Incision of the Youghiogheny River through the Laurel Highlands determined by a new river terrace stratigraphic age model, Ohiopyle State Park, southwestern Pennsylvania

Kurak, E.[1], Pazzaglia, F. J.[1], Li, C. X.[2], Patching, A.[1], Shaulis, J.[3], Corbett, L.[4], Bierman, P.[4], Nelson, M.[5], and Rittenour, T.[5]

[1]Earth and Environmental Sciences, Lehigh University

[2]Earth, Ocean, and Environment, University of Delaware

[3]Pennsylvania Geological Survey

[4]Community Cosmogenic Lab, University of Vermont

[5]Luminescense Lab, Utah State University

Abstract

New surficial mapping and dating of alluvial deposits along the Youghiogheny River in southwestern Pennsylvania has generated a new terrace stratigraphic model linking well-known deposits of the Carmichaels Formation with terraces further upstream through Ohiopyle State Park. Flights of four to six terraces are found in three distinct zones with gradients that are subparallel to the channel, including a steep convex reach of the river. Numeric ages obtained from 25 terrestrial cosmogenic nuclide (TCN) samples and one optically stimulated luminescence (OSL) sample constrains the timing of terrace genesis on the Youghiogheny River, over the past 1.2 Ma, with terrace deposition coinciding with glacial climates. TCN burial and isochron ages of ~610 ka and ~300-350 ka are used to construct long-term incision rates ranging from ~20 m/Myrs upstream of Ohiopyle where the channel gradient and subparallel terrace profiles are gentle to ~50 m/Myrs downstream of Ohiopyle where the river profile is steeper in a broad convex knickzone. There were at least two base level falls totaling ~81 m conflated in the knickzone between Ohiopyle and Connellsville, the top of which includes Ohiopyle Falls and is retreating at a rate of ~1 cm/yr. Of the total base level fall, ~45 m is likely attributed to the draining of Glacial Lake Monongahela and formation of the Ohio River now dated at ~1.8 Ma by TCN burial ages on type-Carmichaels lacustrine facies exposed along the river in the Pittsburgh

low plateau. The other ~36 m is attributed to non-uniform uplift of the Laurel Highlands, with a hinge more or less at Connellsville, which may be ongoing.

Introduction

Fluvial terraces have long been used to reconstruct the incision histories of rivers that are known to be driven by unsteady changes in climate and base level (Pazzaglia, 2013). Rivers draining the Laurel Highlands in southwestern Pennsylvania are inherited from a syn-Appalachian drainage that has been impacted by several, major post-orogenic changes in base level ranging from the formation of the Atlantic passive margin to the integration of the Ohio River (Granger et al., 2001). Evidence for these base level changes are encoded in several steep channel reaches called knickzones that also locally coincide with steep-walled gorges incised through structural and topographic highs. The Youghiogheny River, a major tributary of the larger Monongahela catchment, rises at the continental divide near the Allegheny escarpment and flows northwest nearly orthogonal to the Laurel Highlands before joining the trunk Monongahela River in the Pittsburgh low plateau (**Fig. 1**). Like all rivers draining this part of the Appalachians, the Youghiogheny River is flanked by fluvial terraces that, in their downstream reaches, have an unclear relationship with the former Glacial Lake Monongahela and associated deposits of the Carmichaels Formation (Campbell, 1902; Harper, 1997, 2002; **Fig. Figs. 1c, 2**).

Since 2017, a combination of new exposures of Youghiogheny River terrace deposits in Ohiopyle State Park, material support from the PA Geologic Survey and the USGS EDMAP program, and logistical support from Ohiopyle State Park has resulted in an age model of the terraces, based primarily on terrestrial cosmogenic nuclide (TCN) dates, assembled through several undergraduate and graduate projects at Lehigh University. Detailed 1:24,000-scale mapping of terraces from Connellsville through Confluence, PA has resulted in several possible terrace correlations that reconstruct the incision of the Youghiogheny River over the past million years (Kurak, 2021). The terrace map reveals a coherent suite of terraces at the reach scale, but a proposed correlation across the Laurel Highlands downstream to Pittsburgh requires two or more regional base level falls, only one of which is demonstrably related to the draining of Glacial Lake Monongahela and formation of the Ohio River. The terrace map also adds an important data layer to a new generation of bedrock maps in and around Ohiopyle State Park (Shaulis, 2020). Ohiopyle is the most visited park in the PA State Park system with several large waterfalls and other evidence of active river incision that the terrace map and age model help place into a broader landscape evolution context.

The goal of this paper is to use the terrace map and a stratigraphic age model anchored at Ohiopyle, PA to propose tectonic, climatic, and river integration processes responsible for base level change and river incision across the Laurel Highlands. It also presents new evidence for the age of Glacial Lake Monongahela and critically evaluates ideas regarding the formation of tight bedrock meanders in the Ohiopyle area.

Location and geologic setting

The Youghiogheny River study reach and Ohiopyle State Park are primarily located in Fayette County, Pennsylvania southeast of Pittsburgh (**Fig. 1**). The region mapped for the EDMAP project is an irregular strip ~ 1-2 km wide and 30 km long following the Youghiogheny River from Confluence, PA to Connellsville, PA (**Figs. 1a, b**) spanning parts of the South Connellsville, Ohiopyle, Mill Run, Fort Necessity, and Confluence 7.5 minute quadrangles. Terraces in regions outside of the park are compiled from existing sources (Wagner et al., 1975; Marine, 1997; Marine and Donohue, 2000). The Youghiogheny River is a major tributary of the Monongahela River, falling 600 m over 216 km, and draining 4,440 km^2 of the Allegheny Plateau portion of the Appalachian foreland north and west to the Ohio River. The long profile has a broad knickzone (convexity) that stretches from Connellsville to Ohiopyle, coincident with the river's path through the Chestnut Ridge anticline (**Figs. 1d, 3**). The knickzone is decorated by several rapids and waterfalls, the highest and most spectacular being the ~6 m high Ohiopyle Falls (**Fig. 1d**). The Youghiogheny River and its tributaries are deeply incised into the rolling uplands of the Allegheny Plateau generating a local, valley-side relief of ~200 m.

This part of the Appalachian foreland is underlain by gently folded middle and late Paleozoic siliciclastics, carbonates, and coal (**Fig. 1a, inset column**). The oldest rocks are exposed in the partially breached cores of the Chestnut Ridge and Laurel Hill anticlines where the river traverses the Devonian and Mississippian Maple Summit, Catskill, Oswayo, Shenango, Burgoon, and Mauch Chunk formations. Some of these units, in particular the Shenango Formation, contain distinctive facies including the flat-pebble Long Run Conglomerate that can be used to distinguish clasts that have been fluvially-transported great distances in the terraces of the Youghiogheny River from locally-sourced material. In contrast to these older rocks, the broad intervening syncline centered on Ohiopyle State Park exposes the Pennsylvanian Pottsville Formation and overlying coal-bearing Allegheny Group. Within the Pottsville Formation is the thickly-bedded, cross-stratified, pebbly orthoquartzite Homewood Sandstone, a particularly resistant unit that forms the crests of many waterfalls including Ohiopyle Falls (**Fig. 2d**).

The rocks currently exposed on the Allegheny Plateau were formerly covered by 2.5-4 km of late Paleozoic strata (Zhang and Davis, 1993), a thin wedge of which is still preserved further west in the foreland. Apatite fission track thermochronology and coal rank indicates that the rocks at the surface cooled below ~120ºC in the early Mesozoic, suggesting long-term rates of erosion of ~10-30 m/Ma (Blackmer et al., 1994). Pleistocene glaciation has played a large role in rearranging the recent drainage of the Allegheny Plateau and in lowering base level through the formation of the Ohio River as an ice-marginal stream. The cumulative result of Pleistocene drainage rearrangement in the Allegheny Plateau has been a wave of recent incision by rivers presumably including the Youghiogheny at rates as high as ~40 m/My, and local, short-term rates that approach ~100 m/My (Ward et al., 2005) resulting in the steep walled gorges, numerous knickpoints, and waterfalls on tributary channels.

Fluvial terrace, lacustrine, debris-flow, and fluvial-deltaic deposits collectively known as the Carmichaels Formation (Campbell, 1902; Hickock and Moyer, 1940), some of which lie 10-100 m above the modern channel, are preserved along the Youghiogheny River (**Fig. 1c**). The Carmichaels Formation is a complex lithostratigraphic unit that most likely represents not only multiple facies, but also multiple phases of deposition spanning a large age range across the Pleistocene. The Carmichaels Formation is traditionally thought to be genetically related to one or more phases of the early to mid-Pleistocene glacial Lake Monongahela (White, 1896; Jacobson et al., 1988; **Fig. 2**); however, Carmichaels Formation deposits are found at elevations both above and upstream of the commonly agreed upon extent of the lake(s) leading to alternative explanations for their genesis (Campbell, 1902).

Glacial Lake Monongahela and Carmichaels Formation

Glacial Lake Monongahela (Leverett, 1936; Marine, 1997) is the name given to the body of water that flooded the valleys of the Monongahela and Youghiogheny rivers when a pre-Illinoian ice margin dammed the pre-glacial north-flowing river systems of the Allegheny Plateau. This lake filled to a level of ~336 m (1,100 ft) before finding an outlet to the paleo-Ohio River in the vicinity of New Martinsville, WV, creating a propagating knickpoint as the river adjusted to a new elevation of 186 m (610 ft). As Lake Monongahela drained, it incorporated systems including the ancestral Allegheny and Monongahela rivers into the new Ohio River system (Harper, 1997). In addition to its initial formation, subsequent ice sheet advances are hypothesized to have reblocked outlets, causing one or more additional phases of Glacial Lake Monongahela.

Closely associated with the formation of Glacial Lake Monongahela is deposition of the Carmichaels Formation (Campbell, 1902; Marine 1997; Marine and Donahue 2000; Kite and Harper, 2011). The Carmichaels Formation consists of a stratified mix of clay, silt, and gravelly sand, weathered to reddish-orange to tan colors with polymict, rounded, fluvial gravel, cobbles, and occasional boulders (Campbell 1902; Kite and Harper, 2011). The Carmichaels Fm is commonly located within broad, flat, abandoned meander bends on the northward flowing tributaries of the Ohio River (**Fig. 2b**). These abandoned meanders represent the paleo-valleys of a formerly high sinuosity, low gradient river. The Carmichaels Fm likely represents multiple facies, as well as multiple phases of deposition spanning the Pleistocene, representing one or more phases of Lake Monongahela, and the accompanying glacial-interglacial climate changes. Past studies (White, 1896; Jacobson et al., 1988; Morgan, 1994; Marine, 1997) have recognized several distinct low gradient terrace levels associated with the Carmichaels Fm on the Monongahela and Allegheny Rivers in the vicinity of Pittsburgh. The highest level terrace (Jacobson et al., 1988) is thought to be the maximum extent of Lake Monongahela, consisting of deposits currently at ~320-335 m (1050-1100 ft), while lower terrace levels down to 280-296 m (920-970 ft) are thought to result from subsequent ponding events. Two lowest terrace levels at 253 m (830 ft) and 267 m (875 ft) more closely match the grade of the modern river, and are thought to represent Wisconsinan glaciation (White, 1896; Marine, 1997).

The Carmichaels Fm has been dated using paleomagnetism (Jacobson et al., 1988; Marine, 1997), with samples from the highest terrace level being paleomagnetically reversed, indicating that they are > 788 Ka. In contrast, deposits of the Carmichaels Fm lower in the landscape are normal polarity, indicating that these terrace levels were formed < 788 ka. Marine (1997) conducted further mapping and paleomagnetism studies on the Carmichaels Formation in the Allegheny River valley sampling terraces at multiple levels. All of those samples except one are normal polarity, with the one reversed polarity sample interpreted as pre-lake terrace material. In contrast to Jacobson et al., (1988), Marine (1997) concludes that all Carmichaels Fm terraces represent the result of one Lake Monongahela event which deposited the Carmichaels Fm across a range of elevations, burying older, mostly fluvial terrace deposits of the ancestral Monongahela River system. Marine's (1997) interpretation suggests that the mapped terraces are more indicative of the paleo-base level, and slow, pre-early Pleistocene incision of the ancestral Monongahela River system, rather than the ponding event associated with Glacial Lake Monongahela.

Methods

Data for terraces and the longitudinal profile of the Youghiogheny River include mapping and fieldwork, collection of samples for terrestrial cosmogenic nuclide (TCN; https://www.uvm.edu/cosmolab/methods.html) and luminescence dating (Rittenour, 2018), and river long profile analysis from a digital elevation model (Whipple and Tucker, 1999). TCN field samples, including bulk sand and rounded cobbles, were chosen based on access, terrace distribution, and opportunity to obtain best estimates for erosion rates and age of significant landforms. Samples collected for exposure ages included corrections for topographic shielding. Samples collected for burial or isochron analysis were sampled from the deepest possible location in order to provide for maximum, post-burial shielding. All TCN samples were processed and ^{10}Be and ^{26}Al extracted at the University of Vermont Cosmogenic Lab. Luminescence dating was completed at the Utah State Luminescence Laboratory. Minimum exposure ages and steady-state erosion rates were calculated using the Cronus online calculator (https://hess.ess.washington.edu/; Balco et al., 2008). Burial and isochron ages were calculated following methods outlined in Hidy et al (2010) and Erlanger et al. (2018), respectively. All results, data sheets, uncertainties and modeling of TCN and luminescence data are reported in Kurak (2021). Mapping was done by foot, boat and bike on a 1:10,000 scale using a 1-m lidar topographic base between Confluence, PA and Connellsville, PA. Mapping between McKeesport, Pa and Connellsville, PA was done on a 1:24,000 scale based primarily on historical literature, 1 m LiDAR digital elevation models (DEM), and field visits. Terrace treads and straths were identified in the field and have been further verified using the DEM. Terrace thickness has been determined through field measurements, and the use of topographic metrics such as changes in slopes in areas where fluvial deposits were found.

The resulting terrace map notes the location and elevation of the erosional base of the terraces, called a strath, and the constructional tops, called a tread. The gradient of adjacent straths reconstructs a paleo-reach of the river's former longitudinal profile. These paleo-longitudinal profiles can be compared in gradient and separation from the modern channel profile to determine the location, rate, and steadiness of river incision. A river long profile is a simple plot of channel distance with respect to channel elevation (**Fig. 3, solid blue line**). It has been long known that the concave-up shape of most river long profiles reflects a power law relationship between reach-length gradient (S, m/m) of a stream channel and drainage area (A, m^2), a proxy for channel discharge (Hack, 1957). The long profile plot has properties of concavity (θ), defined by the negative slope of the *logS-logA* regression, and steepness (k_s), defined by the intercept where A is 1 m^2,

$$S = k_s A^{-\theta} \quad (1).$$

To model the incision of a river channel into bedrock (E, m/yr) it is now accepted to use a stream power-based rule (Howard, 1994),

$$E=KA^m S^n \quad (2),$$

where K is a rock erodibility term, essentially a velocity with units of $m^{0.1}$ yr^{-1} when stream concavity is the reference concavity (θ_{ref}) of 0.45, and where the exponents m and n describe power-law dependencies for A and S respectively. Combining equations (1) and (2) under uniform, steady-state base level fall (uplift, U) and erosion (E) conditions when the elevation of the channel does not change over time (dz/dt = 0), and solving for S gives:

$$dz/dt = U - E = 0 \quad (3a),$$

and

$$U = KA^m S^n \quad (3b),$$

and

$$S = (U/K)^{1/n} A^{-m/n} \quad (3c).$$

Comparing equation (1) to (3c) it is immediately evident that θ and m/n are equivalent and

$$k_s = (U/K)^{1/n} \quad (4).$$

Because θ and k_s co-vary, it has become common practice to apply the reference concavity for all of the streams in the watershed, resulting in a normalized k_s value (k_{sn}). For the case where the channel erosion is a detachment limited quarrying and plucking process, which is a good first-order assumption for sediment-starved Appalachian streams, the exponent dependency on slope (n) is ~1 (Whipple, 2004). With the simplifying assumption that n=1 and using θ_{ref} = 0.45, the units on channel steepness (k_{sn}) are $m^{-0.9}$ and equation (4) becomes

$$k_{sn} = (E/K) \quad (5).$$

Combining equations (1) and (5) and substituting dz/dx for S, an expression for the response time (τ, yrs) of the system (Whipple and Tucker, 1999) emerges:

$$(dz/dx) = ((dz/dt)/K)A^{-m} \quad (6a)$$

$$K(dz/dx) = (dz/dt)A^{-m} \quad (6b),$$

$$dt = dx / K A^{m} \quad (6c),$$

$$\tau = \int_{x_0}^{x} \frac{dx}{K(x')A(x')^{m}} \quad (6d),$$

where x_o is the starting distance at the mouth of the stream. Equation (6d) describes the amount of time (τ) it takes for a transient erosional step (a knickpoint) to move up the long profile as a kinematic wave (Howard, 1994; Whipple and Tucker, 1999).

Results

Long Profile

The Youghiogheny River downstream of Confluence consists of a distinct and unique shape, with two shallow gradient zones separated by a broad convexity between Connellsville and Ohiopyle (**Fig. 3**). The river is underlain throughout by sedimentary rocks from the middle to late Paleozoic, with the oldest Devonian and Mississippian rocks exposed in the partially breached cores of the Chestnut Ridge and Laurel Hill anticlines (Wagner et al., 1975; Shaulis et al., 2021; **Fig. 1**). Channel reach steepness is greatest at the obvious knickzones, including the broad convexity between Connellsville and Ohiopyle as well as where the channel is flowing over the Pottsville Formation including the Homewood Sandstone (**Fig. 3, red line, unit PP1**). The response time of the Youghigheny trunk channel can be modeled assuming a uniform rock erodibility (*K*) derived from a catchment average channel steepness (k_{sn}) or from a reach-length rock-erodibility (*K(x)*) determined locally from the reach-length channel steepness, in both cases using a catchment-wide average erosion of 30±10 m/Myr for equation (5) (**Table 1**). Inserting those values of K into equation (6d) results in two similar plots of response time (τ) with respect to channel distance (**Fig. 3**; **yellow and brown lines)**. The variable K model (Fig. 3, yellow line) indicates that a base level fall that initiated at the confluence of the Youghiogheny River with the Monongahela River, perhaps in response to integration of the Ohio River following the drainage of Glacial Lake Monongahela, would reach Connellsville after ~3.5 Myr, Ohiopyle after ~6 Myr, and take ~35 Myr in total to reach the catchment's headwaters. If the Ohio River drainage integration base level fall impacted the entire Monongahela and lower Youghiogheny River all the way to the lower part of the Chestnut Ridge gorge more or less instantaneously, a possibility supported by the terrace deposits at Camp Carmel discussed below, that knickpoint would essentially arrive at Ohiopyle in ~2 Myrs. These response time models further indicate that the current mean retreat rate for the top of the knickzone, including Ohiopyle Falls, is ~ 10 km/Myr or 1 cm/yr. Real retreat rates probably have varied with changes in Pleistocene climate, that impact both A and K in equation 6d.

***Table 1**: Values for k_{sn} and K on the Youghiogheny River based on the whole catchment (constant K scenario), as well as underlying rock type (variable K scenario). Unit nomenclature is the same as that of **Fig. 3**.*

Rock Unit	k_{sn} ($m^{-0.76}$)*	K ($m^{0.24}$ yr^{-1})**	K stdE ($m^{0.24}yr^{-1}$)***
Catchment	8±0.2	3.75E-06	1.25E-06
PP4	4.84±0.07	6.20E-06	2.18E-06
PP3	4.86±0.04	6.17E-06	2.06E-06
PP2	9.2±0.05	3.26E-06	1.09E-06
PP1	11.92±0.08	2.52E-06	8.39E-07
M	10.89±0.19	2.75E-06	5.06E-06
D	0.02±0.05	1.50E-03	7.52E-03

*m/n (θ) = 0.38 **E= 30±10 m/Myr ***stdE= standard error for K

Terrace Stratigraphy

Alluvial and lacustrine deposits of the Carmichaels Formation form the basis for Youghiogheny River terrace maps, geochronology, age models, and long profile evolution models. These alluvial deposits range from those just above the modern floodplain of the river to up to 60 m above the modern channel in abandoned meander bends (White, 1896; Campbell 1902; Marine 1997) (**Fig. 2c**). Terrace stratigraphic models are separated into three “zones” based on their topographic signature and spatial distribution along the Youghiogheny River long profile. These three zones (**Fig. 3**) are named the Connellsville Zone consisting of the reach between McKeesport, PA and Connellsville, PA, the Gorge Zone, which is the reach between Connellsville and Ohiopyle that includes the gorge carved through the Chestnut Ridge anticline, and the Ohiopyle Zone, which is the reach between Ohiopyle and Confluence that includes the gorge carved through the Laurel Hill anticline.

Ohiopyle Zone

The upstream portion of the Youghiogheny River, called the Ohiopyle Zone, consists of the stretch between Ohiopyle and Confluence containing six terrace levels (Qto1-6, **Fig. 4a,b; Fig 5a,b**) plus a modern floodplain (Qal). In the vicinity of Ohiopyle, these terraces are exposed as broad, relatively flat benches within the town and along the Ferncliff Peninsula, along a wide meander called Victoria Bend farther upstream (**Fig. 4b**) and at Confluence. Between Victoria Bend and Confluence, these terraces are commonly underlain by steep, hanging, alluvial fans with tributary catchment provenance. Terraces in the Ohiopyle zone tend to follow the shallow gradient of the upper Youghiogheny River. These terraces vary in thickness between 2-10 m, and often have 1-4 m of colluvium capping the treads. Straths are only locally exposed, but around Ohiopyle are constrained by drill cores and a few outcrops or estimated through breaks in hillslopes and the presence of rounded cobbles, often increasing in size and quantity near the base of a deposit.

The highest terrace level (Qto1) found at Ohiopyle and the crest of Ferncliff is characterized by a colluviated slope with large, rounded boulders of clasts such as the Homewood Sandstone and the Long Run Conglomerate, both of which have an upstream provenance.

The next highest terrace level (Qto2) is most easily defined by a sharp terrace riser with a base of around 384 m (1260 ft) on the Ferncliff Peninsula. Much of this terrace is covered by colluvium, but exposures showing several meters of weathered sand and gravel along stream cuts are accessible from the Sugarloaf hiking trail connecting the Great Allegheny Passage Trail to Sheridan Street in Ohiopyle as well as on the Ferncliff Trail on the Ferncliff Peninsula.

The third (Qto3) and fourth (Qto4) highest terraces have their straths constrained by drill cores and exposures around Ohiopyle, where the strath elevation may vary by as much as 10 m locally, particularly for Qto4. Most of Ohiopyle is constructed on the treads of these two terraces, resulting in significant human modifications of the original terrace morphology. On Ferncliff and Victoria Bend, these terraces exist with less anthropogenic modification, but as is common with the previous terraces, the treads tend to have a colluvial cover.

The fifth highest terrace (Qto5) is relatively thin at Ohiopyle, but appears to thicken once it wraps downstream around Ferncliff (**Fig. 4a**). It is expressed there as a distinct flat step, with rounded cobbles well-exposed through the riser. Rounded cobbles are also found within stone walls on the top of the terrace which were evidently constructed using local materials.

The lowest terrace level (Qto6) only exists downstream of and directly at Ohiopyle Falls, and likely represents the elevation of the top of Ohiopyle Falls knickpoint as it retreated around Ferncliff. Lower alluvium deposits representing the modern floodplain also periodically occur downstream of Ohiopyle Falls.

In the Ohiopyle Zone between Victoria Bend and Confluence, the Qto5 terrace level appears to transition into the river's modern floodplain, while Qto4 becomes host to the local segment of the Great Allegheny Passage Rail Trail (**Fig. 4b**). Exposures of the Qto2-Qto3 levels become expressed as perched alluvial fans originating from smaller tributary streams that are able to capture the larger round cobbles found in the main channel, and the occasional apparent terrace benches. The highest terrace (Qto1) is only found in a few places upstream of Ohiopyle.

Soils developed through the terrace treads are broadly consistent with their relative stratigraphic age. Thick orange-red, clay rich soils are developed in the higher terraces (Qto1,2, and 3), reddish-brown and yellow clay loam soils are formed in Qto4, and brown loamy soils are formed in the lowest, youngest terraces (Qto5, 6).

The map pattern of terraces in the Ohiopyle zone indicates that the flight of terraces at Ohiopyle and the flight of terraces on the west slide of the Ferncliff Peninsula have co-evolved as the Youghiogheny channel has shifted west and incised downward. These are classic inner-meander loop terraces. Coupled with the axial stream provenance of Qto1 at the crest of Ferncliff, they indicate that the tight bedrock meander loop forming the Ferncliff Peninsula has always been part of the axial Youghiogheny river channel (c.f. Campbell, 1902), at least in the context of the current regional topography.

Gorge Zone

The Gorge Zone of the Youghiogheny River comprises the middle section of the long profile from Connellsville, PA to Ohiopyle, PA. Here the Youghiogheny River narrows and carves a deep gorge through Chestnut Ridge where the long profile is convex. Four terraces are preserved in this reach ranging in elevations from 2 m to 30 m above the modern channel, collectively defining a cluster of terraces sub-parallel to the modern channel. The two lowest (Qal and Qtg3 of **Figs. 4c; 5c**) levels of these terraces are close to the modern floodplain level, and are very likely fill-cut terraces of the modern Youghiogheny River.

The next highest terrace (Qtg2) is typically found 15-20 m above the modern river channel and is mostly identified by the presence of a significant number of rounded cobbles above the modern channel. This terrace is expressed as flat benches on the side of the river gorge that can be quite extensive, reaching up to 1.3 km in length along the course of the river, often on inside meander bends or near the mouth of larger tributaries. Deposits vary in thickness, ranging from

5-25 m, commonly with a colluvial cover 1-6 m thick and topped with large stone blocks that have fallen from above. Straths are difficult to find in this stretch due to colluvial cover and steep slopes. They are exposed locally either as a result of stream cuts, horizontal incision by the Youghiogheny River, or because they intersect the Great Allegheny Passage Rail Trail. At one location west of Camp Carmel, the Great Allegheny Passage Trail intersects terrace Qtg2. Temporary excavation there exposed ~2 m of dark sandy gravel and sand Carmichaels Fm lacustrine facies (**Figs. 4c, 5c, 6**), overlain by ~ 1 m of rounded fluvial gravel encased in a dark orange-brown, weathered matrix, that is unconformably overlain by ~ 2m of reddish-brown and brown colluvium. The lacustrine facies have been sampled for a TCN burial age that is still pending in the summer of 2021.

The highest terrace level (Qtg1) is poorly preserved and exposed, but where present, has a strath ~30 m above the modern channel. The tread and risers of the Qtg1 are covered by colluvium and littered with large, rounded boulders mixed in a sand and clay matrix.

Connellsville Zone

The Connellsville Zone includes the characteristic Carmichaels Formation of the literature (White, 1896; Campbell, 1902; Jacobsen et al., 1988). Closely related to studies on terraces done by White (1896) on the Monongahela River and Marine, (1997) on the Allegheny River, four terrace levels are identified (Qcm, Qtc1-Qtc3). However, while these earlier studies identified the top three terraces as Carmichaels Fm deposits from Lake Monongahela, only the top two terrace levels (Qcm & Qtc1, **Fig. 4d,e; 5d**) were identified as such in this study on the Youghiogheny River. While there are undoubtedly Lake Monongahela deposits higher in the landscape than these mapped terraces, Qcm represents the highest Lake Monongahela deposits that have unambiguously buried older Youghiogheny River terrace straths. Any higher deposits along the main Youghiogheny River lack the topographic signature of a mappable terrace deposits, and very likely represent alcoves or bays within Lake Monongahela where lake deposits could be preserved against buttress unconformities. This inference is supported by the apparent decrease in the presence of cobbles above 304 m (1000 ft) (Campbell, 1902). However, it should be noted that measured elevations for the two highest terraces (White, 1896; Marine, 1997) are generally above the maximum elevation of topography within a 3 km swath (**Fig. 3**) indicating a potential preservational bias for lower terraces over the upper terraces.

The Qcm and Qtc1 (**Fig. 4d,e**) terrace deposits occur in broad flat abandoned meander bends that follow a shallower, more sinuous gradient then the modern channel, and most closely correlate to the third terrace level of White (1896) and Marine (1997). Deposits of Qcm tend to vary in thickness from 8-25 m and consist of clays, silts, and sands ranging in color from reddish-orange to tan. At some locations, the more deeply buried portions of the deposit take on a more brown-grey color. Within the matrix is a scattering of rounded to subangular cobbles derived from local sandstones, which appear to be most abundant close to bedrock straths (Campbell, 1902).

Bedrock straths for these deposits are difficult to locate, but some can be identified through stream cuts or through well or drilling records (White, 1896). The lowest bedrock straths in these abandoned meander bends tend to occur 50-60 m above the modern channel (Campbell, 1902), although this difference decreases to ~25 m around Connellsville on the Youghiogheny River. This strath surface is mostly buried and included as part of the Qcm deposit due to lack of exposure, however in locations where it is visible, it has been labeled as Qtc1. The bedrock straths also show considerable variation in elevation, being higher on inside bends of the loops and lower on the outside.

In contrast to the upper two levels of terraces on the Youghiogheny River, the lower levels of terraces in this reach (Qtc2-4 and Qal) more closely follow the gradient of the modern stream channel. These terraces are found along the straighter, steeper course of the modern long profile, often preserved as small deposits in the inside loops of modern meander bends. While still consisting of clays, sands, and rounded cobbles, these terraces were not recognized as being part of the Carmichaels Fm in this study (c.f. Kite and Harper, 2011).

***Table 2**: Terrace stratigraphy, nomenclature, and descriptions for the Youghiogheny River.*

Unit Name	Description
Qls	Landslide and debris flow deposits consisting of host material of unknown age.
Qal	Alluvial bars and floodplains of the modern Youghiogheny River consisting of rounded to subangular clasts supported by a sandy matrix. Usually thin with treads located <5 m above the modern channel level. Often yellow-brown in color.
Ohiopyle Zone	
Qto6	Terrace with a thin yellow-orange sandy matrix and the occasional cobble. Terrace is located on a bedrock strath with elevations at or below that of Ohiopyle Falls.
Qto5	Terrace consisting of yellow-orange sandy matrix with rounded cobbles, appearing very similar to the modern floodplain, and essentially taking its place upstream of Ohiopyle Falls. Downstream of Ohiopyle Falls it often has a colluvial cover.
Qto4	Thick deposit of sand, silt, and clay containing rounded cobbles of various sizes, with a large concentration near the strath. Color consists of a distinct orangish-red color with occasional yellow layers consisting mostly of sand. At Ohiopyle the deposit is heavily altered, but elsewhere often contains a colluvial cover. Strath elevation constraind by drill logs to ~370 m (1214 ft) at Ohiopyle. Upstream of Ohiopyle often houses the Great Allegheny Passage Rail Trail. Strath often <10 m above the modern river channel.
Qto3	Terrace with a strath constrained by drill cores at 378 m (1240 ft) at Ohiopyle. Consists of a reddish-orange sandy matrix with generally small rounded cobbles. Is preserved as both a fluvial terrace deposits and as an alluvial fan terrace from tributaries of the Youghiogheny River in the stretch between Victoria Bend and Confluence. Some exposures indicate the development of a soil. Often is covered by colluvium of varying thickness. Streth is usually between 11-16 m of the modern river channel.
Qto2	Terrace consisting of fluvial and alluvial fan deposits often preserved along tributaries, identifiable by the presence of rounded cobbles. Uppermost portions of the deposit also appear to be developing a soil. Terrace tread often covered by thick alluvial deposits, but on the Ferncliff Peninsula hosts a distinct terrace riser confirming its presence. often found 18-24 m above the modern river channel.
Qto1	Oldest terrace in the Ohiopyle Zone. Deposits are heavily colluviated, but contain rounded boulders of fluvially transported sandstones such as the Homewood Sandstone and Long Run Conglomerate. Strath elevation poorly constrained but inferred by changes in slope to be ~30 m above modern river channel.
Gorge Zone	
Qtg3	Fill terrace ~8 m above the modern Youghiogheny River channel, above modern alluvial deposits. Consists of sand and rounded to subangular cobbles.
Qtg2	Most common terrace level fround 15-25 m above the modern channel. Often preserved as parts of alluvial fans or broad extensive "benches" within the Gorge Zone. Consists of rounded to subangular cobbles and small boulders within a sand/silt/clay matrix reddish orange to brown in color, with some deposits looking similar to the classic Carmichaels Formation This unit often has a thick colluvial cover which sometimes contains large (>10 m radius) boulders originating from the steep rock walls of above.
Qtg1	Highest and rarest terrace level within the Gorge Zone, generaly 30 m or higher above the modern channel. Often contain large rounded to subangular boulders derived of the Long Run Conglomerate and Homewood Sandstone. Collluvial cover of at least 1 m in many instances.
Connellsville Zone	
Qtc3	Lowest terrace in the Connellsville Zone, with a strath on average 8 m above the modern channel. Relatively thin deposit of sands and gravels with rounded to subangular cobbles. Corresponds to the 1st terrace of Jacobsen et al. (1988) and Marine (1997).
Qtc2	Highest terrace that generally follows the course of the modern Youghiogheny River rather then the old, shallow gradient path indicated by the abandoned meander bends. Strath elevation is consistently ~16 m above the modern channel. Deposits consists of sand and silt with rounded cobbles of sandstone of local origin. Terrace deposits are mostly found on the inside of modern meander bends. Corresponds to the 2nd level terrace of Jacobsen et al. (1988) and Marine (1997).
Qtc1	Lowest terrace strath level preserved that follows the course of a paleo-river channel characterized by the broad abandoned meander bends. Consists of thick fills of sands and clays with large rounded cobbles. Color is generally reddish orangish to brown. Corresponds to the 3rd terrace level of Jacobsen et al. (1988) and Marine 1997). Strath level is generally 30-50 m above the modern channel level, but this decreases upstream due to the steeper grade of the modern river vs the paleo-river. In most areas, is incorporated into Qcm and only found as a representative strath elevation, but is present as a distinct terrace level at Connellsville.
Qcm	Classic Carmichaels Formation of Campbell et al. (1902) consisting of thick deposits reddish to orange clays, silts sands and rounded cobbles. Interpreted as terraces reworked by deposits of Lake Monongahela. Likely represent multiple strath levels of an older, low gradient paleo-river, and sometimes incorporates unit Qtc1. Ranges from 50+ m above the modern channel at McKeesport, PA to 25+ m above the modern channel at Connellsville, PA. Corresponds to the 3rd and 4th terrace level of Jacobsen et al. (1988) and Marine (1997).

Geochronology and sample ages

Geochronological analysis from twenty-six samples (**Table 3**) are assembled to calculate incision and erosion rates, and construct a terrace age model used for correlation. This project contributed 21 new samples; an additional 5 samples providing exposure ages/erosion rates, come from previous unpublished projects (Li, 2018). These twenty six samples provided 19 ages and/or erosion rates in the form of 5 burial ages, 13 exposure ages/erosion rates, two isochrons from 7 samples, and one OSL/IRSL age (Kurak, 2021).

^{10}Be concentrations on bedrock faces are used to calculate a minimum exposure age for samples OPC1 – OPC5, SRY-OP6 – SRY-OP8, and OPFC2 – OPFC6, based on no surface erosion, or a steady-state erosion rate and saturated exposure. OPC1-OPC4 represent recent erosion processes such as rock falls in the steep gorges of the Youghiogheny valley, yielding exposure ages ranging from 10.6 ± 0.5 ka to 43.7 ± 1.4 ka, and steady-state erosion rates ranging from 17.0 ± 0.6 m/Myr to 71.7 ± 3.5 m/Myr. In contrast OPC5 is located high in the landscape on a visibly highly weathered outcrop indicating that it is more readily interpreted as a long-term steady state erosion rate. It yields an exposure age of 248.0 ± 4.9 ka and a steady state erosion rate of 3.05 ± 0.1 m/Myr. Overall the oldest ^{10}Be exposure ages come from the most deeply weathered bedrock exposures, which are farthest from the ground surface. In contrast, when solved for steady-state erosion rates, the most weathered surfaces reveal slow erosion, whereas the freshest, steepest surfaces have rapid erosion rates. For example, five fluval boulders embedded in a colluvial slope at the crest of the Ferncliff Peninsula, samples OPFC2-6 have an average exposure age of ~50 ka and mean steady-state erosion rate of ~16 m/Myr, a value consistent with their stratigraphic position in the landscape and colluvial erosion of the slope (Bierman et al., 1995; Hancock and Kirwan, 2007; Matmon et al., 2003).

Burial ages were taken at a number of sites along the Youghiogheny River terraces from the vicinity of Ohiopyle to broad meander bends downstream near Cedar Creek Park (**Figs. 2, 4, 5**). Near Ohiopyle, samples OPC-Soil and OPPL provide middle Pleistocene ages of 608.6+74.5/-93.7 ka and 384.4+86.7/-73.2 ka for intermediate to lower terrace levels in the stratigraphic section. SRY-BV1 and CCPTCNS burial ages were taken from deposits at two different levels near Belle Vernon, PA, yielding ages of 1,746+143/-146 ka, and 1,811+95/-126 ka respectively. These two samples yielded overlapping uncertainties indicating that they are the same age despite coming from different elevations. These early Pleistocene ages are consistent with the reversed magnetism of Glacial Lake Monongahela deposits.

The isochron age obtained using samples OPPL1-OPPL5 and burial age sample OPPLS both originate from the same site on the Qto4 terrace level at Ohiopyle (**Table 3**). The OPPL isochron yields an age of 305.3±58.6 ka, an age which is within the uncertainty of the burial age reported above. The second isochron age was generated using samples taken from a site near Connellsville (**Fig. 4d**). Unfortunately, half of the intended samples for the isochron consisted of chert rather than fine quartz sand, and thus were unusable for TCN dating. As a result, this isochron only has two data points, making it statistically unsound, but still useful as a crude age estimate. The isochron generated from these two points provides an age of 1.061±0.098 Ma.

One OSL/IRSL sample labeled SRY-BV2 was taken at the same location as the SRY-BV1 site. This sample yields a minimum, saturation age of >295±60 ka.

Table 3. *TCN and OSL/IRSL samples with associated numeric ages and erosion rates from this study and Li et al. (2018).*

Sample	Deposit	Lat	Long	Elev (m)	10Be Concentration (a/g)	10Be Uncertianty (a/g)	26Al Concentration (a/g)	26Al Uncertainty (a/g)	Exposure Age (ka)[1]	Steady-State Erosion Rate (m/Myr)[1]	Burial Age (ka)	Isochron Age (ka)[2]
OPC1	Rock	39.8638	-79.5017	360	8.296E+04	3.413E+03	N/A	N/A	15.1 ± 0.6	50.1 ± 2.1	N/A	N/A
OPC2	Rock	39.8642	-79.5017	360	2.238E+05	7.055E+03	N/A	N/A	43.7 ± 1.4	17.0 ± 0.6	N/A	N/A
OPC3	Rock	39.8644	-79.5016	360	6.964E+04	4.108E+03	N/A	N/A	17.9 ± 1.1	45.3 ± 2.7	N/A	N/A
OPC4	Rock	39.8631	-79.5027	360	5.923E+04	2.858E+03	N/A	N/A	10.6 ± 0.5	71.7 ± 3.5	N/A	N/A
OPC5	Rock	39.8227	-79.4331	863	1.655E+06	2.493E+04	N/A	N/A	248.0 ± 4.9	3.05 ± 0.1	N/A	N/A
SRY-OP6	Rock	39.8339	-79.4327	863	1.814E+05	5.008E+03	N/A	N/A	30.5 ± 0.9	24.2 ± 0.7	N/A	N/A
SRY-OP7	Rock	39.8227	-79.4331	863	1.085E+05	3.999E+03	N/A	N/A	12.9 ± 0.5	55.6 ± 2.1	N/A	N/A
SRY-OP8	Rock	39.8227	-79.4331	863	7.698E+04	3.232E+03	N/A	N/A	9.0 ± 0.3	79.5 ± 3.4	N/A	N/A
OPFC2	Rock	39.8638	-79.5017	399	2.990E+05	1.008E+04	N/A	N/A	53.9 ± 1.9	13.5 ± 0.5	N/A	N/A
OPFC3	Rock	39.8642	-79.5017	399	3.177E+05	1.322E+04	N/A	N/A	57.5 ± 1.9	12.7 ± 0.5	N/A	N/A
OPFC4	Rock	39.8644	-79.5016	399	2.450E+05	6.845E+03	N/A	N/A	43.7 ± 1.3	16.8 ± 0.5	N/A	N/A
OPFC5	Rock	39.8631	-79.5027	399	2.228E+05	6.052E+03	N/A	N/A	39.6 ± 1.1	18.5 ± 0.5	N/A	N/A
OPFC6	Rock	39.8227	-79.4331	399	2.928E+05	7.513E+03	N/A	N/A	52.7 ± 1.4	13.8 ± 0.2	N/A	N/A
OPPLS	Sediment	39.8840	-79.4930	378	5.905E+05	1.139E+04	3.335E+06	9.478E+04	84.2	N/A	368.4 +86.7/ -73.2	N/A
OPC-Soil	Sediment	39.8748	-79.4914	372	5.427E+05	1.122E+04	2.810E+06	8.023E+04	82.1	N/A	608.6 +74.5/ -93.7	N/A
SRY-BV1	Sediment	40.1620	-79.7636	277	3.794E+05	8.822E+03	1.380E+06	5.287E+04	156.6	N/A	1,745.7 +143.1/ -146.0	N/A
CCPTCNS	Sediment	40.1631	-79.7756	292	6.427E+05	1.385E+04	2.224E+06	6.656E+04	86.4	N/A	1,811.0 +95.0/ -126.0	N/A
CCW	Sediment	39.9650	-79.5291	302				Pending				
OPPL1	Cobble	39.8840	-79.4930	378	3.319E+05	9.471E+03	1.999E+06	8.537E+04	N/A	N/A	N/A	
OPPL2	Cobble	39.8840	-79.4930	378	4.219E+05	1.035E+04	2.494E+06	8.589E+04	N/A	N/A	N/A	
OPPL3	Cobble	39.8840	-79.4930	378	3.932E+05	1.397E+04	2.452E+06	8.333E+04	N/A	N/A	N/A	305.3 ± 58.6
OPPL4	Cobble	39.8840	-79.4930	378	3.679E+05	1.187E+04	2.125E+06	1.102E+05	N/A	N/A	N/A	
OPPL5	Cobble	39.8840	-79.4930	378	3.554E+05	1.174E+04	2.328E+06	8.690E+04	N/A	N/A	N/A	
SRY-KL3	Cobble	40.0351	-79.6063	300	2.695E+05	7.281E+03	1.133E+06	4.208E+04	N/A	N/A	N/A	1,061 ± 98
SRY-KL4	Cobble	40.0351	-79.6063	300	1.985E+05	5.617E+03	8.521E+05	3.070E+04	N/A	N/A	N/A	

Sample	Deposit	Lat	Long	Elev (m)	Num of Aliquots	Dose Rate (Gy/kyr)	Fading Rate (%/decade)	Equivalent Dose (Gy)	Age (kyr)	Method
SRY-BV2	Sediment	40.1620	-79.7636	280	11(16)	3.19 ± 0.15	3.0 ± 0.6	700 ± 130	>295 ± 60	IRSL

[1]Uses STD exposure age method [2]Uses Stone Isochron method

Terrace Stratigraphic Age Models

Fluvial stratigraphy, numeric ages, and landscape geometry and distribution are used to construct a representative terrace stratigraphic model for the Youghiogheny River between Confluence and McKeesport (**Figs. 5 and 7**). The correlation hinges on the terrace stratigraphy synthesis in the four schematic cross sections representing key stretches of the river where terraces are best preserved (**Fig. 5**).

In the Ohiopyle Zone, ages for the full flight of terraces can be estimated by extrapolating the ages of the dated Qto3 and Qto4 terraces, resulting in ages of ~1.26 Ma for Qto1, 870 ka for Qto2, ~610 ka constrained by a TCN date for Qto3, ~300 ka to ~350 ka constrained by TCN burial and isochron samples for Qto4, ~196 ka for Qto5, and an age of ~46 ka for Qto6 on Ferncliff. This age model results in incision rates of ~51 m/Myr and 26 m/Myr for the channel reaches within the steepened Gorge Zone and Ohiopyle Zone respectively (**Figs. 3, 7**). The Ohiopyle zone terraces are similar in distribution and gradient to those further upstream stretching across the Victoria Bend and continuing to Confluence (**Fig. 4b**). Through this reach, the rate of incision is ~20 m/Myr (**Figs. 3, 7**).

In contrast, correlation downstream through the Gorge Zone and into the Connelsville Zone is more challenging. A proposed connection between Qtc1 at Connellsville and Qtg2 at Camp Carmel (**Fig. 4c**; TCN burial age pending) based on elevation and sediment texture can be made, potentially creating a link between these two zones and establishing the upstream extent of Glacial Lake Monongahela. The long term mean incision rate of the river based on the 1.8 Ma age for Glacial Lake Monongahela in the Connellsville Zone would be ~17 m/Myr (30 m/1.8 Myr) which compares well to the ≥15 m/Myr for Qgt2 given that Qtc1 is stratigraphically younger than the ~1.1 Ma Qcm isochron age (SRY-KL). This ambiguity in terrace age and correlation in the Gorge Zone will be improved by the pending age of the Camp Carmel sample. Even though the correlation of the Camp Carmel or Connellsville cross sections to the Ohiopyle or Victoria Bend cross sections is unclear (**Fig. 5**), the topographic distribution of terraces in the region seems to indicate that Qtg2 may transition into the Qto5 terrace at Ohiopyle. The fragmentary terrace preservation between Ohiopyle and Connellsville preclude any firm correlation through the Gorge region, but the terraces here seem to have a gradient similar to that of the modern channel.

Interpretations

Incision record of base level fall

The incision history of the Youghiogheny River is constrained by the distribution and age of the river terraces and comparison with modern and paleo-river profiles (Fig. 7). The channel reach from Ohiopyle to Confluence, PA was carved through the Laurel Hill anticline, crossing rocks of variable erodibility (**Fig. 3, Table 1**). Nevertheless, the variation in stream steepness is modest, and the channel maintains a nearly constant gradient indicating that this reach is near or at grade. Paleo-channel gradients determined by the terraces in this reach are all parallel to the modern channel, indicating that incision has been uniform and steady when averaged over long periods of time.

Downstream projection of the graded reach between Ohiopyle and Confluence using equation (1) indicates that the modern long profile projects far out over the Gorge reach, passing first through the hanging mouths of tributary channels (**green triangles in Figs. 3 and 7**) and then through the maximum topographic envelope of the Pittsburgh low plateau, arriving at the Monongahela River confluence at an elevation of ~300 m. In summary, ~81 m of total base level fall is apparent at the confluence of the Monongahela and Youghiogheny Rivers from the downstream channel projection (**Figs. 3 and 7**). Based on the elevation of the now dated Carmichaels Fm (~1.8 Ma) and its preferential preservation in abandoned meander loops along the flanks of the incised Youghiogheny valley, ~45 m of the total base level fall, or the mean separation of the Qcm and Qtc1 strath with the Youghiogheny channel, can be attributed to the draining of Glacial Lake Monongahela and integration of the modern Ohio River. The remaining ~36 m of base level fall, nearly all of it lying in the Gorge knickzone, must have an alternative origin. Furthermore, the ages of the terraces at Ohiopyle are all < 1.2 Ma, and must be correlative, at least in time, to terraces far below the projected channel in the Connellsville zone. Time-correlative terraces must therefore increase in gradient considerably as they traverse the Gorge zone carved through the Chestnut Ridge anticline.

Two possibilities emerge from these long profile and paleo-long profile constraints. The first is that the knickzone in the Gorge reach is not transient, but rather a long-lived feature of the Youghiogheny River long profile. This is an unlikely explanation. The rock types in the Gorge reach are exactly the same as those in the Ohiopyle to Connellsville reach, yet the breached

Chestnut Ridge anticline is a steep knickzone whereas the breached Laurel Hill anticline is not. The second possibility is that the Gorge reach knickzone is a transient composite of two base level falls, one in the past ~1.8 Ma related to the integration of the Ohio River through the draining of Lake Monongahela, with the other being an older but also perhaps ongoing, non-uniform rock uplift of the Laurel Highlands with respect to the Pittsburgh low plateau, accommodated more or less at Connellsville. Most of the ~36 m of the Gorge reach knickzone would have to be attributed to this uplift-driven base level fall as the more recent drainage integration base level has yet to fully propagate through the Gorge reach based on the inferred slow rates of incision below the lacustrine beds exposed in the Qtg2 terrace at Camp Carmel (**Figs. 4c, 5c, and 6**).

Assuming that the Gorge reach knickzone is a composite transient of at least two different and ongoing base level falls, then the river incision history and ages of the terraces becomes complicated by overlapping relative uplift processes. For the reach between Ohiopyle and Confluence, the incision is uniform, a given terrace deposit has a similar age throughout, and the given strath would have been abandoned more or less isochronously. In contrast in the Gorge Zone, a given terrace deposit may have a similar age throughout, but the strath would have been abandoned in a time-transgressive manner determined by the retreat velocity of the knickzone. The response time curves (**Fig. 3**) indicate that the knickzone around Ferncliff leading up to Ohiopyle Falls is retreating at a mean rate of ~ 1 cm year (10 km/Myrs). At that rate, the knickzone has moved through the hanging mouths of the tributary channels in ~2 Myrs (**Figs. 3, 7**). This time-transgressive migration and abandonment of straths and tributary mouth confluences in the Gorge Zone has the summary effect of taking any terrace timeline upstream of Ohiopyle and steepening it more than the current channel profile, so that it can converge and ultimately project below the early Pleistocene Carmichaels Fm terraces of the Connellsville reach (**Fig. 7**). This steepening of the terraces is geomorphic marker evidence of non-uniform uplift.

The terrace correlation and relative uplift problem is further complicated by the fact that we do not know the location of the base level falls and furthermore, it is unlikely that they originated at a single point. So, for convenience and reference in **Figures 3 and 7**, we could choose the confluence with the Monongahela River or Connellsville as the base level fall point. From the confluence with the Monongahela, any base level fall would take ~6 Myr to get to get up to

Ohiopyle, or ~3.5 Myrs to travel from Connellsville to Ohiopyle. The draining of Glacial Lake Monongahela and formation of the Ohio River is one of those base level falls that we assert occurred 1.8 Ma. This drainage integration event involved a drop of ~45 m that is represented in a strongly reclined knickzone that stretches from the Monongahela confluence all the way to the core of Chestnut Ridge upstream of Connellsville. The second base level fall involves the uplift of the Laurel Highlands with respect to the Pittsburgh Plateau that may have initiated before the drainage integration event, but may also be ongoing involving ~36 m of differential uplift. In summary, we envision the big knickzone between Connellsville and Ohiopyle to be the juxtapostion of these two base level fall processes.

Possible mechanisms driving the non-uniform uplift processes include dynamic support (Moucha et al., 2008; Rowley et al., 2013; Moodie et al., 2017) perhaps focused through inherited basement heterogeneities such as the early Paleozoic Rome Trough that underlies the Laurel Highlands and is known to have a long and complicate post-rift reactivation history (Gao et al., 2000). Flexural isostatic (Pazzaglia and Gardner, 1994) and glacial isostatic adjustment (GIA; Pico et al., 2019) effects are also possible explanations for the apparent warping of terrace time lines, but these have yet to be fully investigated.

Climatic influences on terrace genesis

Terraces in the Ohiopyle zone offer some insights into the terrace formation mechanism for graded river profile reaches. TCN ages obtained on terraces Qto3 and Qto4 both indicate terrace deposition during known glacial periods (**Fig. 5a, cross-section A-A'**). Using the incision rate constrained by these two dated terraces, the projected age of the other terraces in the Ohiopyle flight similarly indicate terrace alluvium being deposited during known glacial stages (Railsback et al. 2015). The unsteadiness of Pleistocene climates through numerous glacial-interglacial cycles likely impacted Youghiogheny discharge, sediment yield from hillslopes, or both leading to unsteady incision punctuated by terrace alluvium deposition (van den Berg, 1996; Vandenberghe, 2003; Wegmann and Pazzaglia, 2009; Gunderson et al., 2014).

Downstream of Ohiopyle, the more rapid incision associated with multiple downstream base level falls and propagation of the transient knickzone seems to have precluded similar genesis and preservation of sub-parallel climatic terraces. Here the terraces have been forming more locally by stochastic processes as meander loops are truncated (Finnegan and Dietrich, 2011).

However, the Qtg2 terrace is preserved almost contiguously for over a kilometer distance with a steep gradient subparallel to the modern channel. It is possible that the formation of this terrace was influenced in places by climatically-influenced changes in sediment load.

Conclusions

Detailed mapping and numeric dating of river terraces together with modeling of the longitudinal profile of the Youghiogheny River focused on Ohiopyle State Park allowed reconstruction of the history of base level fall and river entrenchment across this portion of the Laurel Highlands. The river terraces in the study area are a younger, fluvial facies of the Carmichaels Formation, which in its type section in the Pittsburgh low plateau is intimately related to the formation of Glacial Lake Monongahela, here dated ~1.8 Ma by TCN burial ages. A flight of six fill terraces that bury irregular straths in and around Ohiopyle indicate that the main terraces were created by unsteady incision in step with glacial-interglacial climate changes over the past 1.2 Ma. The map pattern is consistent with the Youghiogheny River forming and being locked into its tight meandering pattern around Ferncliff for the period of time represented by the terraces. TCN burial and isochron ages of ~610 ka and ~300-350 ka are used to construct long-term incision rates ranging from ~20 m/Myrs upstream of Ohiopyle where the channel gradient and subparallel terrace profiles are gentle to ~50 m/Myrs downstream of Ohiopyle where the river profile steepens into a broad convex knickzone. Modeled channel response time idicate that the current rate of retreat for the top of the knickzone, including Ohiopyle Falls, is ~10 km/Myr or ~ 1 cm/yr. Comparison of the river profile to the terrace profile and the response time model further indicates that there have been at least two base level falls conflated in the knickzone between Ohiopyle and Connellsville. A total of ~81 m of base level fall is suggested by projection of the graded channel between Ohiopyle and Confluence downstream to the river's confluence with the Monongahela River. Of that total, ~45 m is likely due to the draining of Glacial Lake Monongahela in the early Pleistocene and formation of the Ohio River. The other ~36 m is attributed to non-uniform uplift of the Laurel Highlands with respect to the Pittsburgh low plateau, with a hinge more or less at Connellsville, which may be ongoing.

Acknowledgments

Research supported by EDMAP grant G20AC00152, the Pennsylvania Geological Survey, and Lehigh University. The authors would like to thank the leadership and staff of Ohiopyle State Park, in particular superintendent Ken Bisbee and Chief Maintenance Officer Bruce King (retired) for their generous cooperation with this study. We also acknowledge Lehigh student Mike Simoneau who helped with some of the TCN sample preparation and analysis. We thank reviewers Dru Germanoski and Fred Zelt for constructive comments that have improved the paper.

References

Balco, G., Stone, J. O., Lifton, N. A., and Dunai, T. J., 2008, A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurments: Quaternary Geochronology, 3, 174-195.

Bierman, P.R., and Steig, E.J., 1996, Estimating rates of denudation and sediment transport using cosmogenic isotope abundances in sediment: Earth Surface Processes and Landforms, v. 21, p. 125-139.

Blackmer, G. C., Omar, G. I., and Gold, D. P., 1994, Post-Allegheny unroofing history of the Appalachian Basin, Pennsylvania, from apatite fission track analysis and thermal models: Tectonics, 1259-1276.

Campbell, M. R., 1902, Masontown-Uniontown folio, Pennsylvania: U.S. Geological Survey Geologic Atlas of the U.S., Folio 82, 21 p.

Erlanger, E. D., Granger, D. E., and Gibbon, R. J., 2012, Rock uplift rates in South Africa from isochron burial dating of fluvial and marine terraces: Geology, 40, 1019-1022.

Finnegan, N. J. and Dietrich, W. E. 2011. Episodic bedrock strath terrace formation due to meander migration and cutoff. Geology, 39:143-146.

Granger, D. E, Fabel, D., Palmer, A.N., 2001, Plio-Pleistocene incision of the Green River, KY from radioactive decay of cosmogenic 26Al and 10Be in Mammoth Cave sediments: Geological Society of America Bulletin 113, 825–836.

Gao, D., Shumaker, R. C., and Wilson, T. H., 2000, Along-axis segmentation and growth history of the Rome Trough in the central Appalachian basin: AAPG Bulletin, 84, 75-99.

Hack, J. T. 1957, Studies of longitudinal stream profiles in Virginia and Maryland. U.S. Geological Survey Professional Paper. 294-B:45-97.

Hancock, G.S., and Kirwan, M.L., 2007, Summit erosion rates deduced from 10 Be: Implications for relief production in the central Appalachians: Geology, v. 35, p. 89-92.

Harper, 1997, Of ice and waters flowing: The formation of Pittsburgh's three rivers: Pennsylvania Geology, 28, 2-8.

Harper, J. A., 2002, Lake Monongahela: Anatomy of an immense ice age pond: Pennsylvania Geology, v. 32, no1/4, p. 2-12.

Hickok, W. O. and Moyer, F. T., 1940, Geology and Mineral Resources of Fayette County: Pennsylvania Geological Survey 4th series, County Report 26, scale 1:62,500.

Hidy, A. J., Gosse, J. C., Pederson, J. L., Mattern, J. P., and Finkel, R. C., 2010, A geologically constrained Monte Carlo approach to modeling exposure ages from profiles of cosmogenic nuclides: An example from Lees Ferry, Arizona: G3, 11, Q0AA10, doi:10.1029/2010GC003084.

Jacobson, R. B., Elston, D. P., and Heaton, J. W., 1988, Stratigraphy and magnetic polarity of the high terrace remnants in the upper Ohio and Monongahela Rivers in West Virginia, Pennsylvania, and Ohio: Quaternary Research, v. 29, p. 216–232.

Kite, S., and Harper, J. A., 2011, STOP 6, Laurel Point Falls Park – Cassville Shale and Carmichaels Formation, in Harper, J. A., ed. Geology of the Pennsylvanian-Permian in the Dunkard Basin: Field Conference of Pennsylvania Geologists Guidebook 76, 305-316.

Kurak, E., 2021, Terrace and long profile evolution of the Youghiogheny River, Ohiopyle State Park, Pennsylvania: MS Thesis, Lehigh University, Bethlehem, PA, 93 p.

Leverett, F., 1934, Glacial deposits outside the Wisconsin terminal moraine in Pennsylvania: Pennsylvania Geological Survey, 4th series, General Geology Report 7, 123 p.

Li, C., 2018, Age and retreat rate of Ohiopyle Falls. Unpublished senior thesis, Lehigh University, Bethlehem, PA, 23 p.

Marine, J. T., 1997, Terrace deposits associated with ancient Lake Monongahela in the lower Allegheny drainage, western Pennsylvania: University of Pittsburgh, M.S.thesis, 182 p.

Marine, J.T, Donahue, J., 2000 Terrace Deposits associated with ancient Lake Monongahela: Annual field conference for Pennsylvania geologists, 65th, Pittsburgh, Pa., Guidebook, p. 28-36

Matmon, Ari, Bierman, P.R., Larsen, Jennifer, Southworth, C.S., Pavich, M.J., Finkel, R.C., and Caffee, M.W., 2003, Erosion of an ancient mountain range, the Great Smoky Mountains, North Carolina and Tennessee: American Journal of Science, v. 303, p. 817-855.

Morgan, S. A., 1994, Depositional facies associated with Lake Monongahela. Unpublished MS thesis, West Virginia University, 13 p.

Moodie, A. J., Pazzaglia, F. J., and Berti, C.: Exogenic forcing and autogenic processes on continental divide location and mobility, Basin Research, 30, 344–369, https://doi.org/10.1111/bre.12256, 2017.

Moucha, R., et al., 2008, Dynamic topography and long-term sea-level variations: there is no such thing as a stable continental platform, Earth Planet. Sci. Lett., 271, 101–108,

Pazzaglia F.J., 2013, Fluvial Terraces, in, John F. Shroder (Editor-in-chief), Wohl, E. (Volume Editor), Treatise on Geomorphology, Vol 9, Fluvial Geomorphology, San Diego: Academic Press, p. 379-412.

Pazzaglia, F.J., and Gardner, T.W., 1994, Late Cenozoic flexural deformation of the middle U.S. Atlantic passive margin. Journal of Geophysical Research 99(B6): 12,143–12,157.

Pico, T., Mitrovica, J. X., Perron, J. T., Ferrier, K. L., and Braun, J., 2019, Influence of glacial isostatic adjustment on river evolution along the U. S. mid-Atlantic coast: Earth and Planetary Science Letters, 522, 176-185.

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G., and Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quaternary Science Reviews 111, 94-106.

Rittenour, T. M., 2018, Dates and rates of Earth-surface processes revealed using luminescence dating: Elements, doi: 10.2138/gselements.14.1.21.

Rowley, D.B., et al., 2013. Dynamic topography change of the eastern United States since3 million years ago. Science 340 (6140):1560 1563.http://dx.doi.org/10.1126/science.1229180.

Shaulis, J. R., 2020, Bedrock geologic map of the South Connellsville, Mill Run, Fort Necessity, and Ohiopyle 7.5-minute quadrangles, Fayette and Somerset Counties, Pennsylvania: Pennsylvania Geologic Survey Map xx, 1:36,000.

van den Berg, M. W., 1996, Fluvial sequences of the Maas, p. 181. PhD dissertation, Landbouw Universiteit.

Vandenberghe, J., 2003, Climate forcing of fluvial system development: An evolution of ideas. Quaternary Science Reviews 22: 2053–2060.

Wagner, W. R., Craft, J. L., Heyman, Louis, and Harper, J. A., 1975, Greater Pittsburgh region geologic map and cross sections: Pennsylvania Geological Survey, 4th ser., Map 42, scale 1:250,000, 4 sheets.

Ward, D.J., Spotila, J. S., Hancock, G. S., and Galbraith, J. M., 2005, New constraints on the late Cenozoic incision history of the New River, Virginia: Geomorphology, 72, 54–72.

Wegmann, K. and Pazzaglia, F.J., 2009, Late Quaternary fluvial terraces of the Romagna and Marche Apennines, Italy. Quaternary Science Reviews 28: 137–165.

Whipple, K. X. and Tucker, G. E. 1999. Dynamics of the stream power river incision model: Implications for height limits of mountain ranges, landscape response timescales and research needs. Journal of Geophysical Research. 104:17,661–17,674.

Whipple, K.X., 2004, Bedrock rivers and the geomorphology of active orogens: Annual Reviews of Earth Planetary Science, 32, 151-85.

White, I. C., 1896, Origin of the high terrace deposits of the Monongahela River: American Geologist, v. 18, p. 368–379.

Zhang, E. and Davis, A., 1993, Coalification patterns of the Pennsylvania coal measures in the Appalachian foreland basin, western and south-central Pennsylvania: Geological Society of America Bulletin, 105, 162-174.

Figure Captions

Figure 1: (a) Geologic Map showing underlying stratigraphy for the mapped section of the field area between Confluence, PA and McKeesport, PA. White boxes represent locations shown in Figures 4 and 5: A=Ohiopyle, B=Victoria Bend, C=Camp Carmel, D=Connellsville, and E= Cedar Creek Park. (b) Inset map showing the geology of the area surrounding Ohiopyle State Park and the Youghiogheny River Gorge in more detail. (c) Example of the Carmichaels Formation as exposed along the Youghiogheny River, see Figure 6 for details. Lower tape for scale is 2 m long. (d) View of Ohiopyle Falls as seen from the Ohiopyle State Park visitor center in Ohiopyle, PA.

Figure 2: (a) Reconstruction of Glacial Lake Monongahela showing extent of the lake and location (modified from Harper, 2002). Blue line indicates the course of the Youghiogheny River, showing geographic locations mentioned in the text. (b) Example of broad abandoned meander with terraces at Connellsville, PA. Terrace nomenclature discussed further in **Table 2**.

Figure 3: Youghiogheny River long profile, steepness, and response time. The blue line represents the Youghiogheny River base elevation obtained from 1-m LiDAR DEM data from its headwaters down to its confluence with the Monongahela at McKeesport, Pa. The dashed blue line represents a projected steady-state river level projected downstream from the knickzone at Ohiopyle (eq. 1). Green triangles depict projected elevations of knickzones along tributaries of the Youghiogheny R., also representing the paleo-elevation of the tributary confluence with the Youghiogheny channel. The gray and lighter gray shading in the background represent the mean and max elevations of a 3 km swath based around the course of the river (**Fig. 1**). The values of k_{sn} are represented in the graph in red below the long profile calculated using eq. 1. The peak in k_{sn} at Confluence is an artifact of the dam. Geology traversed by the Youghiogheny River is shown in boxes along the bottom with symbols representing the group or formation. PP4 = the Pennsylvanian shales, limestones and coals of the Monongahela Formation. PP3 = Pennsylvanian sandstones, shales, and red beds of the Conemaugh Group. PP2 = the relatively more resistant shales sandstones and limestones of the Pennsylvanian Allegheny Group. PP1 = the resistant Pennsylvanian Pottsville Formation, including the hard Homewood Sandstone that forms the lip of many waterfalls in the region, the top of which is represent in the cross section as

a green line. M represents the various formations of the Mississippian, including the Mauch Chunk Formation, the Burgoon Sandstone, and the Shenango Formation with the resistant basal Long Run Conglomerate. Also included within this section is brief outcroppings of Devonian units such as the Catskill Formation that are too thin to depict on the long profile. River response time, or tau (τ), in millions of years is depicted in brown and yellow for constant K and variable K dependent on geology respectively (**Table 1**).

Figure 4. Terrace distribution at 5 key sites, along with locations of TCN samples and ages (See **Fig. 1** for locations). Cross section lines correspond by letter to the terrace stratigraphic models detailed in **Fig. 5**, as well as white boxes of **Fig. 1**. Terrace nomenclature is presented in **Table 2.** and dated samples are noted and presented in **Table 3.** (a) Terrace distribution at Ohiopyle and the Ferncliff Peninsula in the Ohiopyle Zone (b) Terrace distribution at Victoria Bend in the Ohiopyle Zone. (c) Terrace distribution at Camp Carmel in the Gorge Zone. (d) Terrace distribution at Connellsville in the Connellsville Zone. (e) Terrace distribution at Cedar Creek Park in the Connellsville Zone.

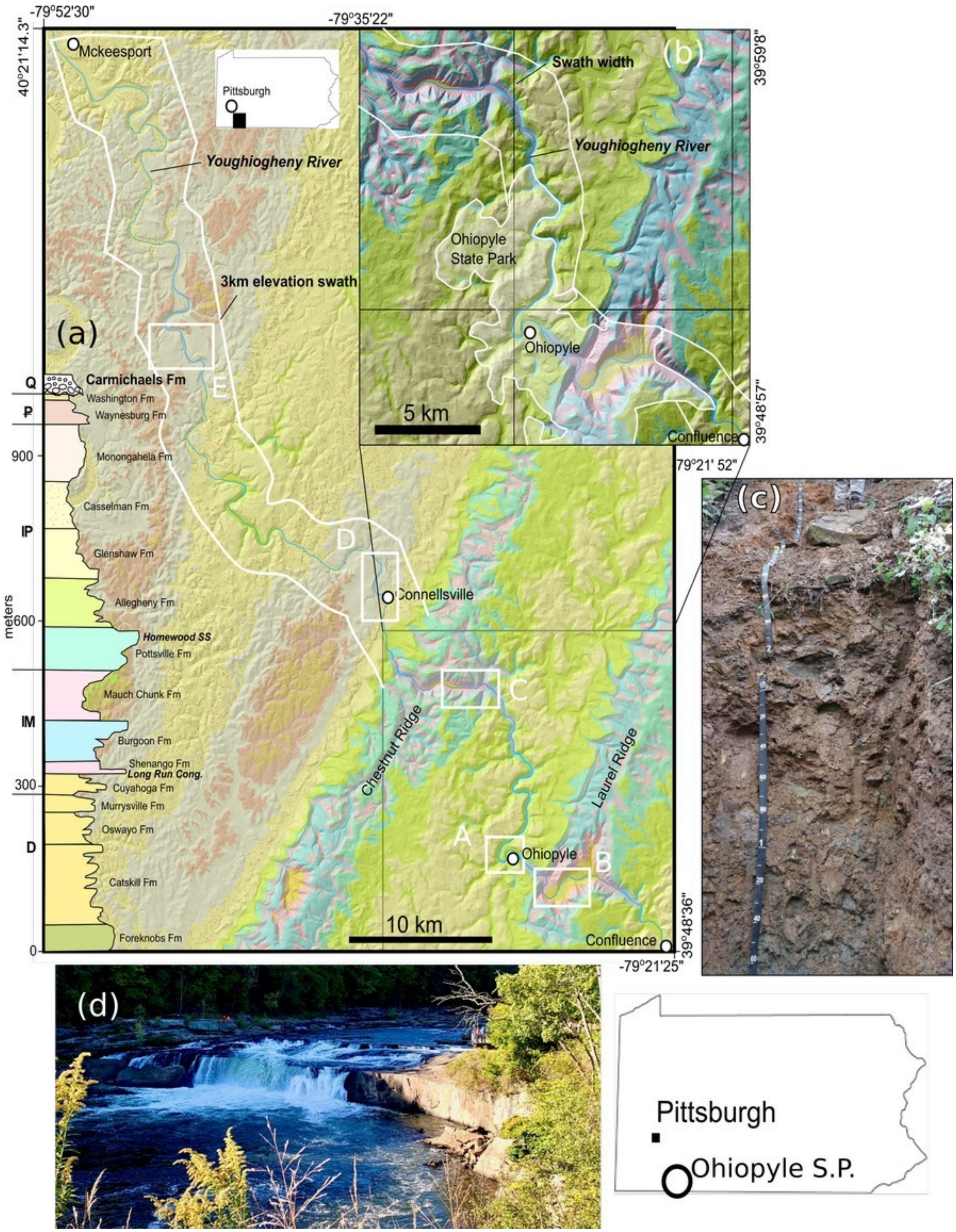
Figure. 5: Schematic cross sections of four key sections of the Youghiogheny River, aligned to the cross-section lines of **Fig. 4**. Terrace nomenclature and sedimentology is presented in **Table 2**. TCN sample locations and approximate elevations indicated as a star, along with corresponding dates. Terrace colors are a representation of position in the landscape, not of unit correlation through each site.

Figure 6. Photo of the excavated exposure of terrace Qtg2 west of Camp Carmel on the Great Allegheny Passage Trail showing the lower 2+m (tape for scale) and the dark lacustrine facies at the base of the exposure. The terrace strath was not exposed, but estimated to be another 2 m below the level of the trail at ~264 m at this location.

Figure 7: Interpretation of terrace stratigraphy and correlations along the long profile. Thin gray lines represent proposed terrace correlations. Blue dotted line represents a steady-state profile projection downstream, offset by ~36 m to account for the discrepancy in its projected elevation at the Monongahelea confluence and the elevation of the Ohiopyle-Confluence steady-state

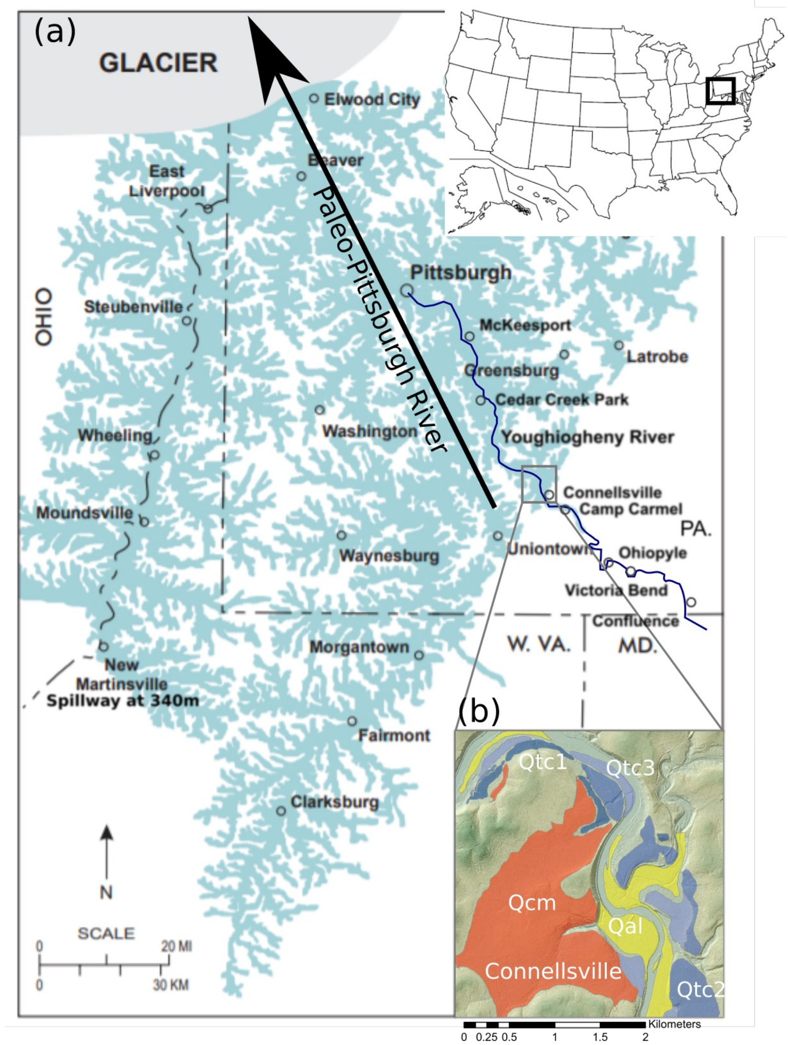
elevation (see **Fig. 3**). Gray dashed line suggests a correlation between the similar-aged Qto1 and Qtc1 that requires steep bending through the convex reach. Other symbols and lines as in Figure 3.

Figure 1.



-79°52'30"
40°21'14.3"
Mckeesport
Pittsburgh
Youghiogheny River
3km elevation swath
(a)
Carmichaels Fm
Washington Fm
Waynesburg Fm
Monongahela Fm
Casselman Fm
Glenshaw Fm
Allegheny Fm
Homewood SS
Pottsville Fm
Mauch Chunk Fm
Burgoon Fm
Shenango Fm
Long Run Cong.
Cuyahoga Fm
Murrysville Fm
Oswayo Fm
Catskill Fm
Foreknobs Fm
Q
P
IP
IM
D
900
600
300
0
meters
E
D
Connellsville
C
Chestnut Ridge
Laurel Ridge
A
Ohiopyle
B
10 km
Confluence
-79°35'22"
Swath width
(b)
39°59'8"
Youghiogheny River
Ohiopyle
State Park
Ohiopyle
5 km
Confluence
39°48'57"
79°21' 52"
39°48'36"
-79°21'25"
(c)
(d)
Pittsburgh
Ohiopyle S.P.

Figure 2.



(a)
GLACIER
Elwood City
Beaver
East
Liverpool
Paleo-Pittsburgh River
Pittsburgh
OHIO
Steubenville
McKeesport
Latrobe
Greensburg
Cedar Creek Park
Wheeling
Washington
Youghiogheny River
Connellsville
Camp Carmel
Moundsville
PA.
Waynesburg
Uniontown
Ohiopyle
Victoria Bend
Confluence
Morgantown
W. VA.
MD.
New
Martinsville
Spillway at 340m
(b)
Fairmont
Qtc1
Qtc3
Clarksburg
N
Qcm
Qal
SCALE
0
20 MI
0
30 KM
Connellsville
Qtc2
0
0.25
0.5
1
1.5
2
Kilometers

Figure 3

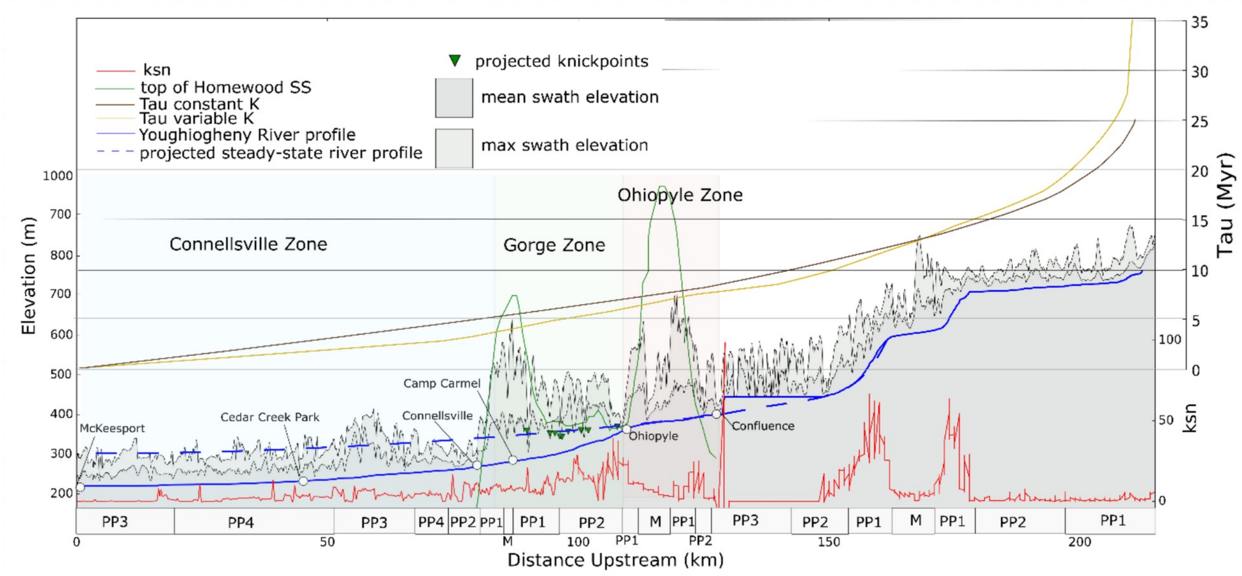

ksn
top of Homewood SS
Tau constant K
Tau variable K
Youghiogheny River profile
projected steady-state river profile
projected knickpoints
mean swath elevation
max swath elevation
Connellsville Zone
Gorge Zone
Ohiopyle Zone
McKeesport
Cedar Creek Park
Camp Carmel
Connellsville
Ohiopyle
Confluence
Elevation (m)
Tau (Myr)
ksn
Distance Upstream (km)
PP3
PP4
PP3
PP4
PP2
PP1
M
PP1
PP2
PP1
M
PP1
PP2
PP3
PP2
PP1
M
PP1
PP2
PP1

Figure 4.

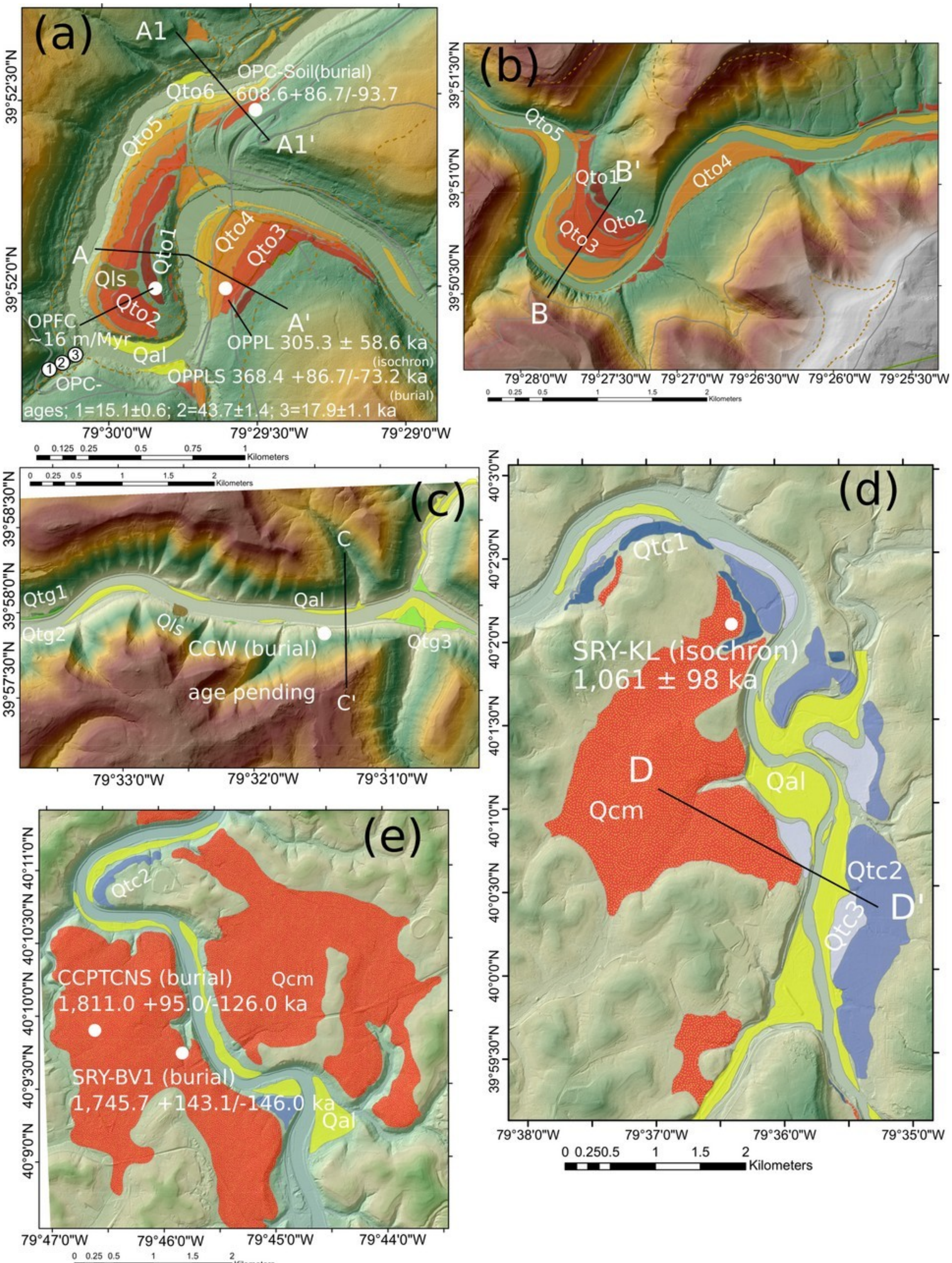

(a)
A1
OPC-Soil(burial)
608.6+86.7/-93.7
A1'
Qto6
Qto5
Qto4
Qto3
Qto1
Qto2
A
A'
Qls
OPFC
~16 m/Myr
OPPL 305.3 ± 58.6 ka
(isochron)
Qal
OPPLS 368.4 +86.7/-73.2 ka
(burial)
OPC-
ages; 1=15.1±0.6; 2=43.7±1.4; 3=17.9±1.1 ka
39°52'30"N
39°52'0"N
79°30'0"W
79°29'30"W
79°29'0"W
Kilometers
(b)
Qto5
Qto1
B'
Qto2
Qto3
Qto4
B
39°51'30"N
39°51'0"N
39°50'30"N
79°28'0"W
79°27'30"W
79°27'0"W
79°26'30"W
79°26'0"W
79°25'30"W
Kilometers
(c)
C
C'
Qtg1
Qtg2
Qtg3
Qal
Qls
CCW (burial)
age pending
39°58'30"N
39°58'0"N
39°57'30"N
79°33'0"W
79°32'0"W
79°31'0"W
Kilometers
(d)
Qtc1
SRY-KL (isochron)
1,061 ± 98 ka
D
D'
Qcm
Qal
Qtc2
Qtc3
40°3'0"N
40°2'30"N
40°2'0"N
40°1'30"N
40°1'0"N
40°0'30"N
40°0'0"N
39°59'30"N
79°38'0"W
79°37'0"W
79°36'0"W
79°35'0"W
Kilometers
(e)
Qtc2
CCPTCNS (burial)
1,811.0 +95.0/-126.0 ka
Qcm
SRY-BV1 (burial)
1,745.7 +143.1/-146.0 ka
Qal
40°11'0"N
40°10'30"N
40°10'0"N
40°9'30"N
40°9'0"N
79°47'0"W
79°46'0"W
79°45'0"W
79°44'0"W
Kilometers

Figure 5

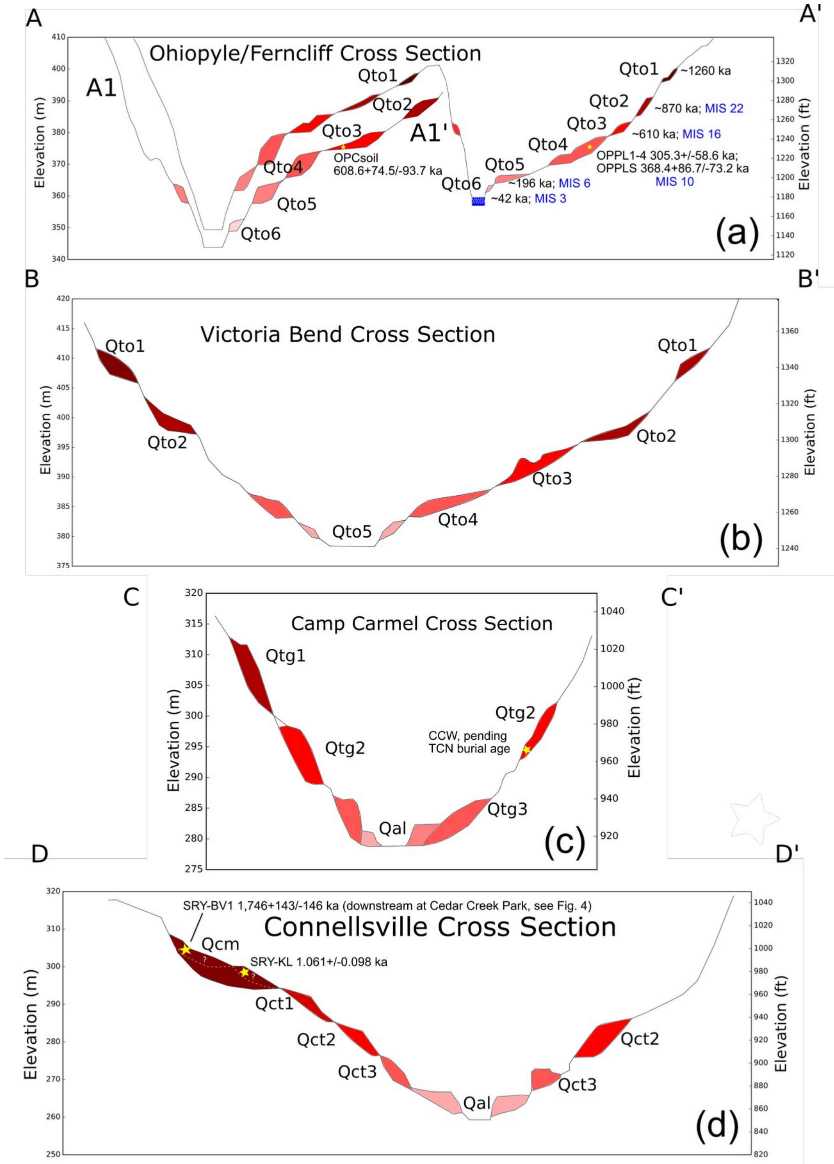

A
A'
Ohiopyle/Ferncliff Cross Section
A1
A1'
Qto1
Qto2
Qto3
Qto4
Qto5
Qto6
OPCsoil
608.6+74.5/-93.7 ka
~1260 ka
~870 ka; MIS 22
~610 ka; MIS 16
OPPL1-4 305.3+/-58.6 ka;
OPPLS 368.4+86.7/-73.2 ka
MIS 10
~196 ka; MIS 6
~42 ka; MIS 3
Elevation (m)
Elevation (ft)
(a)
B
B'
Victoria Bend Cross Section
Qto1
Qto2
Qto3
Qto4
Qto5
(b)
C
C'
Camp Carmel Cross Section
Qtg1
Qtg2
Qtg3
Qal
CCW, pending
TCN burial age
(c)
D
D'
Connellsville Cross Section
SRY-BV1 1,746+143/-146 ka (downstream at Cedar Creek Park, see Fig. 4)
SRY-KL 1.061+/-0.098 ka
Qcm
Qct1
Qct2
Qct3
Qal
(d)

Figure 6

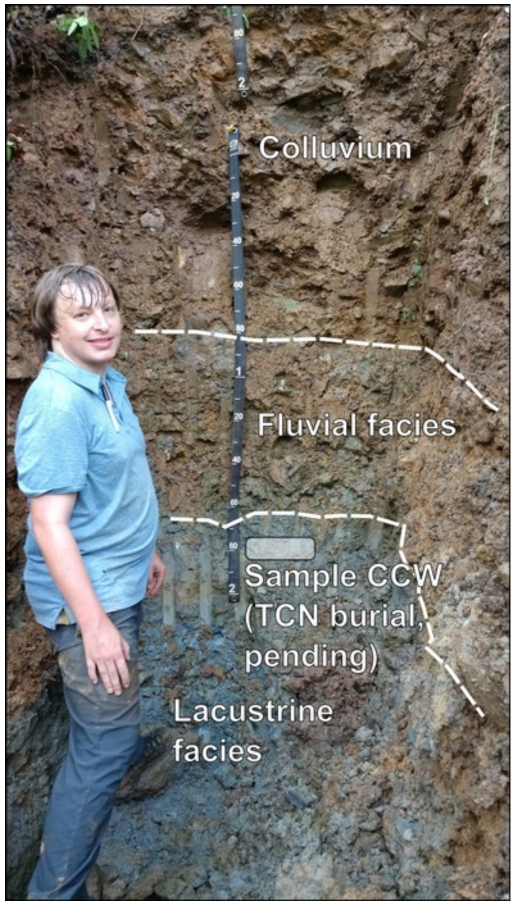
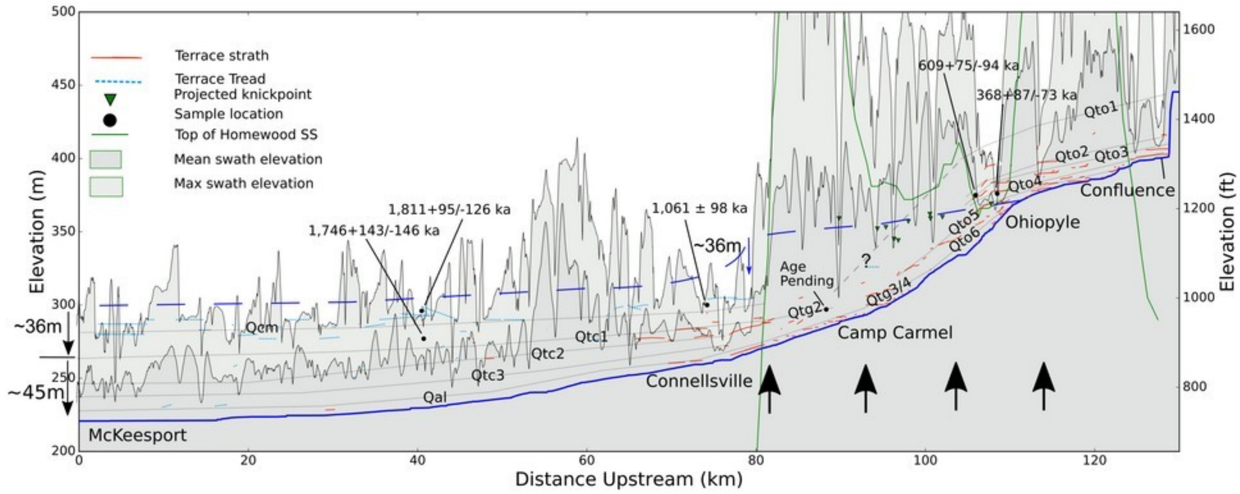

Colluvium
Fluvial facies
Sample CCW
(TCN burial,
pending)
Lacustrine
facies

Figure 7



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