsylvanian sandstones and shales to form the 300-m deep New River Gorge. Just below the gorge, the New River joins the Gauley River and becomes the Kanawha River, with a very shallow gradient for its last 100 km before its confluence with the Ohio River.

In the Valley and Ridge, the New River has deposited flights of unpaired, fill-cut and strath terraces between the city of Radford and the town of Pearisburg (Figs. 1C and 2). These alluvial terraces are extensively preserved at elevations ranging from a few to over 100 m above modern river level (AMRL) (Mills and Wagner, 1985), with remnants of terrace deposits preserved even higher and many kilometers from the river's present course (Bartholomew and Mills, 1991). However, because the New River terraces are unpaired and laterally discontinuous and because many have been obscured in form from dissolution of the carbonate bedrock on which they rest (Mills and Wagner, 1985), only tentative correlation between terrace suites along the New River has been possible without absolute age constraints. Concentrations of well-preserved terrace tread area at certain modal elevations may represent times of aggradation or floodplain widening, while elevations with few preserved terraces may represent periods of incision in the river's history (Mills and Wagner, 1985). Modal terrace elevations upstream of the Big Falls knickpoint are ~27 m AMRL lower than modal elevations downstream, possibly representing differential rock uplift and greater incision downstream associated with the Giles County Seismic Zone (Mills, 1986). Alternatively, this offset of modes could be an artifact of differences in terrace formation and preservation on varying bedrock lithologies (Bartholomew and Mills, 1991).

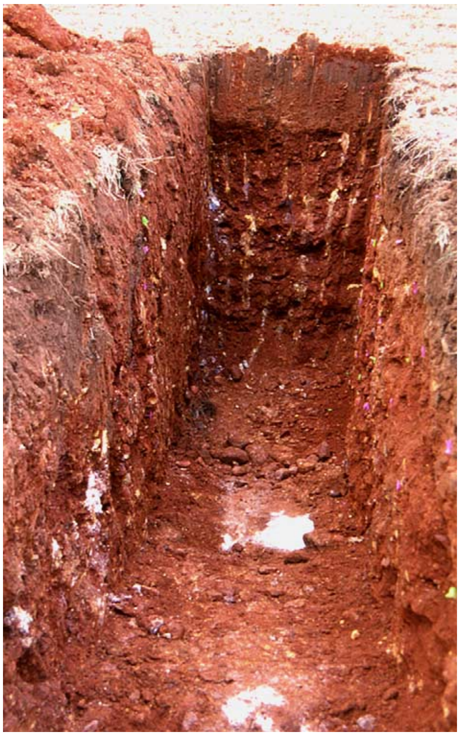

Fig. 2. Typical alluvial terrace soil with abundant rounded sandstone cobbles. Soil is extremely red (Munsell 10R). Cobbles are dominated by Valley and Ridge sandstones, and many are friable. From Pearisburg terrace, 80 m AMRL. Trench is ~3 m deep. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Harris et al. (1980) reported that soil development and mineral weathering vary systematically with terrace elevation. Thus, soil weathering characteristics are relative age indicators in New River terrace deposits and imply that terrace surfaces at a given elevation are of similar age (Mills, 1981; Mills and Wagner, 1985). Absolute dating of New River deposits was performed by Granger et al. (1997), in a study that used a cosmogenic burial technique (differential decay of ^{10}Be and ^{26}Al) to date river sediments emplaced in limestone caves and alluvial fill along the river between Big Falls and Pearisburg. The results from five caves and two horizons in alluvium 12–55 m above the river imply a mean downcutting rate of 27.3 ± 4.5 m/my over the past 2 Ma (Granger et al., 1997). However, these burial ages do not constrain the magnitude and frequency of variability of the New River's incision rate. To examine this variability, we used cosmogenic exposure techniques to constrain the timing of formation of fluvial terraces. Four terraces at the Kentland site (upstream of Big Falls), one terrace downstream near Pearisburg, and bedrock at the Big Falls knickpoint were sampled to constrain incision rates through time, along the river, and in the modern setting of the actively eroding knickpoint.

3. Geologic observations

Geologic observations build the depositional and erosional context for terrace cosmogenic exposure ages. These observations are summarized below, and additional details on the character of these terraces can be found in Ward (2004).

The geometry and extent of terraces and straths were mapped using aerial photos and in the field at sites above and below the Big Falls knickpoint. A terrace sequence ranging from 128 m AMRL down to the modern floodplain (~1 m AMRL) occurs at the Kentland site, upstream of Big Falls (Fig. 3). This flight of terraces consists of a thick fill sequence stacked on bedrock straths that are exposed as high as ~60 m AMRL. The extent of bedrock straths under higher terraces is inferred from indirect evidence, such as colluvial float on sideslopes, and is not well constrained. The upper fill-cut terraces are more dissected than the low straths. The highest levels are preserved as remnant hills with little flat tread area remaining. Above the modern floodplain, the most extensively preserved terrace level is ~50 m AMRL. Its morphology varies widely from gently sloping treads cut into large hills, to small remnant hills, to broad areas with common, prominent sinkholes and karst features. This terrace is underlain by a strath that is, in parts of the area, the highest occurrence of bedrock above the river. A 20-m AMRL terrace is also a strath terrace, with ~1 m of alluvium overlying saprolitized bedrock. The extent of the 20- and 50-m terraces implies that the river spent an extended time creating floodplains at these elevations.

Soil profiles were logged at each cosmogenic sampling site to a depth of ~2.5 m, using standard soil survey procedures and terminology. A clear chrono-

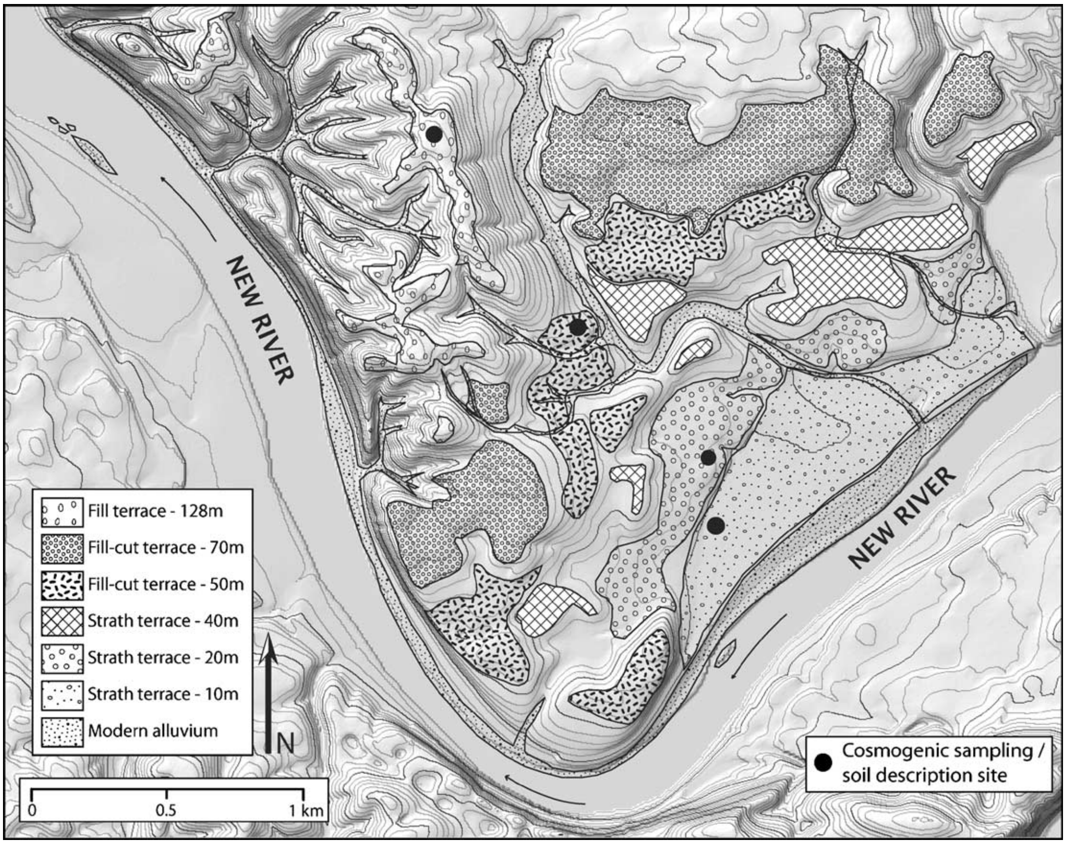

Fig. 3. Kentland site topography, terraces, types, and elevations above modern river level. Note increased terrace dissection with increasing elevation.

sequence is described by the soil profiles of terraces at 128, 50, 20, and 10 m AMRL at the Kentland site. Soil classification ranges from Hapludults and Hapludalfs on lower terraces to Paleudults and Kandiudults on high, old terraces (Soil Survey Staff, 1999). B horizon clay content, kaolinite content, and redness increase consistently with elevation. Texture ranges from loam and gravelly loam on lower terraces to clay and sandy clay on higher terraces. Color ranges from 10YR 4/6 (dark yellowish brown) on lower terraces to 10R 3/6 (dark red) on the highest terraces. Soil profiles are generally more cobble-rich with depth, implying that upper layers consist of overbank fines deposited as the terrace was abandoned. This is consistent with the common occurrence of mica at shallower depths in these soils, including those as high as 80 m AMRL (Ward, 2004). These observations suggest that little erosion has taken place from these surfaces since abandonment.

Terraces downstream of Big Falls with similar morphologies are less common and poorly preserved, and complete suites of terraces such as those at Kentland are not present. In the Pearisburg area (Fig. 1), the best-preserved terrace surfaces are about 80 m AMRL and are underlain by carbonate bedrock at a depth of ~5–10 m. The 80-m Pearisburg terrace features a strongly developed soil and flat tread morphology, but possibly represents the gentle sideslope of a slightly higher terrace remnant, suggesting that surface erosion may have occurred here. Although significantly lower AMRL, the Pearisburg cosmogenic sampling site's soil (Rhodic Kandiudult with 10R 3/6 color and sandy clay texture in the B horizons) is similar to that of the Kentland 128-m terrace (Ward, 2004).

A centimeter-scale log of the color, texture, and other visible characteristics of a 40-m borehole core through a 55-m AMRL terrace at Pembroke, VA (Fig. 1), indicates steady aggradation of channel gravels and overbank fines, with only short-duration hiatuses or incision events represented by three weak paleosols (Ward, 2004). Cobble provenance in excavated terraces was estimated in the field to evaluate the source area of such aggradational events. Based on visual comparison of hand samples of regional bedrock to ~50 cobbles from each excavation, cobble provenance in Kentland terraces is dominated by Blue Ridge meta-sandstone (e.g., Antietam Quartzite) from ~100 km upstream and changes little with terrace elevation (Fig. 4). This is consistent with the high concentration of metamorphic mica in these soils. The dominance of Blue Ridge provenance is logical, given that the portion of the Valley and Ridge upstream of the Kentland site contains mainly limestone and shale. Below Big Falls, provenance shifts to a dominance of Valley and Ridge clasts. Based on visual estimates of clasts in the

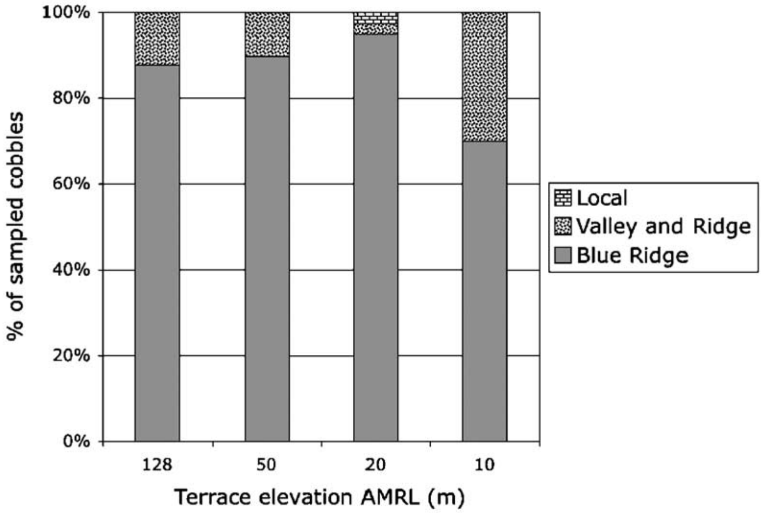

Fig. 4. Provenance of cobbles in Kentland Farm terrace alluvium. All terraces are dominated by Blue Ridge quartzite and metasediments. Slight increase in Valley and Ridge lithologies in the 20-m terrace may indicate a minor change in upstream drainage configuration.

Pembroke drill core and the Pearisburg excavation, downstream terraces contain ~75% Valley and Ridge sandstone cobbles (from Tuscarora, Juniata, and Rose Hill formations) with a smaller component (~25%) of Blue Ridge meta-sandstone cobbles.

At the Big Falls knickpoint, ribs of resistant Tuscarora Fm. sandstone emerge from the riverbed. These bedrock ribs typically strike perpendicular to the river and have a steep upstream dip. Exposed bedrock exhibits classic abrasion features such as potholes and flutes, along with quarry voids where the river has plucked out large rectilinear blocks of sandstone (Fig. 5). The largest, meter-thick ribs of Tuscarora sandstone erode more slowly than thinner ribs as they are only fully submerged during a few high flow events each year and are subject to less abrasion by suspended sediment and mobile bedload. Though quarrying is generally regarded as a more efficient erosion mechanism than abrasion (e.g., Whipple et al., 2000), the two processes are likely to interact strongly at Big Falls. The smooth, continuous upper surfaces of the bedrock ribs, which do not exhibit scars from plucking of small blocks, suggest long periods of exposure of rib surfaces between quarrying of

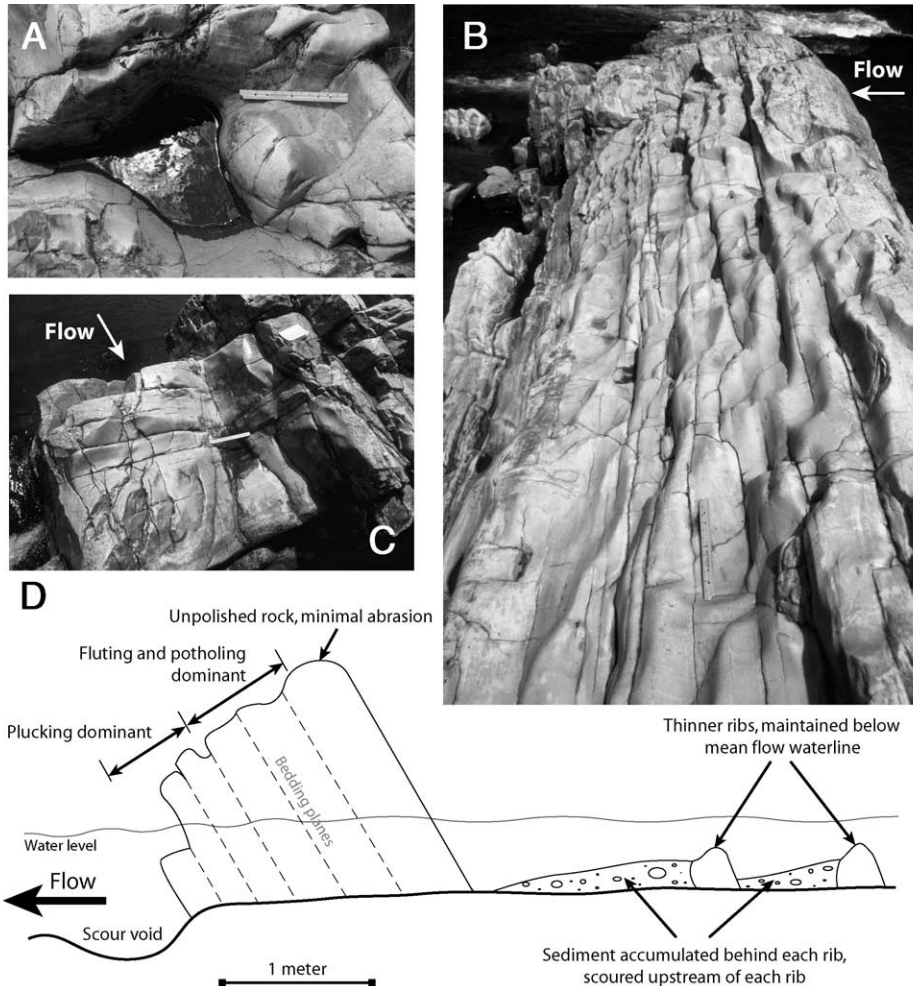

Fig. 5. Bedrock incision features at Big Falls. Ruler is 30 cm. (A) Large pothole. Potholes vary in diameter from ~2 to ~50 cm. (B) Fluting on large rib. Flutes range from ~7 to ~30 cm in length and ~4 to ~18 cm in width. Note flutes oriented parallel to bedding strike and perpendicular to river flow, indicating local flow along the strike of the bedrock. (C) Plucking scars. Note polishing and rounding of scar by abrasion since quarrying occurred. (D) Summary of erosion forms and mechanisms at Big Falls.

meter-scale blocks. The uniform elevation of high bedrock surfaces across the knickpoint suggests that the ribs may be analogous to an abandoned strath. However, the size of quarried joint blocks varies greatly on thinner ribs or lower surfaces of the large ribs, and many are small (<10 cm thick). This implies that different erosion mechanisms apply to different portions of the outcrop, or that the entire outcrop is eroding irregularly but at a steady average rate despite persistence of some more solid ribs. Whatever the mechanism, the erosion rate of the bedrock at Big Falls should be similar to the modern rate of incision of the New River.

4. Cosmogenic radionuclide exposure dating

Well-preserved terraces at the Kentland and Pearisburg sites were chosen for CRN exposure dating. A vertical series of terraces at Kentland was chosen to provide an incision history for the river at that site and an additional terrace at Pearisburg to place constraint on downstream variations in incision rate. Sampling sites were chosen at elevations with the greatest terrace area, so that ages would represent significant periods of floodplain and terrace development. Locations were selected on mostly flat terrace treads away from eroding sideslopes and obvious sources of deposition where upper soil horizons were not gravel-capped or cobbly suggesting that significant surface erosion had taken place. Terraces affected by karst collapse, which are pitted by sinkholes and exhibit irregular surfaces, were avoided. Terraces situated over noncarbonate rock were preferentially selected. Four representative sites at Kentland (10, 20, 50, and 128 m AMRL; Fig. 3) and one downstream at Pearisburg (80 m AMRL) were excavated and sampled for quartz sand at 25- or 50-cm depth intervals using methods modified from Hancock et al. (1999). Additional site characteristics and methods are presented in Ward (2004).

In addition to the terrace soil sampling sites, three samples were collected along a Tuscarora sandstone bedrock rib protruding from the river at Big Falls. Sites were chosen to be horizontal to avoid an inclination correction of CRN production rates. The upper surface of the rib exhibited two 1-m^2 areas that lacked abrasion features and evidence of recent plucking. These areas should represent the longest exposure period of the bedrock at the knickpoint and were sampled in two spots ~3 m apart and ~2 m above the riverbed. If quarrying of large blocks (1 m or more in thickness) is the dominant mode of erosion and blocks remain in place for tens of thousands of years between quarrying events, dating this surface yields a reasonable estimate of the time since the last plucking event. A third bedrock sample, ~1.5 m above the riverbed, consisted of a loose, cobble-sized joint block that had been exposed by plucking but had subsequently been abraded, which should represent a more frequent timescale of bedrock erosion. For blocks of this size, the calculated average erosion rate should be within ± 10% of the steady erosion rate (Small et al., 1997).

Targets for ^{10}Be measurement by accelerator mass spectrometry were prepared from amalgamated sand samples (or bedrock samples crushed to sand) using standard procedures (e.g., Kohl and Nishiizumi, 1992). Targets were processed at the Center for Accelerator Mass Spectronomy at Lawrence Livermore National Laboratory, and ^{10}Be concentrations were measured to a precision of ≤4%. Reported errors in calculated ages represent ^{10}Be measurement error only, propagated by calculating age for profiles defined by the minimum and maximum measured concentrations within 2σ error for each sample, and generally do not exceed measurement precision. However, uncertainties on model ages are higher than implied by measurement uncertainty because of assumptions inherent to interpretation of age or erosion rate from a CRN depth profile.

Additional unpropagated errors are derived from variations in interpreted ^{10}Be production rates. Locally, the density of the terrace material, which was measured at each site, affects production rate, but systematic variation of soil density through time cannot be constrained. Production rates were corrected for shielding from topography. Additional shielding from snow, loess, and vegetative cover cannot be constrained through time but is likely to be minor because of the low densities of these materials (Kubik et al., 1998). Production rates can vary through time on a broader scale from changes in solar output, geomagnetic field configuration, and atmospheric density, and a range of rates is accepted depending on cosmic ray flux modeling and calibration on different timescales (Nishiizumi et al., 1986, 1996; Brown et al., 1991; Masarik and Reedy, 1995; Dunai, 2000). We assume a ^{10}Be sea level, high latitude surface production rate of 5.55 atoms/g qtz, which is ~7% higher than short-term (≤13 ka) calibrations and ~7% lower than million-year estimates, and is thus appropriate for 10^4–10^6 year timescales (Clark et al., 1995; Perg et al., 2001). Empirically, choosing a higher or lower production rate from among accepted values changed resulting model ages by no more than ~10%. The chosen surface production rate was scaled to the altitude and latitude of each sampling site using the scaling systematics of Dunai (2000). We used systematics for ^{10}Be production in quartz that follow those outlined by Granger and Smith (2000), allowing production both by neutron spallation and by muon interactions to be taken into account.

Interpreting exposure age from ^{10}Be depth profiles depends on the processes experienced by the upper surface of the terrace. In the simplest case, the CRN depth profile is an exponential decay, which can be fitted and used to calculate ages using production functions (Hancock et al., 1999). More commonly, CRN accumulations are modified by inheritance from erosion and transport of alluvium, mixing of soils from bioturbation (e.g., animal burrowing and tree-throw) and physical pedogenesis (e.g., shrink–swell, freeze–thaw, and translocation), and surface erosion.

In the case of inheritance, an exponential CRN concentration–depth curve should be asymptotic to a concentration that represents the inherited CRN inventory (Hancock et al., 1999). Inheritance may be variable in alluvial stratigraphy, depending on the provenance and specific duration of sediment storage for the quartz used for CRN measurement. However, this variability is generally of minimal concern for old ($>10^5$ year) terraces in which exposure age greatly exceeds depositional lag time and radioactive decay has reduced the inherited CRN inventory. Small inheritance corrections were made for several terraces in this study (Table 1).

Soil mixing can be accounted for in exposure dating by integrating a uniform, mixed CRN depth profile and fitting the integrated inventory to an expected exponential curve using production functions (Perg et al., 2001). We used soil and sedimentary characteristics (e.g., pebble lines), in addition to the CRN depth profiles themselves, to estimate the depth of probable mixing in each terrace excavation. Well-defined exponential CRN profiles occurred at several of the sites, indicating a lack of mixing. Accounting for mixing can be problematic if multiple mixing depth zones are present or if mixing rate varies with depth, which can obscure the maximum depth of mixing and prevent estimation of inheritance in unmixed sediment.

Although significant surface erosion is unlikely on flat, well-preserved terrace treads, higher elevation (AMRL), more poorly preserved terraces may have experienced some hillslope erosion. An exposure age for a high terrace is thus a minimum if the surface has been lowered by erosion. The magnitude of erosion can potentially be estimated from ^{26}Al:^{10}Be ratios (Granger and Smith, 2000). Where erosion is suspected and calculated exposure ages are inferred to be too young (e.g., are younger than terraces at lower elevations), erosion rates can be estimated assuming a steady-state ^{10}Be concentration as

$$\varepsilon = \rho^{-1}\Lambda\left[P_0 N^{-1} - \lambda\right] \quad (1)$$

where ρ is the material density, Λ is a penetration length scale (~160 g/cm^2), P_0 is the scaled spallogenic production rate (muogenic production is ignored), N is the measured concentration of the isotope in the sample, and λ is the decay constant of ^{10}Be (4.6×10^{-7} year^{-1}) (e.g., Bierman, 1994; Hancock et al., 1998).

5. Results

Observed ^{10}Be concentrations in terrace deposits increase with elevation above the river and decrease with depth at each site (Fig. 6). Calculating exposure ages from these data is complex, however, given the apparent variability in geomorphic and sedimentary processes and the exposure history at each site. Therefore, discussion of results and age estimates are presented below and are summarized in Table 1.

The Kentland 10-m terrace yielded a weakly exponential CRN profile with evidence for inheritance and no apparent zone of mixing. The best fitting exponential corresponds to an exposure age of 130 ± 15 ka with an inherited ^{10}Be concentration of

Table 1
Overview of CRN profile analysis results (preferred interpretation for each site in bold; see text for discussion)

		Inheritance/shifted expobential		Mixed			Surface erosion	
Site	Profile fig.	Inheritance (at/g qtz)	Age, ka (shifted exponential)	Evidence for mixing	Assumed mixing depth (cm)	Age, ka (mixed)	Evidence for erosion	Erosion rate, m/my (assumed steady)
Kentland 10 m	6A	**6.42E+05**	**130 ± 15**	None; pebble lines at 100 cm and below	100	235 ± 15	None	N/A
Kentland 20 m	6B	N/A	N/A	Uniform profile, irregular soil/sparolite interface	**125**	**610 ± 20**	None	N/A
Kentland 50 m	6C	1.73E+06	185 ± 20	High, uniform concentration at depth	**275**	**955 ± 25**	Slight surface slope	N/A
Kentland 128 m	6D	0.00E+00	620 ± 20	Profile mismatch w/upper sample	62	500 ± 15	Top of convex hill; age mismatch between mixed and unmixed parts of profile; appt. age unreasonably young	**2.02 ± 0.05**
Pearisburg 80 m	6E	1.45E+05	435 ± 20	None	N/A	N/A	Appt. age unreasonably young vs. relative age indicators	**1.62 ± 0.07**
Big Falls BF01	N/A	N/A	**23.0 ± 0.6**	N/A	N/A	N/A	None; unpolished surface rarely submerged	25.0 ± 0.8
Big Falls BF02	N/A	N/A	**23.6 ± 0.6**	N/A	N/A	N/A	None; unpolished surface rarely submerged	24.4 ± 0.7
Big Falls BF03	N/A	N/A	20.9 ± 0.6	N/A	N/A	N/A	Small joint block surrounded by plucking scars	**28.4 ± 0.7**

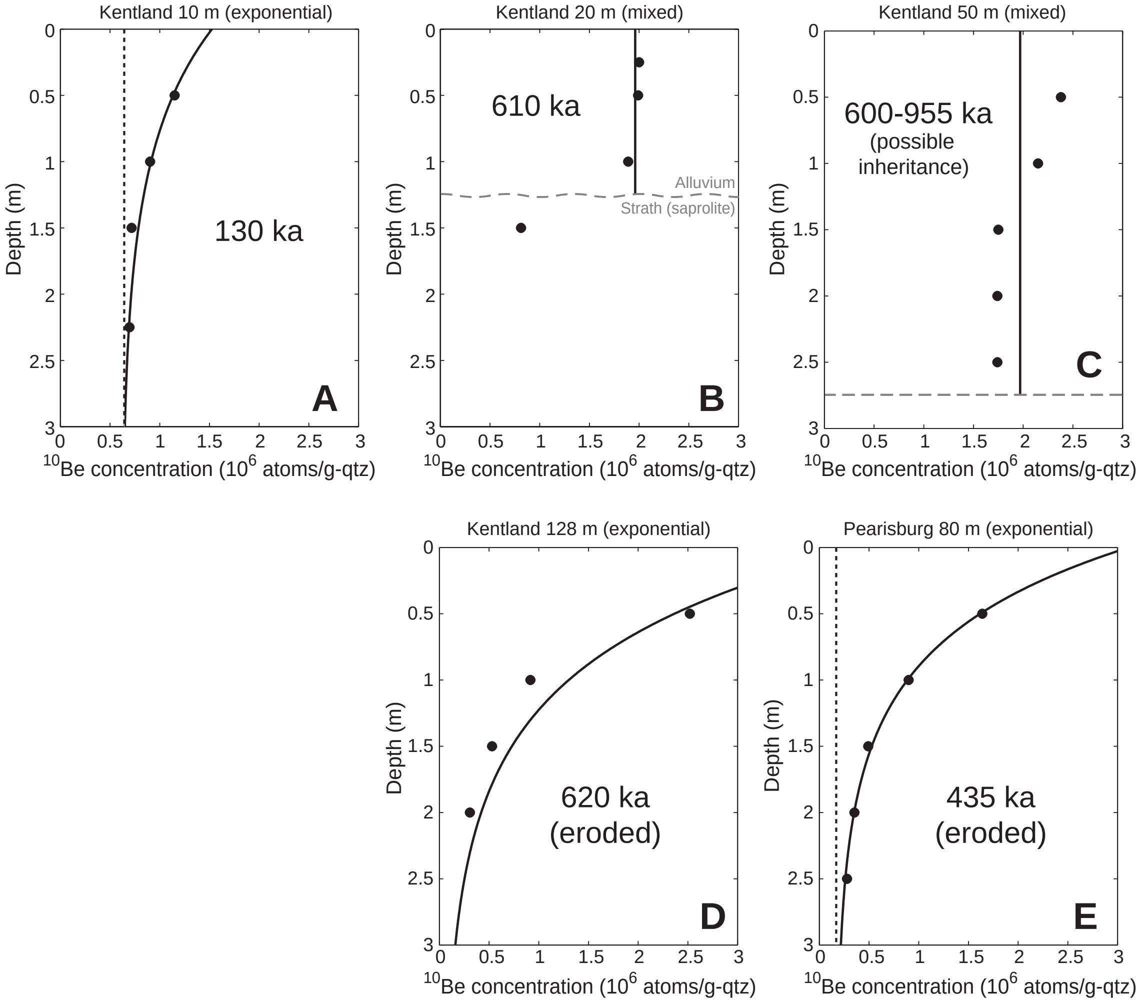

Fig. 6. Interpreted ages from best-fit CRN production profiles (solid black lines). Dotted vertical lines represent best inheritance at time of exposure. Dashed horizontal lines represent base of mixed interval. See text for discussion of individual profiles.

6.42×10^5 atoms/g qtz (Fig. 6A). This apparent inheritance is similar to ^{10}Be activities measured in modern river sediment elsewhere in the Appalachians (Matmon et al., 2003). Elevated ^{10}Be concentrations in the lower part of the profile could also be a result of profile mixing. In the absence of inheritance, integration of the CRN concentration to a depth of 250 cm yields an exposure age several hundred ka higher. However, the CRN profile itself (reasonably exponential in the upper meter) and soil characteristics (e.g., pebble lines at 100 cm depth, relatively shallow upper C horizon at 195 cm) independently suggest that mixing has not occurred.

The Kentland 20-m terrace CRN profile is characteristic of mixing. A uniform ^{10}Be concentration occurs to the bottom of the alluvium at 125 cm, where an irregular, apparently bioturbated contact occurs between the alluvium and shale saprolite that retains its bedrock structure. The integrated CRN inventory over the alluvial deposit, assuming mixing and no erosion or inheritance, yields an exposure age of 610 ± 20 ka (Fig. 6B). The ^{10}Be concentration in saprolite at 150 cm depth is lower than in the soil, but higher than expected at this depth after 610 ka of production. This supports the assumption that the alluvium above has not been affected by inheritance, but suggests that the strath itself may have been exposed prior to deposition of the alluvium. The difference between the expected and measured concentrations is explained by 35 ± 5 ka of surface exposure. This is a minimum estimate, given the likelihood that the saprolite's density has decreased during this time.

The CRN profile of the 50-m Kentland fill-cut terrace is weakly exponential, similar to that of the 10-m terrace. The best-fit exponential gives an age of 185 ± 20 ka with an inherited ^{10}Be concentration of 1.73×10^6 atoms/g qtz. The similarity in age estimate with the 10-m terrace stems from the similarly weak curvature of the upper profile and because ~85% of the 50-m CRN inventory is attributed to inheritance, though the ^{10}Be concentration is 2–3 times higher. The exponential interpretation is questionable for several reasons. The calculated inheritance concentration is greater than or equal to the maximum concentrations measured in the lower terraces and is ~4 times that measured in modern Appalachian river sediments (Matmon et al., 2003) before correcting for ^{10}Be loss from radioactive decay since deposition (which was probably long before the exposure of this terrace). The calculated age also contradicts the relatively stronger soil development of this terrace compared to the 10- and 20-m terraces, as well as geomorphic superposition, given that the river should have cut this terrace much earlier than the lower terraces. Inheritance of this magnitude could be derived from colluvial influx from a higher, slowly eroding sideslope. At the rate of erosion suggested by the apparent inheritance, however, this input must have occurred over a much longer period, ~700–900 ka. A likely alternative explanation is that this profile has been mixed. A maximum age estimate, assuming deep mixing and zero inheritance is 955 ± 25 ka. CRN concentrations at depth are uniform, supporting continuous and steady profile mixing between ~1 m and a depth at or below the deepest CRN sample at 2.5 m (Fig. 6C). The exposure age would be lower if some degree of inheritance is present, although this cannot be constrained with the data. For example, subtracting an inheritance of 6.42×10^5, as observed in the 10-m terrace, then integrating the remainder as a mixed profile yields an age of 600 ka, a reasonable minimum age similar to the age of the 20-m terrace.

The CRN concentration-depth profile at the highest (128 m) Kentland terrace is strongly exponential. The best-fit exponential curve to this profile yields an exposure age of 620 ± 20 ka with no inheritance (Fig. 6D). Some degree of shallow mixing is suggested by the mismatch between the uppermost sample concentrations and the expected exponential. Allowing for mixing to a depth just below the 50-cm-deep sample, which corresponds to the Bt2/2Bt3 soil horizon boundary, results in upper, mixed, and lower, exponential age estimates that are ~100–200 ka younger. In either case, however, these age estimates contradict expectations based on all other available evidence. The extremely well-developed soil, high elevation above the river, and older exposure ages of lower terraces indicate that the age of this terrace should be >1 Ma. In fact, assuming an average incision rate of 43 m/my based on the lower terraces indicates that the age of the 128-m terrace should be ~3 Ma. To be this old with the observed low CRN concentration, ~4 m of surface erosion is required, assuming a constant erosion rate through time. Given that this site is located at the slightly convex summit position of an eroded and ancient terrace remnant, this magnitude of erosion seems plausible. We therefore do not adopt the calculated exposure age and interpret the observed CRN profile as modified by erosion. Using the lower, unmixed exponential CRN profile to estimate the surface CRN concentration (N) and interpreting this as a steady-state concentration, Eq. (1) yields a surface erosion rate from this terrace of 2.02 ± 0.05 m/my.

The 80-m Pearisburg terrace features a strongly developed soil and a flat tread morphology, but possibly represents the gentle sideslope of a slightly higher terrace remnant, suggesting that surface erosion may have occurred here. Its elevation AMRL implies an age of ~2 Ma, using the incision rate based on the lower Kentland terraces. The best-fit exponential CRN profile yields an exposure age of 435 ± 20 ka with 1.45×10^5 atoms/g qtz of inherited ^{10}Be and no indication of mixing (Fig. 6E). Approximately 3 m of surface erosion are needed to reconcile the CRN profile with the expected age range. The measured CRN concentration yields an erosion rate of the terrace tread of 1.62 ± 0.07 m/my, based on Eq. (1).

The three bedrock samples from the Big Falls knickpoint yielded approximately equal ^{10}Be concentrations. These can be interpreted as representing a surface exposure age (with CRN accumulation since exposure) or as representing a steady erosion rate (with constant surface CRN concentration through time). For an estimate of surface exposure age, bedrock surface-sample concentrations were treated as the depth = 0 portion of an exponential CRN curve and analyzed similarly to the soil profiles. This assumes zero shielding by water, which is reasonable given that only rare, high-flow events (< 1% of time) cover these high surfaces (Ward, 2004), and assumes instantaneous exposure with no prior ^{10}Be ingrowth. Samples BF01 and BF02, from a few meters apart on the same bedrock surface, yielded exposure ages of ~23 ka, whereas BF03 yielded ~21 ka (± 0.6 ka, Table 1). If these surfaces were at riverbed level when abandoned, the 2 m of downcutting below BF01 and BF02 implies a local maximum incision rate of 87 m/my. Alternatively, the CRN concentrations yield estimated steady erosion rates of ~25 m/my (BF01/BF02) and 28 m/my (BF03). The steady erosion interpretation may apply to areas where small-block plucking is in evidence (BF03), but the concentrations from continuous upper surfaces represent exposure ages (BF01 and BF02). This means that the average erosion rate across the knickpoint is slower than 87 m/my, but is at least ~25 m/my. An average erosion rate calculated from a statistically significant number of samples across the entire outcrop would yield a more precise estimate of the knickpoint-wide erosion rate (Small et al., 1997).

6. Discussion

These results yield the first constraints on the exposure history of preserved terraces on the New River in the Valley and Ridge. Combining the new cosmogenic exposure ages with previous age constraints allows construction of a partial history for the New River aggradation and incision over the past few million years (Fig. 7). This record allows examination of the behavior of a major Appalachian river and consideration of how changes in variables such as climate, drainage organization, and bedrock lithologies can influence deposition and incision.

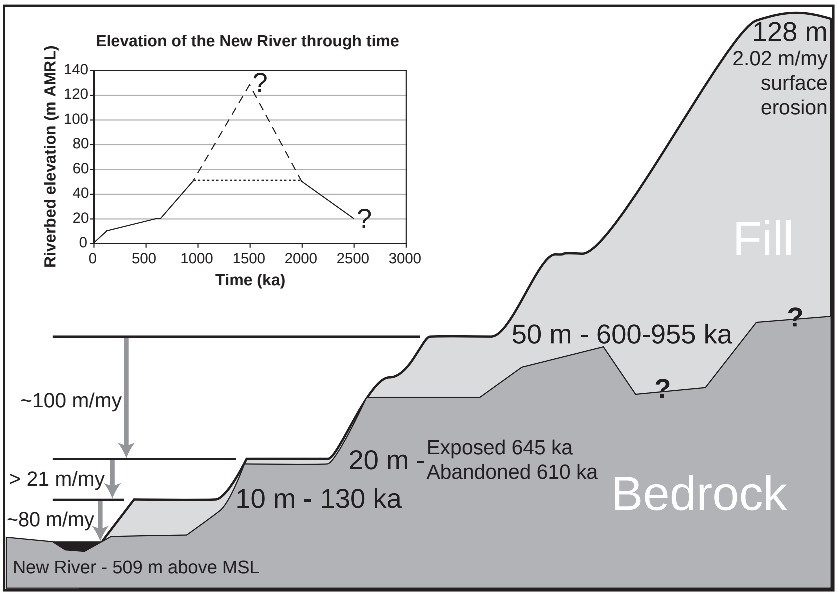

Fig. 7. Schematic profile of terraces and elevations AMRL at Kentland Farm, with terrace ages and inferred incision rates. Exact elevation of bedrock under thick upper fill package is unknown. INSET: Elevation of the New River through time, relative to its current position. Dashed lines represent upper and lower bounds where elevation is poorly constrained. Question marks indicate unconstrained timing of inflection points.

Based on apparent cosmogenic burial ages of terrace sediment near the Pembroke, VA borehole site, the New River deposited a thick sequence of alluvial fill in the Valley and Ridge ~2 Mya (Granger et al., 1997; Law and Robinson, 1999). This fill was deposited on a strath ~15 m AMRL at Pembroke and reached a maximum height of at least 128 m AMRL at Kentland. This deposition appears to have been relatively uninterrupted based on a 40-m core at Pembroke. Prior to ~1 Ma, the New River incised through this fill, abandoning a terrace surface at 128 m or higher and cutting to 50 m or lower AMRL. By 0.6–0.95 Ma, the New River had cut extensive terraces into the fill at the 50-m level and subsequently abandoned them and downcut to 20 m AMRL at a minimum rate of ~100 m/my. The presence of several distinct but discontinuous terraces between 50 and 20 m AMRL indicates that this downcutting was not uniform. By 0.6 Ma, the 20 m AMRL strath had been covered with just over a meter of alluvium and abandoned. Downcutting proceeded to an elevation ~2 m AMRL at a minimum rate of 21 m/my, but the river then aggraded to 10 m AMRL. This terrace was abandoned by renewed incision at 0.13 Ma. The average incision rate to the modern river was ~80 m/my. Linear regression through the age-elevation data (including the origin) yields a long-term average incision rate of 43 m/my for terraces upstream from the Big Falls knickpoint, which is reasonable for a large Appalachian river (e.g., Hack, 1965; Matmon et al., 2003) and consistent with average New River rates (~27 m/my) based on cave sediment Be/Al burial ages as old as ~1.5 Ma. Unfortunately, the apparent erosion from the terrace dated at Pearisburg disallows any comparison of incision rate between the reaches upstream and downstream of Big Falls.

This incision history implies a dynamic river system, controlled by external factors that vary with time on timescales of 10–100 ka. On longer timescales, the New River's average incision rate does not differ greatly from regional rates of regolith production, erosion, and flexural uplift on the Piedmont (4–20 m/my; e.g., Pavich et al., 1985; Pavich, 1989; Pazzaglia and Gardner, 1994), erosion rates of Tuscarora sandstone on ridgetops in the Valley and Ridge based on CRNs (~6 m/my; Kirwan and Hancock, 2002), and basinwide erosion rates on timescales of 10^5–10^6 year in the Great Smoky Mountains and the Susquehanna River basin (~8–27 m/my; Matmon et al., 2003; Reuter et al., 2004). Exhumation rates on timescales $\geq 10^6$ year based on apatite (U–Th)/He and apatite fission track thermochronology range from ~8 to 40 m/my (Roden, 1991; Boettcher and Milliken, 1994; Spotila et al., 2004). Though river incision during the past ~1.5 Ma appears to have been slightly faster than regional denudation rates, this may be a result of fast incision into alluvial fill that must be balanced over longer timescales by slower erosion of bedrock (Mills, 2000). Even so, our results suggest that the long-term average incision rate actually represents the integration of numerous periods of incision and aggradation. This unsteady behavior mimics ideas that fluvial response timescales are long and that steady state erosion is difficult to attain (e.g., Anhert, 1970; Whipple, 2001; Baldwin et al., 2003).

The first-order signal in the history of the New River is a transition from dominant aggradation to dominant incision between 1 and 2 Ma and a consequent increase in incision rates. This is consistent with a transition from stability or aggradation to incision at increased rates by other major rivers in the Appalachians, such as the James River in the Piedmont (Hancock, 2004) and the Green River on the Cumberland Plateau (Granger et al., 2001). It is also consistent with large fluctuations and a general increase in sediment yield in Appalachian basins in the late Cenozoic based on offshore sedimentation records (Poag and Sevon, 1989; Zhang et al., 2001). This implies a region-wide change in fluvial behavior during the late Cenozoic, with increased erosion rates possibly related to the increasing amplitude of glacial–interglacial cyclicity in the northern hemisphere ca. 2–4 Ma (Shackleton et al., 1984; Molnar and England, 1990; Zhang et al., 2001).

The timescale of second-order variability in the New River's incision history is similar to that of late Cenozoic climate fluctuations, 10^4–10^5 year. However, the large uncertainty in terrace exposure ages does not allow direct correlations with specific climate events, such as marine isotope stages. Despite this, it is useful to consider the mechanisms by which climate variability leads to variability in fluvial behavior in a passive margin setting, as well as how this fluvial behavior can arise without climatic forcing. One obvious climate control on rivers is base level change via sea level fluctuation. The depressed sea level of the last glacial period at 30–35 ka is correlated with the onset of rapid incision within 100 km of the coastline on the Susquehanna and Potomac Rivers (Pazzaglia and Gardner, 1994; Reusser et al., 2004), and other coastal Appalachian rivers also seem susceptible to base level change (Colman, 1983). However, interior rivers of the Ohio–Mississippi network such as the New River may be too distant and too insulated by resistant rocks in the Allegheny Plateau to adjust to sea level change at a timescale that keeps pace with climate fluctuations (Hack, 1973; Blum, 1993; Schumm, 1993; Harbor et al., 2004).

Another mechanism, but one that could still be climate-related, is drainage reorganization. Houser (1980) and Bartholomew and Mills (1991) suggested that the New River has changed its course and lost significant drainage area to encroaching Atlantic-draining streams over the past several million years. These adjustments may have resulted in different ratios of discharge to sediment supply, thus promoting aggradation or incision, depending on the dominant bedrock type being eroded. For example, erosion of carbonate rocks results in minimal input of physical sediment, allowing a higher ratio of stream power to sediment load in and downstream of these areas. Granger et al. (2001) argue for drainage reorganization promoting incision in the Ohio River system, related to climate by a major ice advance that may have shifted the course of the Ohio River ca. 1.5 Ma. A similar downstream reorganization could also affect the New River, although the effect would be akin to that of a base level change that would have to propagate up through the Allegheny Plateau.

Alternatively, sediment supply may be the dominant factor linked to climate change that causes aggradation and incision of rivers isolated from short term base level fluctuations (Bull, 1979; Blum and Törnqvist, 2000). Sediment supply may increase during glacial times because of a decrease in stabilizing vegetation, stormier climate, and increased hillslope erosion (Bull, 1991). In turn, increased meltwater from snow and periglacial ice in unglaciated basins could increase discharge and stream power and result in incision during deglaciation. This effect has been suggested in other areas, such as the tectonically active Olympic Peninsula, Washington (Wegmann and Pazzaglia, 2002); the arid and active Transverse Ranges, California (Bull, 1991); European rivers (Maddy et al., 2001); and the glaciated Wind River basin, Wyoming (Hancock et al., 1999; Hancock and Anderson, 2002). In fact, the absolute ages of prominent terrace surfaces, glacial outwash fans, and moraines in the Rocky Mountains (including the Wind River basin) are similar to those of the New River terraces (Fig. 8; Chadwick et al., 1997; Hancock et al., 1999). In these systems, the number of glaciations seen in the marine isotope record exceeds the number of observed terraces. However, numerical modeling of terrace formation suggests that terraces produced during specific glacial oxygen isotope stages should be larger and more likely to be preserved than any others, suggesting in turn that observed terrace distributions and ages can be explained by sediment supply changes driven by glacial–interglacial cycles (Hancock and Anderson, 2002). Deglaciation may thus lead to incision in not only glaciated basins but unglaciated and arid basins, in tectonically active and inactive settings.

An additional insight gained by this study is the importance of geomorphic observations when applying CRN exposure dating techniques to fluvial terraces. This is especially true in tectonically stable settings where alluvial deposits can persist for very long periods of time and are modified by erosion and bioturbation during this time. In our experience, surface erosion is the most limiting problem in CRN exposure dating of ancient alluvium and becomes more severe with elevation AMRL and terrace age. Mixing and inheritance are also problematic to differing degrees, depending on the geologic setting. However, the main difficulty lies in that they affect the modeled exposure age in opposite ways. Fortunately, detailed examination of terrace soils allows evaluation of the likelihood and magnitude of each of these complications. Additionally, more complete soils data should be examined to refine rates of soil development in Appalachian alluvium. Integration of data from previous studies of terrace soils (e.g., Harris et al., 1980; Mills and Wagner, 1985) and attention to soils in future CRN dating efforts should allow a wider range of soil development indicators to be calibrated against cosmogenic exposure ages, in turn aiding in effective interpretation of sources of uncertainty in exposure ages of ancient terraces. Ultimately, complete landscape and soil analysis, multiple sites per terrace,

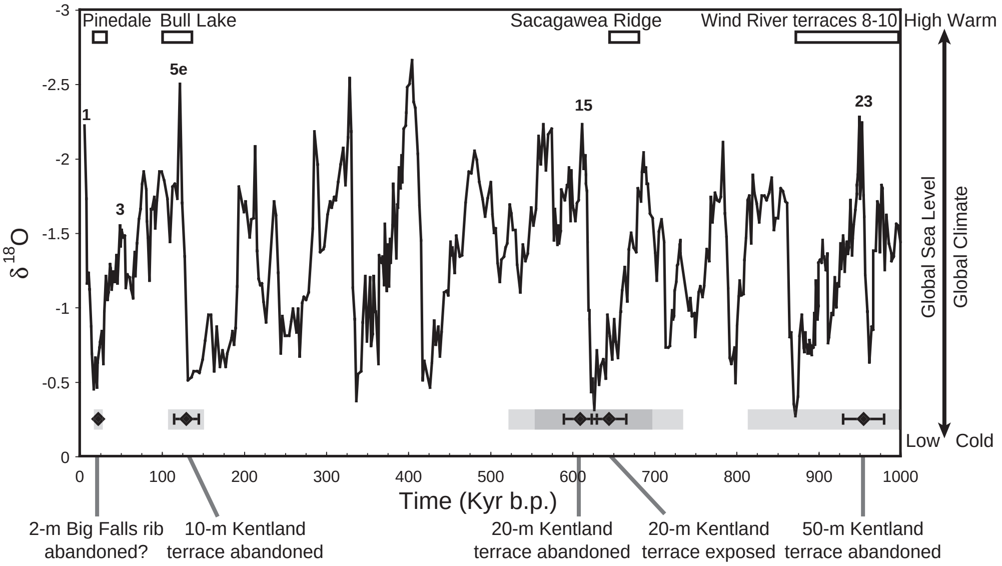

Fig. 8. Exposure ages in context of $\delta^{18}O$, Marine Isotope Stages, and global climate and sea level. Because uncertainties are unconstrained on exposure ages, both propagated analytical uncertainty (black error bars) and ±15% ranges (gray boxes) are shown. Correlations are not meaningful within ±15% for all except the very youngest ages. Upper black boxes show age ranges of deposits from prominent glaciations in the central Rocky Mountains (after Chadwick et al., 1997). These events appear to coincide with exposure ages of the prominent New River terraces dated in this study. Isotope data from *Globigerinoides ruber*, ODP hole 677, courtesy of the Delphi Project, http://delphi.esc.cam.ac.uk/ (isotope stage numbers after Bowen et al., 1986).

more samples per CRN profile, and analyses for multiple isotopes are needed to tightly constrain CRN exposure ages on ancient alluvium.

7. Conclusions

Cosmogenic exposure ages from a series of fill-cut and strath terraces reveal the episodic nature of the incision history of the New River. Since ~955 ka, the New River has incised 50 m through alluvial fill and bedrock at an average rate of 43 m/my. During short-term periods of incision, downcutting rates have reached at least 100 m/my. Between periods of incision, extended periods of aggradation and terrace formation are documented, ending with terrace abandonment events at ~600–955, ~610, and ~130 ka. Because of the nature of the ancient alluvium that was dated, these ages should be considered approximate, with potential for error of 100–200 ka from insufficient constraint on variables such as erosion and inheritance. On Tuscarora sandstone at Big Falls, erosion is currently proceeding at a rate of at least 25 m/my. These results demonstrate the timescale and magnitude of variability in process rates that can occur in Appalachian drainages and suggest a climatic influence on the New River, possibly by way of changes in sediment supply. The similarity of ages of the most extensive New River terraces to glacial deposits and fluvial terraces in the central Rocky Mountains is suggestive of a continent-wide influence of glacial–interglacial fluctuations on fluvial erosion processes.

Strong soil development was aided by extremely slow rates of erosion from terrace surfaces. Even high, convex terrace remnants yielded cosmogenic erosion rate estimates of ~2 m/my or less. These findings echo recent results from other unglaciated Appalachian drainages and imply a quasi-disequilibrium, in which river incision rates far outstrip rates of erosion of surrounding landforms.

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