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**Quantifying the Pleistocene Incision and
Integration History of the Middle Allegheny
River, a Glacial Margin Continental Drainage, in
Northwestern Pennsylvania, USA**

by

Jonathan Wallace

Presented to the Graduate and Research
Committee of Lehigh University
in Candidacy for the Degree of
Master of Sciences
in
Earth and Environmental Sciences
Lehigh University

2025 MAY

THESIS ACCEPTANCE PAGE

This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science

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Quantifying the Pleistocene Incision and Integration History of the Middle Allegheny River, a Glacial Margin Continental Drainage, in Northwestern Pennsylvania, USA

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Acknowledgements

Many and endless thanks to my thesis advisor, Frank Pazzaglia, a true mensch, a man of boundless kindness and energy. His guidance, knowledge, and enthusiasm has mentored and molded me into a better scientist, and I am deeply indebted to him, and hope that I will have a chance to see my work with him through to peer-reviewed publication.

To my committee members, **Steve Peters** and **Dru Germanoski**.

To my wife, **Martina**, for her endless patience and support, despite the many months we spent apart. And this thesis taking three months longer than originally promised.

To **Fred Zelt**, for asking the questions that led to this thesis topic.

To the members of the Geomorphology lab group, especially **Nora Vaughn**, whose feedback made my diagrams and tables more legible. And to the members of the EES department, especially **N. Miller**, for generously coaching me in how to be an effective teacher in my capacities as a lab instructor and teaching assistant.

To **Tammy Rittenour** from Utah State University for OSL and IRSL dates.

To **Jocelyn Spencer**, of the **Allegheny Mineral Company** (formerly Snyder Glacial Sand and Gravel) for allowing us access rights and for graciously allowing us the use of her excavators. And likewise to John Vincent of Vincent Excavating and Gravel of Franklin PA, for allowing us access to his quarry.

And a great thanks to many people from Clarion, Venango, and Armstrong counties, for sharing with me their keen appreciations of the landscape and its human and natural histories. With special mention to: **Timothy and Sarra Terry** of West Monterey, for graciously allowing me to dig test pits and sample on their property; to John English of Kennerdell, for allowing to me to examine and collect samples from his gravel pits; also to the **Sweetapple** family of Kennerdell, likewise. And an extra thanks to **Jeff Mactaggart**, for giving me a boat ride. Finally, a great thanks to the postmasters of Emlenton and of Parker, without whom many valuable connections and introductions would not have been possible.

And a small and only slightly humorous thanks to Costco Corp, for making Kirkland 100% Columbian Canned Brew Cold Coffee, without which I could not have maintained sufficient focus to finish this degree program, instead of chasing squirrels.

The work presented here would not have been possible without the support the of the USGS EDMAP program grant #G22AC00558, as well as support from the Lehigh EES Graduate Funds.

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ABSTRACT

A new ^{10}Be terrestrial cosmogenic nuclide (TCN) and optically-stimulated luminescence (OSL)-based age model for eight fluvial terraces in the middle Allegheny River and upstream correlative glacial deposits has been constructed from a USGS EDMAP-funded surficial geologic map of the Parker and Emlenton 7.5 min quadrangles. The map, age model, and existing data for Glacial Lake Monongahela (GLM) test long-held views for when and where low divides were breached in the assembly of the modern Allegheny River and the respective roles of upstream glacial margin or downstream base level change in driving post-glacial river incision. The age model is anchored by a ~20 m thick paired fill terrace containing abundant rock-types exotic to the Allegheny watershed (Qt3), with a strath ~60 m above the modern channel (AMC). A TCN burial age in Qt3 of $1.1 \pm 0.4 / -0.3$ Ma indicates a south-flowing Allegheny River connected to the glacial margin in the early Pleistocene, and a long-term rate of incision of ~45 m/Ma. In contrast, above Qt3 are few, scattered strath terraces (Qt1 and Qt2) that lack exotic clasts, and have opposing north and south gradients astride a now breached low divide upstream of the Clarion-Allegheny rivers confluence. Inset 5 m below Qt3 lies an extensive, paired, low-relief strath terrace (Qt4-the Parker Strath), followed by scattered, unpaired, and poorly preserved strath terraces (Qt5) that decorate the steep bedrock valley walls and extend down to within ~20 m AMC. At least three thick, paired fill terraces containing abundant exotic material (Qt6, Qt7, and Qt8), the bases of which are not exposed, are inset into the inner Allegheny valley. The tread of Qt6 lies ~15 m AMC; the underlying alluvium has a TCN burial age of $0.513 \pm 0.15 / -0.17$ Ma, and it is subsequently capped by thick colluvial deposits with a TCN burial age of $0.24 \pm 0.071 / -0.06$ Ma. Qt7 is a late Pleistocene terrace with an OSL age of 0.017 ± 0.002 Ma. These middle and late Pleistocene terraces and colluvia have similar ages to two tills exposed ~45 km to the north at Franklin, PA dated to $0.4 \pm 0.31 / -0.18$ Ma and 0.14 ± 0.19 Ma using burial TCN and OSL

respectively. Some preliminary geochemical data for the soils capping the Qt3 and Mapledale units is presented. A key finding is that the Allegheny River has experienced an average incision rate of ~40-45 m/Ma over the past half-million years or more, but this may have been as low as 25m/Ma earlier in the Pleistocene, approaching the unglaciated basin-scale erosion rate of ~30 m/Ma. The location of an early Pleistocene integration reach near modern Foxburg PA is argued. Collectively, these data suggest reversal and assembly of the Allegheny River during a very early glacial advance, perhaps the same one that was responsible for the formation of the Ohio River via spillover of GLM >> 1 Ma.

1. INTRODUCTION

The role of continental glaciation in the assembly of large drainages remains imperfectly understood and fuels one of the longstanding and spirited discussions on the relative importance of exogenic versus autogenic factors in driving landscape evolution over mega-year timescales (Davis and Johnson, 1909; Morisawa, 1989). The assembly and evolution of continental-scale drainage systems, or drainage conformity to topography, are venerable questions (Davis, 1889; D’Agostino et al., 2001; Wegmann et al., 2007; Black et al., 2017; Moodie et al., 2018) with important implications for the processes that shape continental divides (Willett et al., 2014; Whipple et al., 2017b, 2017a) continental-scale erosion rates (Summerfield and Hulton, 1994; Jepson et al., 2021), and coupling to ecosystems (Tukiainen et al., 2023). In the eastern U.S. the advance of the Laurentide ice sheet has long been postulated to have played a primary role in reversing a formerly north and northeast flowing drainage system exiting the Appalachian Mountains via the St. Lawrence River to the current south and west flowing Ohio and Mississippi rivers (Chamberlin and Leverett, 1894; Shaw, 1911). This study re-examines the evidence for this drainage reversal and assembly over Pleistocene time scales, applying a new numeric age model anchored in river terraces and glacial deposits to clarify the respective roles that exogenic forcing, such as glaciation, and endogenic processes, such as stream piracy (Yang et al., 2015) contribute to the assembly of continental drainages.

The Allegheny River, located in western Pennsylvania and New York of the eastern U. S., offers an excellent case study for examining the role of exogenic glacially-driven assembly of continental-scale drainages (Leverett, 1902). Despite being located in the tectonically stable Appalachian foreland, the Allegheny River and its tributaries are deeply inset in narrow sinuous canyons incised through mostly flat-lying sedimentary rocks of the Allegheny Plateau (**Figs. 1 and 2**). This study explores glacial and river terrace deposits for a ~50 km long reach of the middle Allegheny River extending south from the glacial margin at Franklin, PA to East Brady PA, with a focus on the confluence of the Allegheny and Clarion rivers near Parker, PA. The Clarion River watershed flows entirely south of the glacial boundary and has long been considered the ancestral, pre-Pleistocene head of the Allegheny River (Shaw, 1911). A numeric age model constructed for the glacial and terrace deposits constrains rates of river incision, landscape-scale mean erosion, and provides for a direct comparison to other, similar recent age models constructed for terrace and lacustrine

deposits located downstream and associated with the assembly of the modern Ohio River (Kurak, 2021; Kurak et al., 2021).

The terraces and glacial deposits used for the age model are characterized using measured sections, soils, and maps at the 1:24,000 scale. Numeric ages are provided by quartz and feldspar luminescence and concentrations of terrestrial cosmogenic nuclide (TCN) ^{10}Be in quartz. Rates and patterns of river incision are constrained by elevations of geomorphic marker bases. Relative numeric ages are provided by the weathering characteristics of soils.

This study seeks to understand the timing and mechanism of the integration of the Allegheny River over the course of the Quaternary. The study finds that there is strong evidence to support the integration hypothesis, with the hypothesized integration reach being located ~6 km north of the Clarion-Allegheny confluence. The most likely time for the integration is the early Pleistocene, with integration having been completed and major terraces filling the paleo-Allegheny valley by ~1.1 Ma. We find evidence for not fewer than eight distinct cut-and-fill events over the past ~2.5 Ma, with the complex internal stratigraphy of the terrace deposits indicating a greater number.

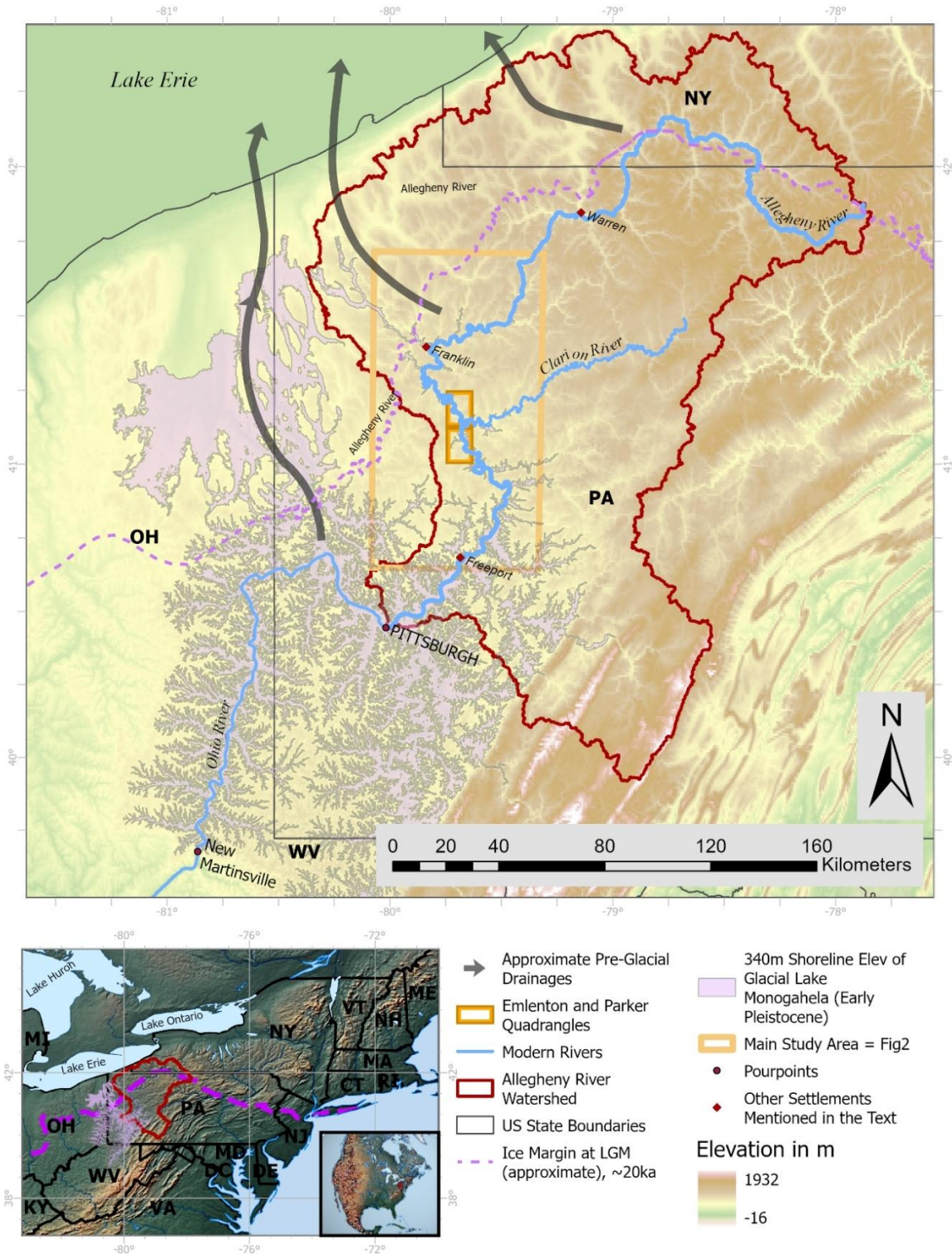


Figure 1

Geographic context and key elements of geological history, including pre-Pleistocene northward flowing drainage, a highly approximate extent of the study reach, the key study quadrangles, and locations

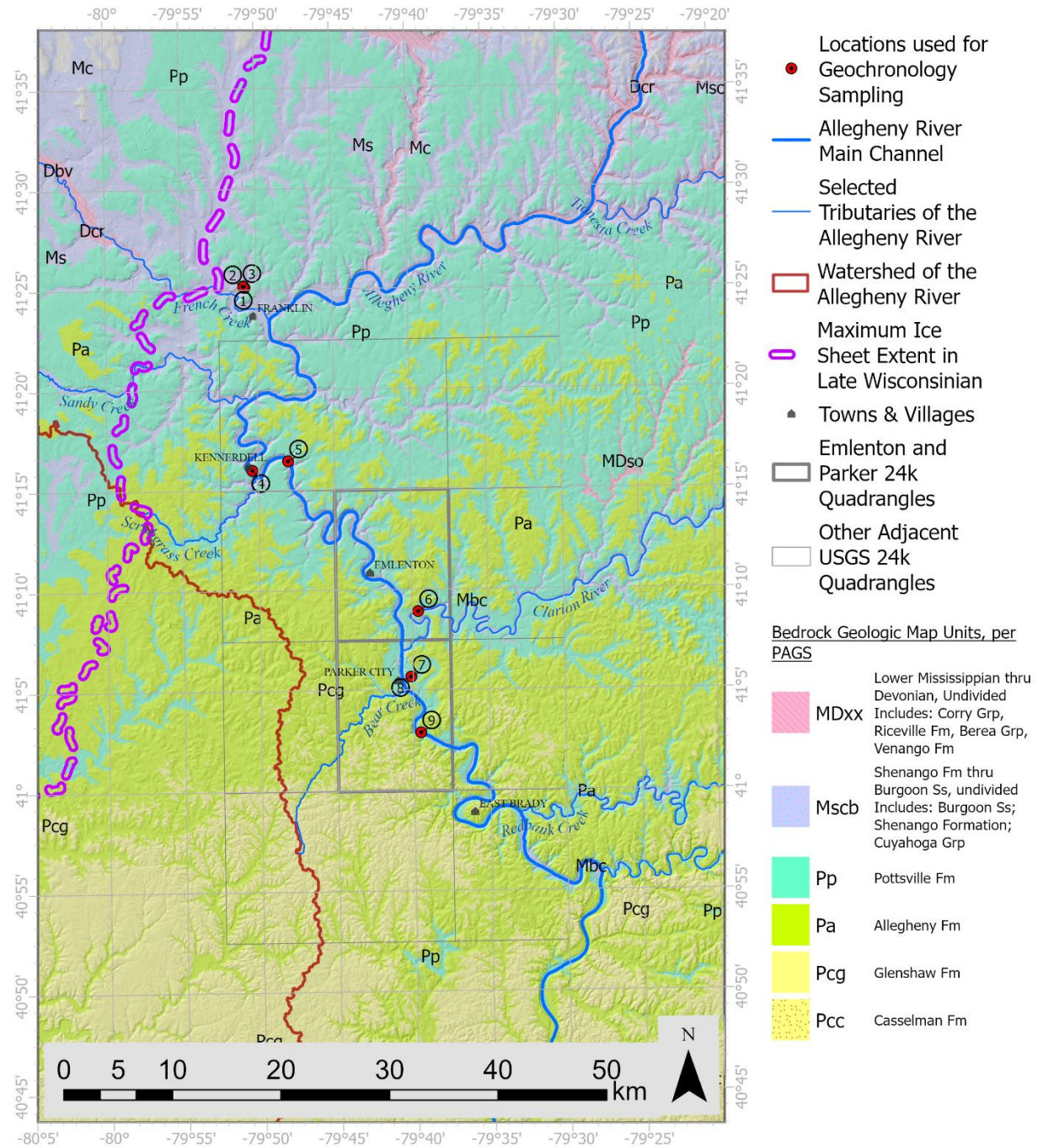


Figure 2

Local Bedrock Geology and Sample Sites. Bedrock dips gently to the north, otherwise undeformed, can be treated as homogenous with respect to erodibility. Sample Numbers are keyed to Table 2, and to Figure 5, as follows: (1) VQ-01-OSL; (2) VQ-02-OSL; (3) VQ-03-TCN; (4) KEN-01-TCN; (5) KEN-02-TCN; (6) FOX-01-TCN; (7) PRK-03-TCN; (8) PKR-03-PMAG; (9) WM-01-OSL.

2. BACKGROUND: PAST WORK AND GEOGRAPHIC CONTEXT

2.1 GEOGRAPHIC AND GEOLOGICAL CONTEXT

The Allegheny River, a tributary of the Ohio River, drains ~ 30,000 km²; more than a quarter of the state of Pennsylvania, as well as parts of several counties in southwestern New York state. It has long been hypothesized that prior to the Pleistocene and northern hemisphere continental glaciation, the middle and upper reaches of the Allegheny River flowed north rather than south, eventually draining out through the Saint Lawrence River, rather than the Ohio-Mississippi system, as it does today (Gilbert 1891; Shaw 1911; **Fig. 1**). More recent work (Marine, 1997) hypothesized that if an integration and reversal of the middle Allegheny took place, the integration point (or integration reach) would have had to be upstream of the confluence with the Clarion River. It is notable that the Clarion River watershed lies south of the glacial margin and its sediments do not have a glacial provenance.

Geologically, the study area is located on the western flank of the Allegheny plateau, in the northern Appalachian foreland. It is underlain by sedimentary rocks of middle to late Paleozoic age, composed of sandstone, conglomerate, mudstone, coal, and lesser amounts of limestone (Berg et al., 1980; Briggs, 1999). The rocks of this region are mostly undeformed, dipping gently to the south, and only locally offset by small faults (Beardsley et al., 1999). The main rock units, in order of oldest to youngest, are the Cuyahoga Group, the Pottsville Formation, the Allegheny Formation and the Glenshaw Formation (**Fig. 2**). In the area of the study reach, the bed of Allegheny River, where not deeply alluvial, rests upon Mississippian sandstones, including the Burgoon Sandstone and other Cuyahoga Group members.

The Allegheny Formation consists of cyclic sequences of sandstone, shale, limestone, clay, and includes economically valuable deposits of both limestone and coal. These sedimentary packages are similar enough that they can be treated as close to homogenous with respect to erodibility on the spatial and temporal scales this study is concerned with. The Vanport Limestone is a common target for local aggregate mining operations, and numerous open-pit mines, present and former, occur in the study area. Mineral extraction from the coal and limestone-bearing units has resulted in large scale modifications of the landscape, presenting challenges for accurate identification and mapping of surficial deposits. The Appalachian Basin is tectonically inactive and has been undergoing gradual exhumation since the culmination of Alleghenian orogeny in the late Paleozoic. The long-term rate of erosion, determined largely from thermochronological data is ~ 20-30 m/Ma (Roden and Miller, 1989; Blackmer et al., 1994; Matmon et al., 2003; McKeon et al., 2014;

Pazzaglia et al., 2015). Unsteadiness in rates of erosion, incision, and shaping of the Allegheny plateau landscape has been produced by continental glaciation over the past ~2.5 Ma (Fleeger et al., 2011).

The Modern Allegheny River is ~523 kilometers long, the lower half of which below the glacial margin flows in a narrow, steep-walled valley ~90 m deep incised into the Allegheny plateau. The middle and lower reaches of the river are characterized by sinuous and deeply incised meanders, both active and abandoned. A particularly large and tight abandoned meander lies in the middle of the study area on the east side of the river at Perryville, PA, ~40-60 m above the level of the modern river (AMR/AMRL).

Previous work in the late 19th and early 20th centuries (White, 1896; Leverett, 1902; Shaw, 1911) identified a succession of fluvial terrace deposits along the lower Allegheny River and its tributaries, and engaged in a study of their internal stratigraphy. However, the geomorphology of this region has been largely ignored in the century-plus since. Renewed interest from recent studies (Marine, 1997) refined and updated the work of Shaw, but still did not have access to current numeric dating techniques. Although previous work in the 20th century identified areas of terrace deposits (Leverett, 1934; Adamson et al., 1949; Marine, 1997; Marine and Donahue, 2000), they did not have at that time high-precision digital elevation models, nor modern GPS tools.

2.2 GLACIAL LAKE MONOGAHELA – ENDURING MYSTERIES, POSSIBLE CONNECTIONS

Important syntheses and new work on the Pleistocene glacial deposits of Northwestern Pennsylvania (Fleeger et al., 2011; Straffin and Grote, 2022) , and on the terraces and glacial lake deposits of the Monongahela (Kurak, 2021) have laid an important foundation for re-opening the question of Allegheny River integration. Past work on the history of the Allegheny River has also been concerned with the question of Glacial Lake Monongahela (**Fig 1**). Previous workers have determined that at some point in the Pleistocene, the valleys of the what are today the Allegheny, Monongahela, and Youghiogheny Rivers, were flooded when a pre-Illinoian ice margin or moraine, dammed one or more of the formerly northward flowing pre-glacial channels (Leverett, 1902, 1934; Marine, 1997; Marine and Donahue, 2000; Harper, 2002). As Glacial Lake (GL) Monongahela drained and filled, likely at least twice ((Kurak et al., 2023), it may have extended up the valley of the modern Allegheny River. **Figure 1** shows one hypothesized extent of Glacial Lake Monongahela, with a reconstructed shoreline elevation of ~340m ASL, as well as the approximate locations of the pre-glacial northwards flowing drainages.

A hypothetical 340 m shoreline elevation for GL Monongahela, corresponds very nearly to the paleo-Ohio pourpoint, with an elevation of 336 m, was long ago identified near New Martinsville, West Virginia (Chamberlin and Leverett, 1894; Leverett, 1902). Past work has also characterized a surficial deposit termed the Carmichaels formation, found in southwestern Pennsylvania, which consists of a stratified mix of clay, silt, and gravelly sand; and is often found located within broad, flat, abandoned meander bends on the northward flowing tributaries of the Ohio and Monongahela Rivers; these tributaries are believed to represent the paleo valleys of a formerly high sinuosity, low gradient river (Marine and Donahue, 2000). In recent decades, careful geochronological work, in combination with modern high-precision elevation controls, has revealed that glacial lake Monongahela emptied and filled at least twice, with the first incarnation dated to ~1100-1000 ka and the final incarnation to 457 ka, with at least one incarnation spanning both sides of the 788 ka paleomagnetic reversal event (Jacobson et al., 1988; Kurak, 2021)

Furthermore, this past work has identified that at the pourpoint at New Martinsville, the GL Monongahela shoreline deposits, and the constructional surface of the Carmichaels formation all have a common elevation of around 336-340m ASL. This is a small enough discrepancy that it has been proposed that these were likely all part of a shared system of lakes and lake deltas (Jacobson et al., 1988; Kurak et al., 2023), representing a common base level during the first incarnation of GL Monongahela. As can be seen in **Figure 1**, the proposed study area for this thesis work is very near the northeastern-most shoreline or lake delta complex of GL Monongahela, in its hypothesized earliest ~1.0+ million years ago.

A short digression is needed here on the terminology of the reaches of the Allegheny River. Previous work has used at least two competing definitions of the term “Middle Allegheny”. The US Army Corps of Engineers (USACE), defines the term Middle Allegheny to be from East Brady PA, upstream to the Kinzua Dam near Warren PA, based on where the major dams have been built. (USACE, 1980) In contrast, the Pennsylvania Department of Conservation and Natural Resources (PA DCNR), following the precedent set by Leverett (1911, 1934), defines the term “Middle Allegheny” as being from Freeport PA upstream to Emlenton PA (Pennsylvania Fish and Boat Commission, 2014; PA DCNR, 2020) For the purposes of my thesis work, I follow the USACE definition of the ‘Middle Allegheny’.

Similarly, for the purposes of this mapping work and thesis project, I use the term “Study Reach” or to refer to the section of the Allegheny River between Kennerdell PA and East Brady PA, but the term “map reach” to refer to the section of the river contained within the Emlenton and Parker

7.5 min quads. The term “glacial boundary deposits” is used to refer to the tills and outwash deposits (including but not limited to kames) found near Franklin PA. In turn my “research reach” is the reach of the Allegheny River between Franklin Pa and East Brady PA, which includes all of the aforementioned locations, and a swath on either side of ~5 km width, in which most of the features of interest to the rest of this research can be found.

3. METHODS

3.1 FIELD MAPPING AND DEPOSIT DESCRIPTIONS

The study area encompasses the middle Allegheny River, within the reach between Kennerdell and East Brady, PA with principal mapping work focusing upon the areas covered by the Parker and Emlenton 7.5-minute USGS quadrangle maps (**Fig 2**). The mapping was completed at the 1:10,000 scale and compiled at the 1:24,000 scale. These two quadrangles combine to cover an area some 28 km N-to-S, and 11 km E-to W, totaling an area of ~292 sq km. Because of channel sinuosity there are roughly 55 river miles (88 km) of the Allegheny River through the study reach. The foci of surficial mapping efforts were the terrace deposits along the middle Allegheny River and lower Clarion River, as well as their tributaries. As part of the field mapping, detailed descriptions were made of select soil profiles developed in the terrace treads, and any (buried) paleosols, with the goal of using this data to infer relative age relationships, correlation characteristics, and, where possible, paleoenvironmental or depositional interpretations.

Surficial deposits were mapped by foot, boat, and bicycle, directly on a 1-m DEM topographic base. Where possible, the erosional base of the terrace, or strath, was mapped as observed, but more often only the tread, or constructional top, of the terrace was visible. Where possible, an attempt was made to measure the relative thickness of the terrace deposits, and distinguish between fill terraces and strath terraces. Terrace locations were often inferred from topographic expression, as colluvial processes and vegetation, often made finding unaltered fill terrace material challenging. All observed units were characterized in their sedimentology, including undertaking standard clast counts (Plumley, 1948; Howard et al., 2012) to determine the ratio of glacially-transported versus locally-derived clasts, for all clasts over 4 cm in shortest axis.

Where soil profiles were both exposed and well-preserved, and a suitable geochronology sample could be obtained, the soil profile and horizon structure was documented in terms of texture, ped pattern, color, and other standard pedological and paleopedological characteristics (Soil Survey Staff, 2024). An attempt was made to obtain at least one geochronology sample from each mapped deposit, to the degree that suitable materials for sampling could be identified. These samples were collected by taking a bulk sample of not less than ~150 grams, sampling ~20-30 cm in the profile, with an effort to collect at least one sample from each identified horizon. The profiles were also

described in the field in their color, texture, grain size, pedon patterns, etc, as per standard pedological field methods (NRCS 2024).

Soil profiles were described in pits or on vertically-exposed highwalls of natural and artificial exposure. Horizons were designated, described, and sampled at ~25 cm intervals. The goal was to obtain at least one geochemistry bulk sample of not less than 100 grams from each described horizon within a given profile. These sediment/soil samples were then prepared as lithium borate glass discs (Ichikawa and Nakamura, 2016), and characterized in their bulk element and trace element geochemistry (see Appendix 1) via a Malvern Panalytical Zetium X-ray fluorescence (XRF) vacuum spectrometer at the Franklin and Marshall College X-Ray Laboratory in Lancaster PA.

3.2 GEOCHRONOLOGY

The terrace age model is anchored by terrestrial cosmogenic nuclides (TCN (Granger et al., 2013)) and luminescence (OSL and IRSL; (Rittenour, 2018)) dating methods. These are both well-established techniques for dating the burial ages of unconsolidated surficial sediments. TCN works by measuring the accumulation in earth materials of certain radioactive isotopes, such as ^{10}Be and ^{26}Al , which are produced only via cosmic ray bombardment. When the sediment, soil, or rock surface is exposed to these cosmic rays at the surface of the earth, they accumulate proportional to the time of exposure and their radioactive decay. Once buried, the production of these cosmogenic nuclides ceases, and the isotope concentration begins to decline only through radioactive decay. By measuring the concentration of these cosmogenic nuclides and already knowing the surface production rates it is possible to calculate the exposure age, burial age, and/or erosion rate of a rock surface or sediment (Granger et al., 2013). TCN dating can be used to date buried samples up to several million years old given the overall slow erosion rates in the Appalachians and the consequent accumulation of high concentrations of cosmogenic nuclides prior to erosion, burial, and transport. Model burial ages based on assumptions of original burial depth and surface erosion rates at the point of burial are reported here for (1) the case of simple burial, meaning long exposure at the surface, and rapid burial to depths of > 10 m, and (2) burial to depths < 10 m with geologic rates of surface lowering at the point of burial.

OSL (optically stimulated luminescence) or IRSL (infra-red stimulated luminescence) is a dating technique that works by exposing buried quartz (or feldspar) grains to a predetermined wavelength of light, and measuring the emitted energy stored in the material from the accumulation of ionizing radiation acquired during burial. This works because crystal defects in quartz grains that trap the

ionizing radiation in the form of are emptied of any trap electrons as the quartz grain is exposed to sunlight on the surface of the earth. Once the quartz grain is buried well beyond the reach of sunlight, the electron traps are once again allowed to accumulate electrons excited by the ionizing radiation. To greatly simplify, the amount of light emitted on re-exposure to long wave radiation (the amount of stimulated luminescence) is a function of both the concentration of the sources of ionizing radiation buried with the sample and the duration of burial. Luminescence data can be applied to quartz or feldspar and have practical dating ranges of ~100 and ~300 ka, respectively. During the fieldwork, both OSL and TCN samples for geochronological workup were collected from exposures targeted to span the range of terrace deposits flanking the river, and glacial deposits at the ice margin. Three samples were analyzed for luminescence ages, and four samples analyzed for TCN burial ages.

3.3 MAJOR ELEMENT GEOCHEMISTRY OF SOIL PROFILES

Field stratigraphic and lab geochemical characterization of soil and paleosol profiles provide a record of the time-dependent degree of alteration of the parent material by pedogenic processes (Sheldon et al., 2002; Tabor and Myers, 2015). This profile geochemistry allows an estimation of the degree of soil development, which is a first-order proxy for how long a soil or paleosol has been developing on the land surface, and under what sets of climate conditions, making profile geochemistry a tool to “unpack the unconformity” that is a soil horizon in the sedimentary records (Sheldon and Tabor, 2009). This study uses X-ray Fluorescence (XRF) to analyze the paleosol profile samples for bulk geochemistry. XRF is an analytical technique that uses the interaction of X-rays with a material to determine its elemental composition. XRF is suitable for solids, liquids and powders, and in most circumstances is non-destructive. XRF spectroscopy is an effective method for qualitative and quantitative analysis of material composition (Towett et al., 2013; Flude et al., 2017).

In the field, samples were collected using the methods described above in the methods section. Soil samples were sieved into the size fraction of 2-phi or less, and then made into fused lithium borate discs, for benchtop batch XRF analysis. (See Supplements for further details of XRF equipment and standards). Insofar that soil profile development is a time-dependent process, similarities in soil profile chemistries between soil or paleosols on terrace tread surfaces provides evidence that those treads have similar weathering histories and therefore may be of similar ages (Jacobs and Davis, 2018).

Extant soil profiles in the treads of the Qt7 deposit at West Monterey, Qt3 deposit at Perryville, and the tills in the Vincent Quarry at Franklin, PA were described and sampled. Of these, the samples of the Qt3 soil and Titusville till in the Vincent Quarry (**Fig. 2**, sample sites 1 &7) were further analyzed for their major elemental chemistry using x-ray fluorescence (XRF). Notably, these soils are all in places where absolute geochronology samples were also obtained, allowing ages of these soil profiles to be estimated in terms of the period of relative landscape stability they represent.

4. DATA AND RESULTS

There are obvious qualitative differences between the topographies north versus south of the hypothesized integration reach near Foxburg PA (**Fig. 3**). Broadly, study results show that the sedimentology, stratigraphy, and height above modern river level of surficial units are different in the Emlenton quadrangle, north of Foxburg, PA and the Clarion River confluence in comparison to the Parker quadrangle south of Foxburg, PA and the Clarion River confluence (**Fig.4**) These changes in surficial units coincide with topographic changes and stream long profile gradients.

4.1 TOPOGRAPHY AND RELIEF

The ~550 km long Allegheny River has a lower ~350 km reach characterized by a gently concave up shape locally interrupted by convexities and knickzones (**Fig. 4**). Several large tributaries flow into the Allegheny River in this lower reach, mostly entering from the east, and resulting in a markedly asymmetric drainage basin shape (**Fig. 1**). Of these east-confluent tributaries, the Clarion River is the largest, with a channel ~200 km long, with a distinctly convex longitudinal profile that falls into the Allegheny River at Parker, PA, in the middle of the study area (**Fig. 3b**)

The valley of the lower Allegheny River is a gorge ~200 m, 2 km wide, and ~100 m deep. The lip of the gorge forms a bench-like step, but is not coincident with a single rock type, as the sedimentary layers all dip gently southward (**Fig. 2**). The modern channel is modified by low-head dams to allow for navigation up to Brady's Bend in the southernmost part of the map area. North of East Brady the river mostly flows on alluvium that is locally in excess of 25 m deep based on water supply wells and historic dredging and gravel bed mining (USACE 1979, Frimpter, 1974). Locally, the alluvium is thinner and bedrock is exposed in the channel bed as small, low islands, as is the case opposite the town of Parker, PA. However, the thick alluvial extends laterally under adjacent floodplains and low terraces, where present, and because it embodies a productive aquifer, has been colloquially known as an "underground river" since the mid-19th century (Babbitt, 1855; Frimpter, 1974)

The gorge north of the confluence with the Clarion River upstream to the confluence with the French Creek is notable in its general lack of tributaries and for being the steepest, deepest reach along the entire river. For the few tributaries that do exist, they have a barbed orientation, with headwaters oriented north, or upstream, before turning more southerly and joining the main channel that is south-flowing (**Fig. 3**) From Kennerdell PA to French Creek, the terrain surrounding the gorge

is less incised and dissected, with broad river valleys choked with glacial outwash sediments. In contrast, the topography south of the confluence with the Clarion River has a well-developed dendritic stream tributary network and an overall greater relief.

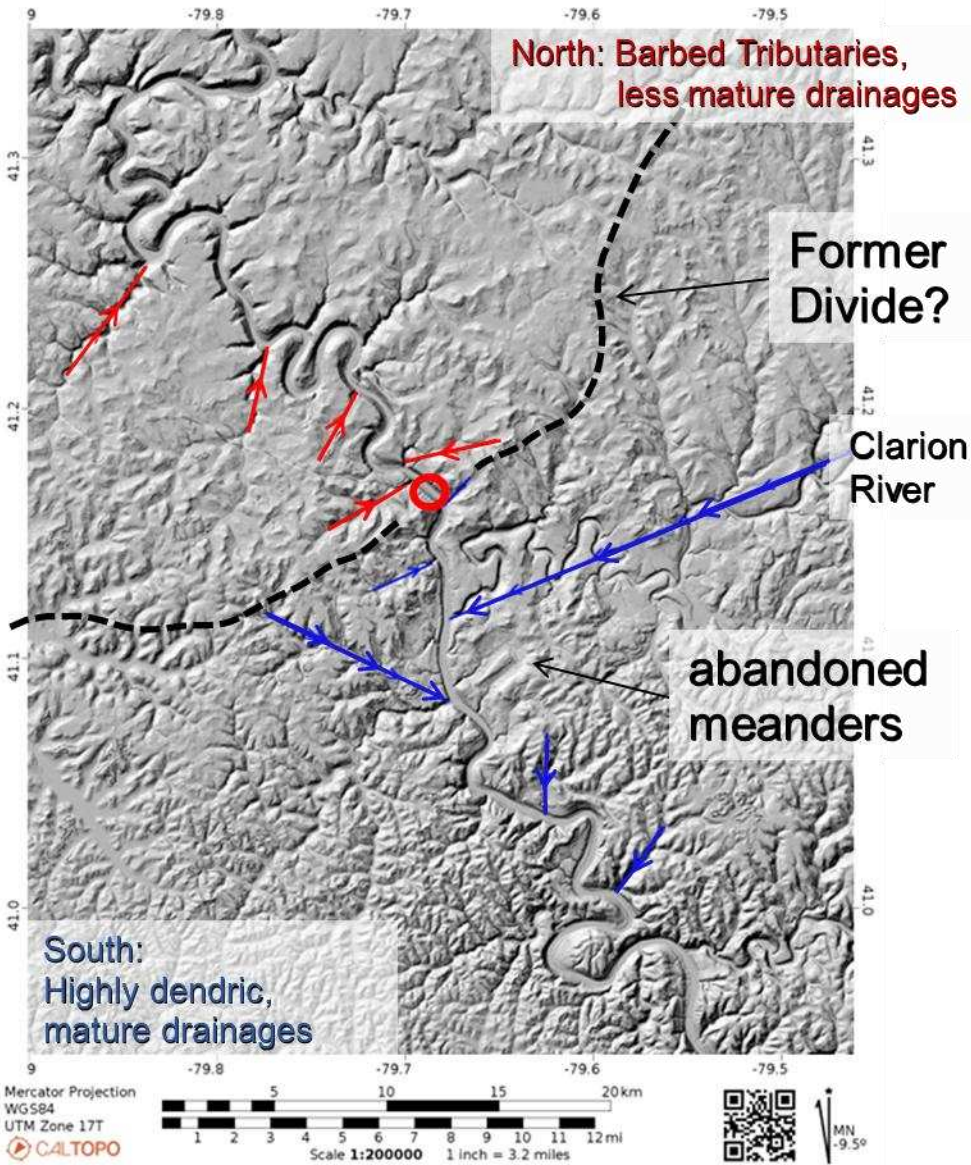
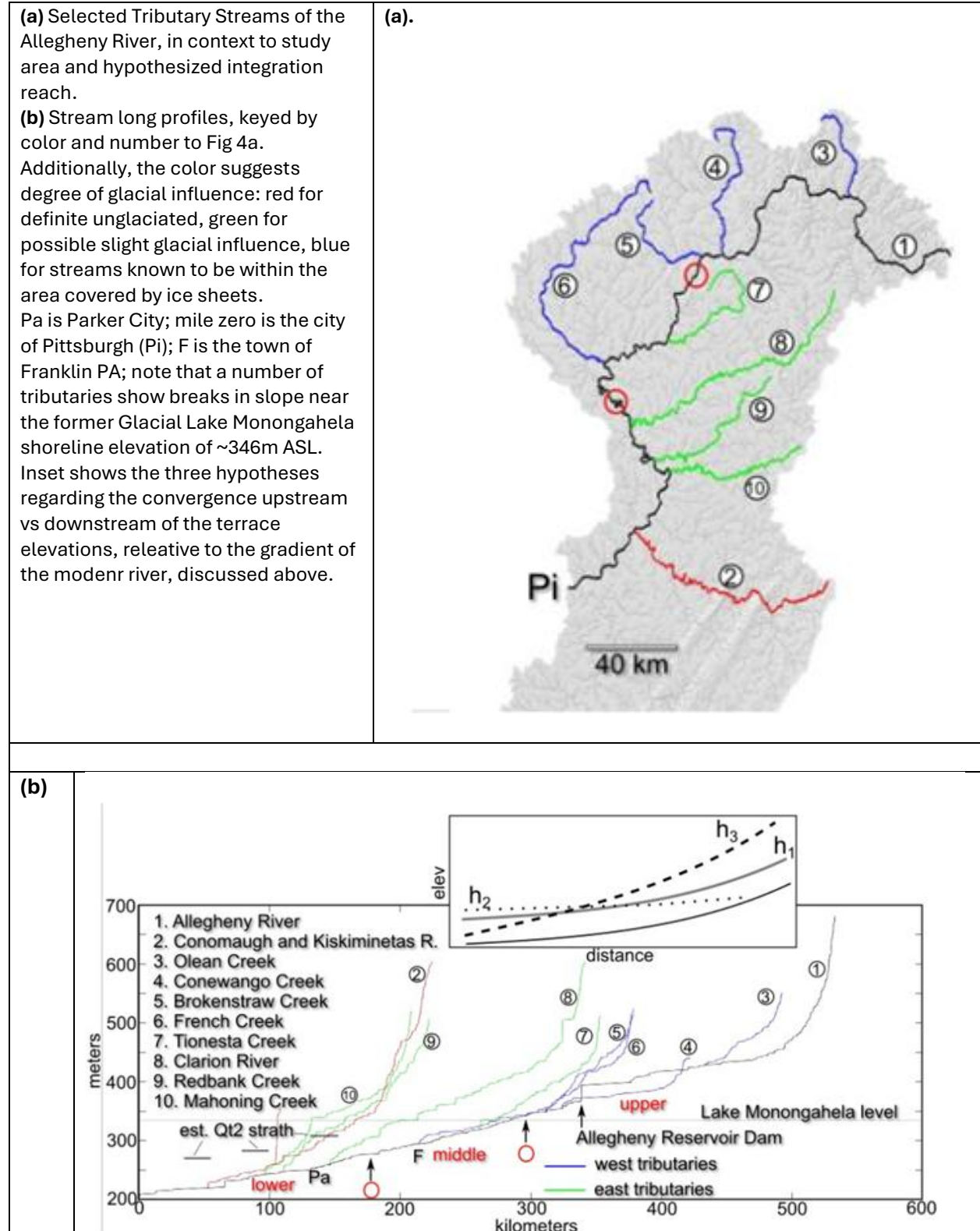


Figure 3: Qualitative differences in drainage patterns north vs south of the hypothesized integration reach (bold red circle), with annotations. The area to the south of the hypothesized former drainage divide has better developed dendritic drainage, and abandoned meanders well above the modern river level. In contrast, the area to the north has less well-developed drainage, and many main-channel tributaries are short and barbed.

Figure 4



4.2 SURFICIAL UNIT DESCRIPTIONS (ALLEGHENY RIVER TERRACES)

Alluvial and colluvial deposits paralleling the Allegheny and Lower Clarion Rivers between the villages of Kennerdell and East Brady provide the basis for geochronology, long profile models, and stratigraphic age models. Surficial units are distinguished on the basis of sediment texture, composition, stratification, and weathering characteristics including soils, and secondarily on criteria of relative elevation to the modern river, herein referred to as height above modern river level (AMR/AMRL). Eleven surficial units mappable at the 1:24,000 scale underlie geomorphic landforms ranging from terraces that are subparallel to and inset into the Allegheny gorge, alluvial fans that are concentrated at the mouths of tributaries where they are confluent with the main Allegheny channel, and floodplains that are widest on the inside bend of channel meanders (**Figs. 5,6**). The terraces in turn range from thin alluvial deposits and gravel lags atop bedrock-cut straths to 20-m thick fills that bury paleotopography, and inset alluvial fills nestled in the gorge near the modern channel (**Fig. 6**). Terrace alluvium has been sampled at key exposures for numeric age dating analysis (**Table 1**).

The oldest deposits are perched at or with a few tens of meters of the gorge lip both north and south of the Allegheny-Clarion rivers confluence. **Qt1n** is preserved north of the confluence and consists of a heavily modified and colluviated strath and fill terraces ~1-10 m (?) thick, at Kennerdell and Emlenton, with a particularly thick and extensive deposit that caps the meander loops at Kennerdell at heights 85– 95 m AMR. Exposures are poor and stratification is not observed, but the deposit appears to lack exotic clasts, being composed entirely of locally-derived sandstone and limestone cobbles, gravel, and pebbles. This unit is absent downstream of Emlenton, PA. In contrast **Qt1s** is a group of bedrock straths generally lacking alluvial deposits that lie greater than 90 m above the Allegheny channel downstream and south of Foxburg (Figs. 3 and 4).

Qt2 is a thin, < 5 m thick fill terrace that lies on an exposed bedrock strath ~ 80m AMR south of Parker, PA along Jackson Road and at the Bear Creek confluence with the Allegheny River (**Fig. 6**). It continues up valley of Bear Creek as a thin (< 1 m) patchy sand and gravel strath terrace on bedrock-cut benches. Because of extensive anthropogenic modification, the presence of exotic clasts is ambiguous. No intact soil profile is preserved in the Qt2 tread.

Table 1: Geochronology sample locations, materials, and type of analysis

Sample	Age (Ma)	1-sigma uncertainty (Ma or m/Ma)	Stratigraphic Unit	Texture	Model surface erosion rate at sample site (m/Ma)	Surface Elevation (m)	Depth below surface (m)	Latitude	Longitude	Method
VQ-OSL-01	0.1419	0.0191	Titusville outwash	sand	N/A	349	4	41.42024	-79.84742	IRSL /OSL
VQ-OSL-02	0.372	0.0395	Maple Dale till/kame	sand	N/A	345	~9	41.41873	97.84570	IRSL /OSL
WM-01-OSL	0.01682	0.00192	Qt7, LGM outwash	sand	1	268.5	1.5	41.04863	-79.65888	IRSL
PKR-03	1.105	+0.379 / -0.258	Qt3, Perryville alluvial fill	sand	1	325	10.2	41.09486	-79.66871	TCN burial
KEN-01	0.240	+0.071 / -0.060	Qc6 colluvium	matrix-supported gravelly sand	1	311	10	41.25737	-79.8401	TCN burial
KEN-02	0.513	+0.146 / -0.165	Qt6 terrace	open-framework sandy gravel	0	307	10	41.27480	-79.80076	TCN burial
VQ-03	0.400	+0.300 / -0.180	Maple Dale till	Sand	1	346.25	>10	41.41910	-79.848	TCN burial
FOX-01	Erosion rate of 29.9 m/Ma	2.5	Qt8 / modern alluvium	gravelly sand	29.9	269	0	41.14896	-79.66068	TCN exposure; for basin-scale erosion rate
PKR-03-PMAG	Reversed	Unknown	Qt3	Sandy silt	N/A	325	7.8	See PKR3	See PKR3	Thermo & AFD PMAG

In contrast **Qt3** is a ~20 m thick paired alluvial fill terrace that buries a paleotopography with at least 5-10 m of relief, with a strath ~45 m and tread ~65 m AMR at Parker, PA. The deposit is particularly well exposed in abandoned gravel pits at Perryville, PA where it fills a former meander loop of the Allegheny River (**Figs. 5, 6**). The Qt3 Perryville meander formation (informal name) consists of a red, orange, yellow, and tan-colored, well-stratified sand and gravel, stacked coarse thalweg, channel and point bar, and finer-grained overbank, and meander-fill facies including cross-bedded pebbly sand interbedded with laminated silty mud (**Fig. 7**). The gravel clasts are heterolithic and contain numerous lithologies exotic to the Allegheny watershed. Exotic lithologies are ~20% of clasts over 4 cm in shortest axis. This unit is widespread near the confluence of the Allegheny and Clarion rivers, and can be traced a short distance up the valley of the Clarion River, where the exotic clasts disappear, replaced solely by locally-derived Paleozoic sandstone and limestone. The base of the deposit, known from rare gravel pit exposures and gravel resource drill cores on the west side of the Allegheny River near Parker, PA, is a diamicton, characterized by a matrix of grey sandy clay with medium-rounded gravels. A deeply-weathered, cumulic, polygenetic soil is developed through the Qt3 tread. The soil is characterized by a 1-2 m thick loess cap, underlain by a ~2-m thick, red argillic horizon developed through both fluvial and colluvial parent material that transitions downward into oxidized ferruginous and mangiferous oxide-cemented stratified sand and gravel. A terrestrial cosmogenic burial age of 1.11 Ma \pm 0.379/-0.258 Ma (sample PKR-03, **Figs. 2, and 5; Table 2**) is calculated for a stratified sand buried 11 m in the deposit at an abandoned sand and gravel quarry at Perryville, indicating an early Pleistocene age for the deposit overall. A bed of sandy silt collected at a depth of 12 m in the exposure has a normal magnetic polarity.

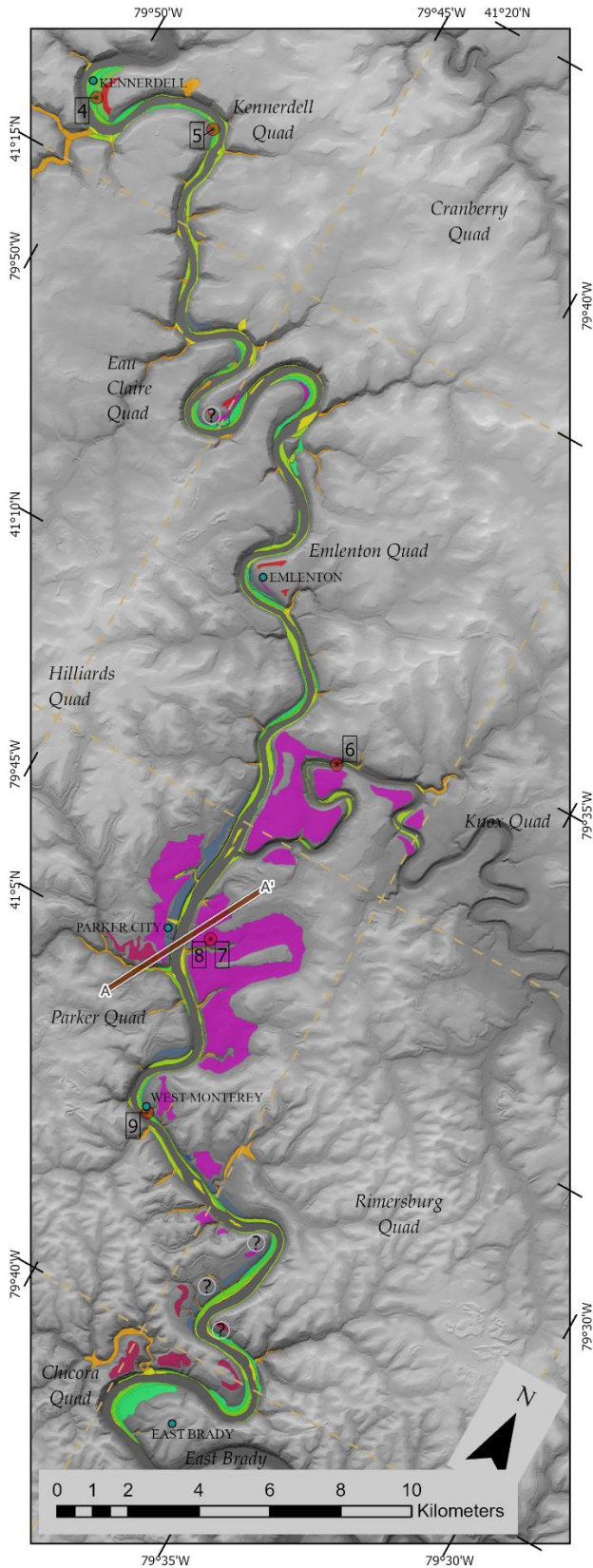
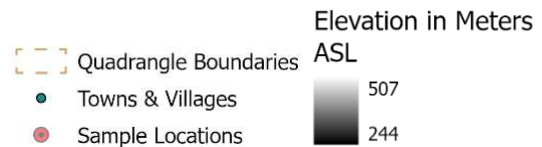


Figure 5. Main Study Reach between East Brady and Kennerdell PA, showing mapped terrace polygons on a greyscale shaded-relief basemap. Again, the qualitative difference in drainage patterns north vs south of the hypothesized integration reach

Boxed numbers are Sample Sites, as follows, see Table 1 for corresponding sample names:

Sample Site Key #	Sample Name	Associated Surficial Unit
1	VQ-01-OSL	Titusville
2	VQ-02-OSL	Mapledale
3	VQ-03-TCN	Mapledale
4	KEN-01-TCN	Qc6
5	KEN-02-TCN	Qt6
6	FOX-01-TCN	Modern River Sediments
7	PKR-03-TCN	Qt3
8	PKR-03-PMAG	Qt3
9	WM-01-OSL	Qt7



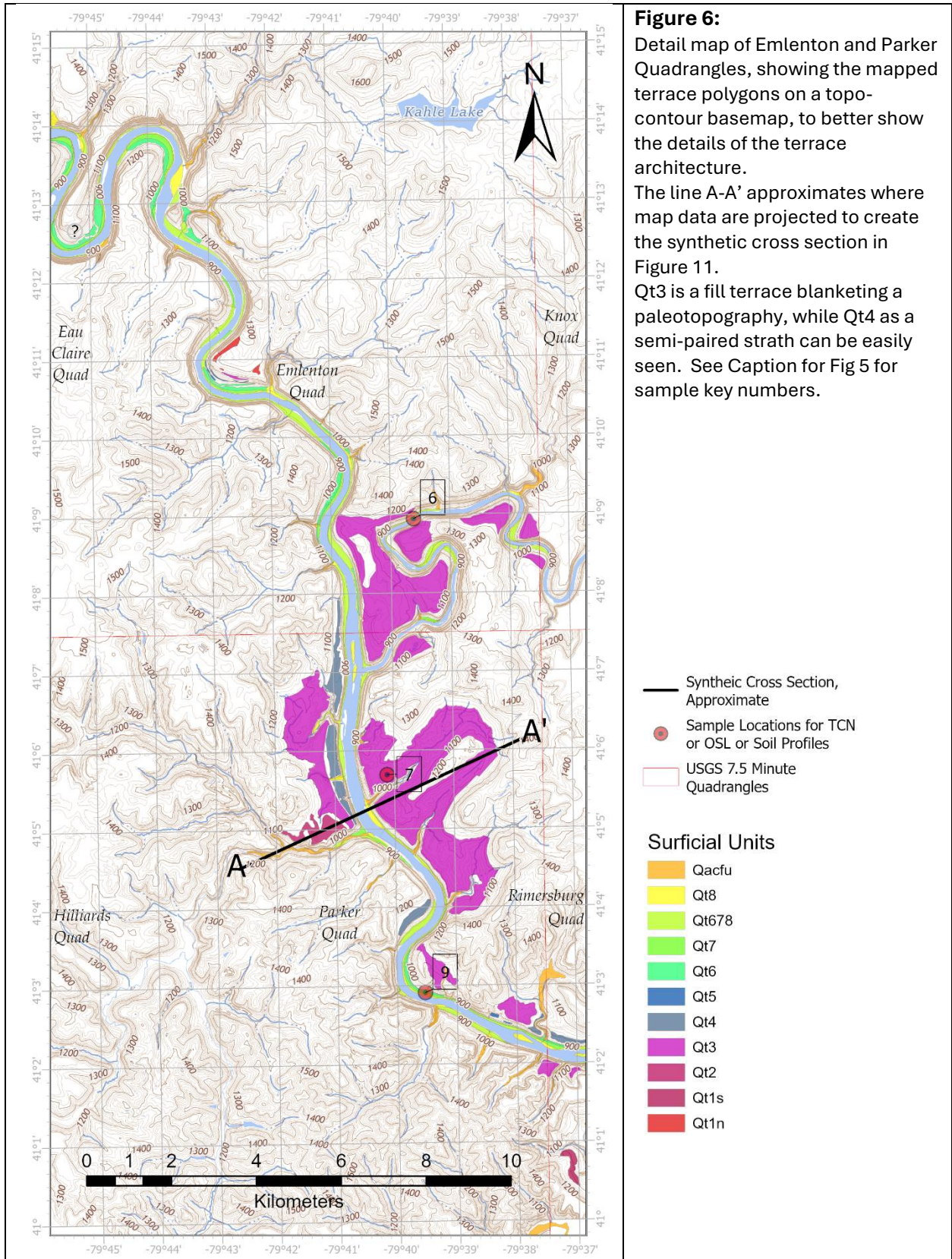
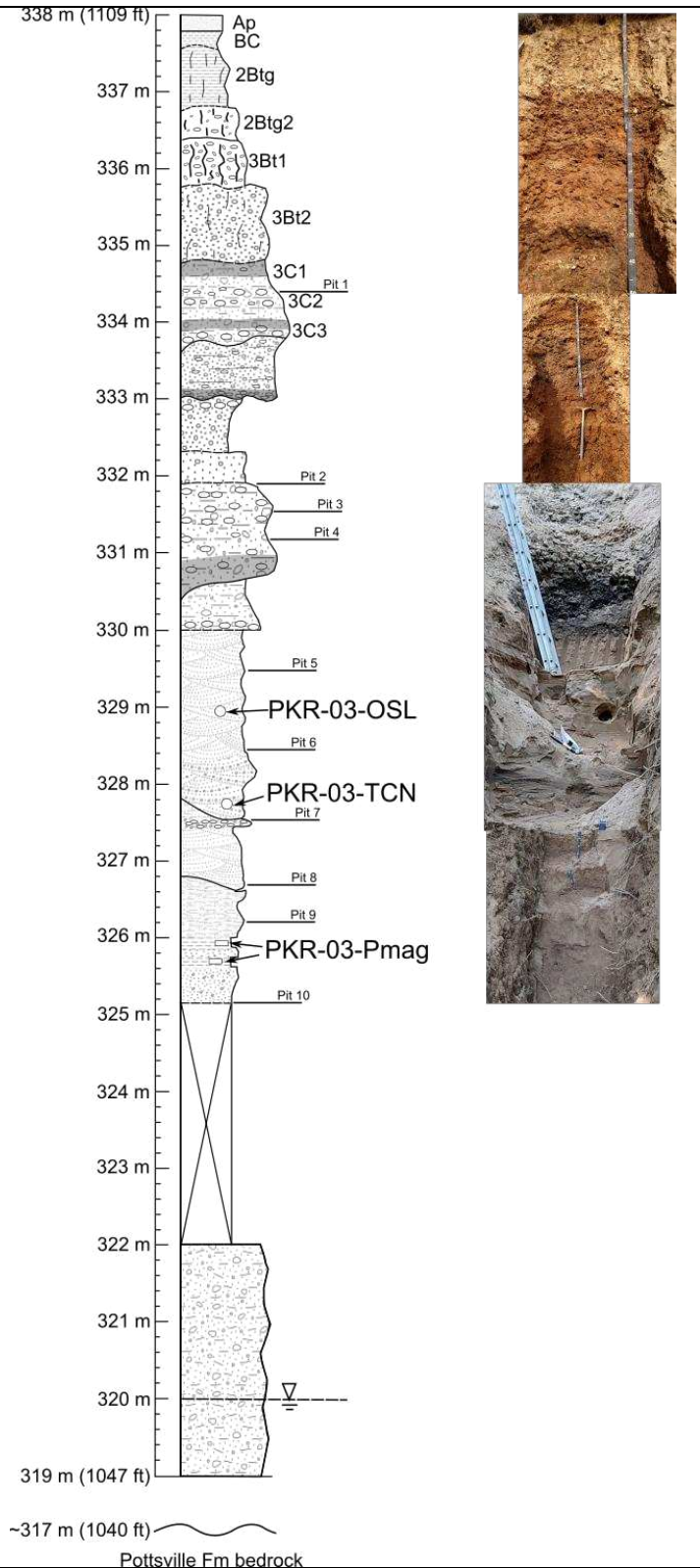


Figure 7.

Combined photographs and sketch of the Qt3 exposure, at the type section site in Perryville Township, sample location #7 on **Fig 6**.

The loess cap described in the text includes both the Ap and BC horizons. Horizons are delineated based on differences in texture and color, per standard pedogenic practice, and may or may not imply differences in parent material; the color differences between the upper and lower photos, while real, are exaggerated by lighting differences. Note also the dominance of sandy silty gravels, often open framework, in the upper 7-8 m of the profile, while below that is dominated more by sands, often crossbedded. The lowermost part of the profile, which elsewhere contains gravelly clays (possible diamict, see text), is not exposed at this site.



Inset several meters below the Qt3 strath is a wide, notably low-relief bedrock strath with a thin, 1-2 m thick alluvial cover mapped as **Qt4**, and identified as congruent with the “Parker strath” of previous workers farther downstream along the Allegheny and Ohio river valleys (Ver Steeg 1946, Norris 1958). The Parker strath is particularly well preserved at and around the confluence of the Clarion and Allegheny rivers at Parker, PA. Qt4 terrace alluvium is a mostly channel facies of coarse, heterolithic sandy gravel including well-rounded exotic clasts. The strath lies at a height of ~43 m AMRL at Parker City and has a more gentle gradient than the Allegheny River, lying ~50 m above the channel at Black Fox Run, 13 km downstream of Parker. Notably this unit is not present north of Foxburg, PA or the confluence with the Clarion River, but is traceable as a thinner, less continuous strath south of the confluence to at least East Brady (**Fig. 5**). Some previous studies have suggested this unit may be traceable even farther downstream into the valley of the Ohio River (Steeg 1934, Anthony & Granger 2006).

Inset below Qt4 and fully within the walls of the Allegheny gorge is **Qt5**, a locally preserved, thin, discontinuous, unpaired strath terrace that lies between ~30 and ~45m AMRL. The unit contains exotic clasts and poor outcrops show considerable variation in texture and grain size, from gravely sand to muddy, likely colluviated gravel. No intact soils are preserved in the treads of Qt5.

A suite of low terraces, **Qt6, Qt7, and Qt8** parallel the modern channel, all within 15 m AMR. These units are both paired and unpaired inset alluvial fills and are mapped as Qt678 undivided in areas where the individual treads are indistinct or unmappable at the 1:24K scale. Despite this, in the field they can often be distinguished, if otherwise not obscured by anthropogenic activity, mass wasting, or the alluvial fans of small tributary streams.

The uppermost member of the low terrace suite is **Qt6** a stratified, mostly open framework, heterolithic sandy pebbly gravel paired alluvial fill inset into the base of the Allegheny gorge (**Fig. 8**). Gravel clasts exotic to the Allegheny basin are ~35% of clasts over 4 cm in shortest axis, based on field observation and a single clast count (Appendix 2). The strath of this terrace is poorly exposed, but where locally exposed, generally the base is ~15 m above the Allegheny River. Qt6 interfingers with hillslope colluvium and is thickest near tributary confluences. In addition, the tread of Qt6 is commonly mantled by a younger hillslope colluvium (Qacfu?) up to ~30 m above the river, constraining the underlying deposit to a thickness of ~15 m. The soil of Qt6 is not well exposed, but the tread is distinct in its dissection by gullies regularly-spaced ~100 m apart. Qt6 has a burial TCN

age of 0.513 Ma \pm 0.146/-0.165 Ma (sample KEN-02, **Figs. 2, 5; Table 2**), indicating a middle Pleistocene age.

A colluvial wedge, noted as **Qc6** is exposed **at a similar elevation to Qt6 at Kennerdell (Figs. 5 and 9)**. This Qc6 unit, includes some well-rounded gravel present, suggesting it may include reworked material from an earlier terrace deposit. This Qc6 unit is a poorly stratified, matrix- and clast-supported colluvium composed of reworked, older terrace gravel interbedded with well-stratified shale-chip ‘greze litee’ texture, and stratified slope deposits derived from bedrock. The deposit locally contains a sticky mud matrix and ranges in thickness from ~3–8 m. Qc6 both overlies and is inset into the terrace Qt6, but it also may interfinger with terrace Qt7 ~20 m above the Allegheny River channel at Kennerdell.



Figure 8.

Photos showing the type section outcrop of Qt6 sampled for TCN, in Scrubgrass Township, downstream of Kennerdell, at sample location [5] on Figure 5. This exposure helpfully created by a local property owner, one Daniel English, whose family has for decades exploited the layers of open-framework rounded gravels for roads and building foundations. Note the cap of colluviated soil at the top of the exposure. The



Figure 9:

The Qc6 outcrop at the Sweetapple Farm locality is seen here. The grey color on the left appears to be partially from a grits litee type slope deposit. Despite this, rounded indurated clasts suggestive of fluvial influence were found toward the base of the unit. The location of this outcrop is sample location [4] on Fig. 5

The middle terrace of the low terrace suite is **Qt7**, a paired alluvial fill terrace inset into Qt6. Qt7 is composed of a gravelly sand to sandy gravel including clasts exotic to the Allegheny basin, and the exposed deposit thickness ranges from ~2-8 m (**Fig. 10**). The tread of terrace Qt7 lies ~10-15m AMR and the base of Qt7 is not exposed and the true thickness is not known except to say water wells located in Qt7 penetrate at least 25 m of saturated alluvium. Soils in the tread are poorly developed, generally lacking a distinct Bt horizon, and are often heavily modified by anthropogenic activities. An exposure of sandy Qt7 in the village of West Monterey, downstream of the Clarion River confluence yielded an IRSL geochronology date of 0.0168 Ma (+/- 0.00192 Ma) (sample WM-01, **Figs. 2 and 5; Table 2**).

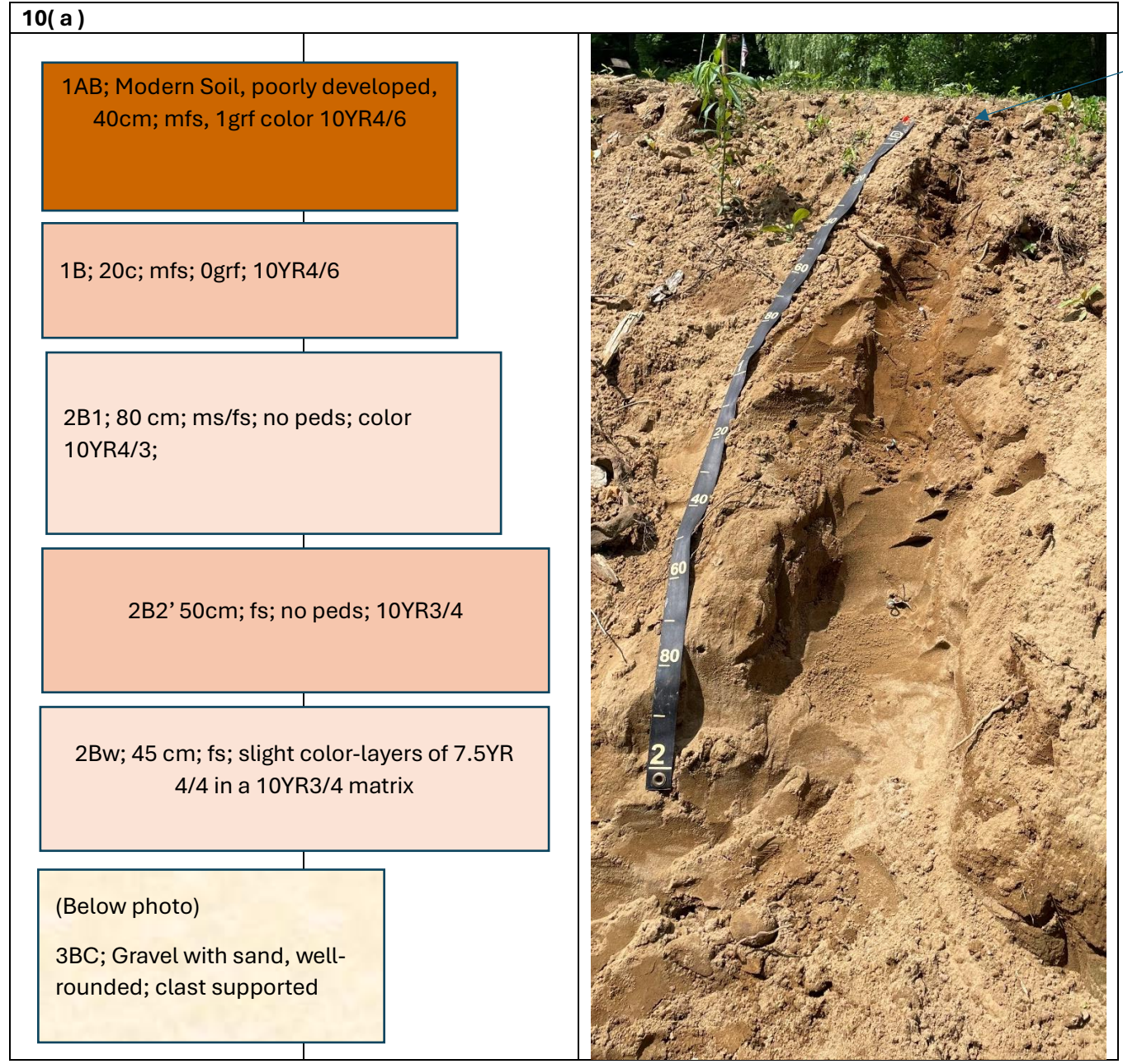
The youngest and lowest of the low terrace suite, the **Qt8** terrace alluvium (**Figs. 5 and 11**), is a paired alluvial fill composed of stratified sand and gravel with exotic clasts. The Qt8 tread mostly lies within ~3-6 m of the mean Allegheny River level and elsewhere is co-incident with the modern floodplain. Exposures of the deposit are typically ~1 – 4 meters. Soils are poorly-developed in the Qt8 tread and heavily modified by anthropogenic activities. On the surficial unit

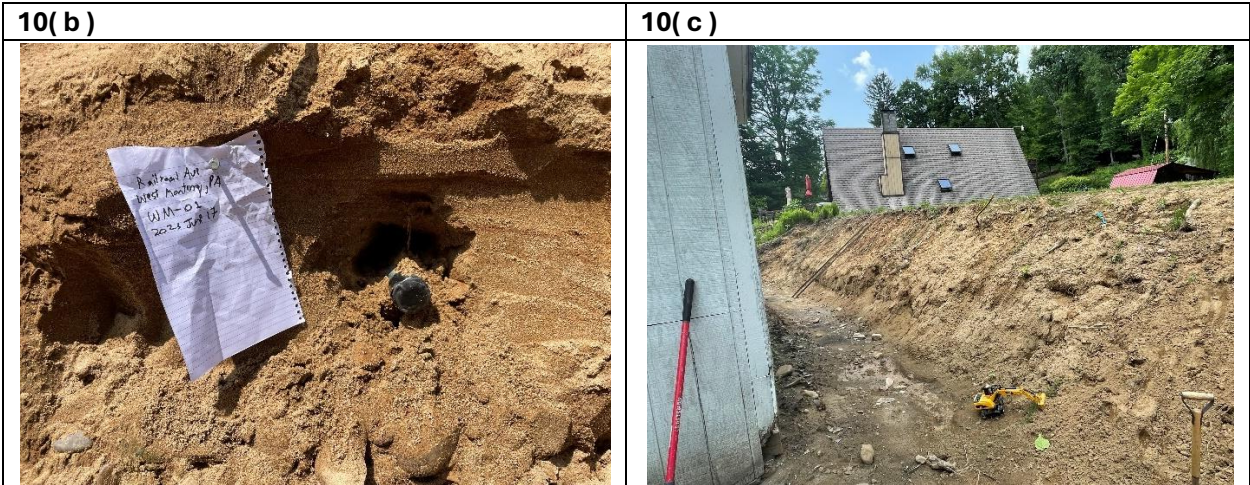
maps, Qt8 also includes late Pleistocene to Holocene, alluvial fan deposits preserved at the confluent mouths of tributary channels to the Allegheny River.

Alluvium and colluvium that lie in the channels of low-order streams, many of which are tributary to the Allegheny and Clarion rivers is grouped into a unit **Qacfu** (alluvium and colluvium undivided). The texture ranges from stratified gravelly sand and sandy gravels, to a poorly stratified and poorly sorted, mostly locally-sourced, matrix-supported sandstone clast diamict. However, the unit actually contains a spectrum of deposits from well-sorted, open-framework, heterolithic channel and overbank facies of the Allegheny River and its larger tributaries all the way to poorly-sorted, monolithic debris-flow like deposits mixed with colluvium in the smaller tributary channels. Outside the main Allegheny channel, it represents a range of hillslope and fluvial deposits in steep, low-order tributaries to the Allegheny River. Exotic clasts are abundant, in excess of 30% of clasts over 4cm in shortest axis. As Qacfu is a composite unit containing many instances of colluvium, it is difficult to assign an age to this unit. While the stream gravels of low-order streams are likely Late Pleistocene to Holocene, if the age of Qt7 can be used inferentially, the colluvial wedges and landslide deposits likely are older, especially when higher above the modern river, as in the colluvial wedge seen placed atop Qt6 in Figure 7.

Figure 10

Schematic soil profile and annotated outcrop photographs of Qt7, where WM-01-OSL was collected; sample location [9] on Fig 5; **(a)** Exposure of Qt7 at West Monterey PA at the IRSL sampling location, on left schematic soil profile with text of observed ped structure and color, on right matching photograph of excavated outcrop; scale approximate; **(b)** closeup of WM-01-OSL sample site, showing sandy sediment texture ; **(c)**. perspective photos of outcrop site behind a 20th century structure, showing anthropogenic disturbance and poor soil development on terrace tread; picture was taken a cut about ¾ down the terrace thickness, the terrace base is ~0.75 meters below the bottom of the photo





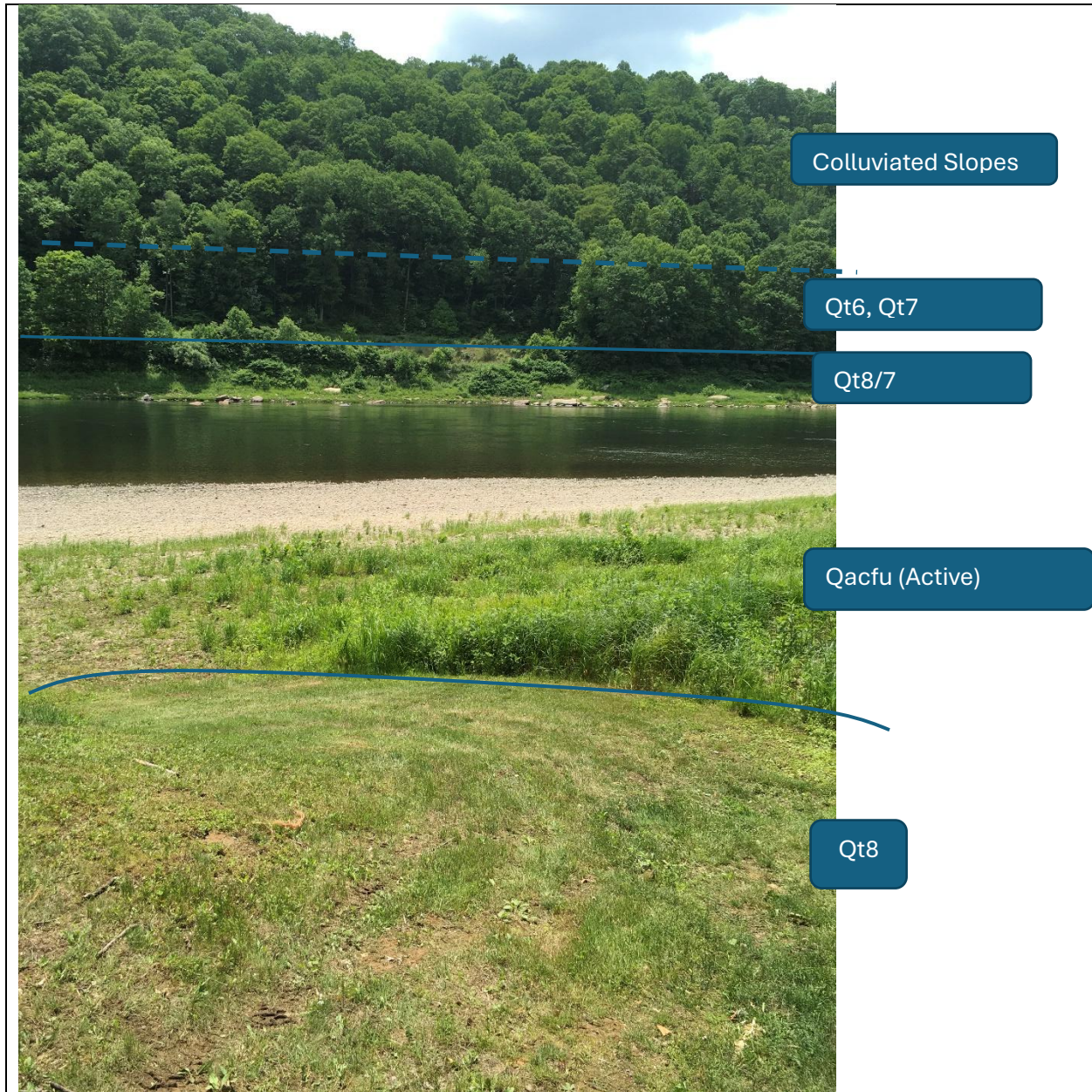


Figure 11. Photo showing Qt8 terrace and generalized low terrace suite. Here is seen the Qt8 terrace, with a Qacfu gravel bar below it, located between Parker City and West Monterey. View is taken standing on the Qt8 terrace, with the Holocene gravels in the foreground. Photo taken on 17 June 2023, at 12:33 pm, with the terrace structure of Qt6, Qt7, Qt8, and Qacfu visible through the vegetation with some difficulty. A railroad track is visible that has been built atop the Qt7/8 terrace. The paired occurrence of these lower terraces is evident. Photo taken while facing east, location approximately 41.06161, - 79.66147.

4.3 GLACIAL MARGIN SURFICIAL UNIT DESCRIPTIONS

Till and outwash are well exposed in an active gravel quarrying operation (Vincent Sand and Gravel) at the glacial margin near Franklin, PA ~45 km upstream of the Allegheny-Clarion river confluence. These deposits are poised at the head of outwash at the French Creek-Allegheny river confluence that would have been directed down into the Allegheny River and may have a temporal and genetic connection to the Allegheny River terraces.

At least two tills and associated outwash facies are exposed in the gravel pit (Straffin & Fleeger 2022). The older till has been associated with the pre-Illinoian Mapledale till of northwestern Pennsylvania (White, 1968). It is a coarse, angular, lodgment till ~3-6 m thick that overlies a well-stratified kame sand and gravel, the exposed thickness of which is ~3-6 m. The Mapledale till is deeply weathered with sandstone clasts being completely altered to saprolite. The soil is orangish-red with a 1-2 m thick argillic horizon composed of coarse, angular blocky peds. The Mapledale till is locally overlain by a colluvial wedge that has in part resulted in a perched water table that imparts a gleyed overprint on the soil. For this unit, identified as the Mapledale till, a minimum burial TCN age of 0.400 Ma, with an uncertainty of +0.310/-0.180 Ma (sample VQ03 TCN, **Table 2**) was obtained from the stratified kame material ~ 9 m below the surface.

Elsewhere in the gravel pit the Mapledale till is overlain by a younger ablation till with a finer texture and local crude stratification called the Titusville Till (Fleeger et al 2022; White, 1968). Outwash of the Titusville till overlies the till and is composed of well-stratified sand with minor gravel lenses. A soil developed in the Titusville outwash is ~2 m thick with a dark red, subangular blocky argillic horizon that has well defined clay films on ped faces. An IRSL age of 0.1419 +/- 0.002 Ma was obtained from stratified sand above the till (VQ01-OSL), and below the argillic horizon of the red soil.

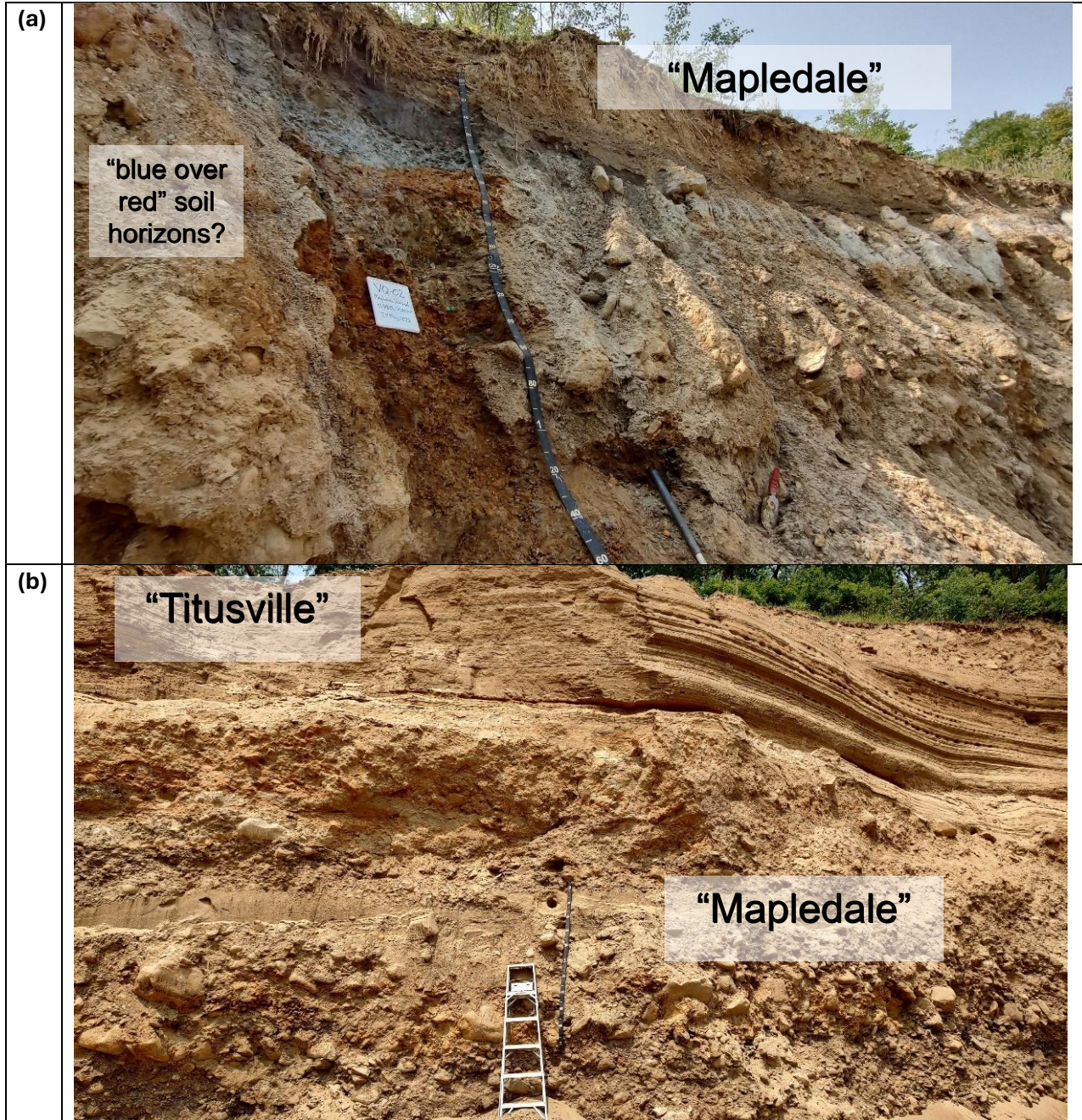


Figure 12. Photographs showing the outcrops of the Titusville and Mapledale kame and til., from the Vincent Quarry site near Franklin PA.
(a) shows the distinctive soils of the Mapledale.
(b) shows the stratigraphic relationship, with the laminated kame sands of the Titusville often inset into the eroded surface of the Mapledale.

4.4 GEOCHRONOLOGY AND AGE MODELS

The combination of alluvial stratigraphy, sedimentology, relative weathering characteristics preserved in soils, and numeric ages are used to construct representative terrace stratigraphic models for the middle of the study area at Parker, PA (**Figs. 4 and 5**). These findings, presented in more detail below, are briefly summarized in **Table 2** below, while **Figure 13** depicts relative stratigraphic relationships of the various surficial units while summarizing the known age information.

Table 2: Geochronology Sample Summary

Sample Name	Map Key #	Age (Ma)	1-sigma uncertainty (Ma or m/Ma)	Stratigraphic Unit
VQ-OSL-01	1	0.1419	0.0191	Titusville till/kame
VQ-OSL-02	2	0.372	0.0395	Mapledale till/kame
WM-01-OSL	9	0.01682	0.00192	Qt7, LGM outwash
PKR-03-PMAG	8	n/a	n/a	Qt3, Perryville alluvial fill
PKR-03-TCN	7	1.105	+0.379 / -0.258	Qt3, Perryville alluvial fill
KEN-01-TCN	4	0.240	+0.071 / -0.060	Qc6 colluvium
KEN-02-TCN	5	0.513	+0.146 / -0.165	Qt6 terrace
VQ-03-TCN	3	0.400	+0.310 / -0.180	Mapledale till
FOX-01-TCN	N/A	Long-term erosion rate of 29.9 m/Ma	2.5	modern alluvium (Qacfu)

4.1 TERRESTRIAL COSMOGENIC NUCLIDE (TCN) EVIDENCE

Samples from terraces Qt3, Qt7, Qt6, and Qc6, were dated via TCN. This involved measuring the amount of ^{10}Be and ^{26}Al in the specimen, and then modeling these results with different possible burial depths and erosion rates, to obtain a “most probable” TCN age model and uncertainty parameter. The simple burial TCN age model has three key assumptions: 1) assumes that sample was “maxed out” in its exposure to cosmic rays to maximize possible TCN generation prior to burial; 2) assumes “simple burial” that the burial was rapid and that the sample was not subsequently re-eroded to be partially exposed to cosmic rays; and 3) the model assumes that the sample was buried with sufficient shielding (ideally at least 10 m) that secondary cosmogenic production effects are minimized. In the real world, any or all of these assumptions may not be entirely valid. Indeed, that these assumptions may not be entirely and completely valid is suggested both by the asymmetric and “hummocky” shape of the PDF curves

Terraces Qt3, Qt7, and Qt6 have been dated by modeling the ^{10}Be and ^{26}Al concentrations of samples assumed to have simple burial histories. The model ages assume at least 9-10 meters of

shielding, and that the burial was rapid relative to the age of the deposit, and that subsequent re-erosion rates are under 1 m/Ma. Supplementary figures (Appendix 2) show the non-best fit dual-isotope plot used for each of these samples, from which the most probable set of assumptions and outcomes was chosen, as well as the raw nuclide measurements from which these analyses are derived.

PKR-03 (Qt3), has a most probable TNC age of 1.105 Ma, with an uncertainty of +0.379 / - 0.258 Ma. This is obtained via a simple burial model; it assumes that there is a near-zero erosion rate, which is supportable by the existence of a loess cap within the soil profile at the top of Qt3; the assumption of simple rapid burial is also supportable by the sample depth of 10.2 m, which is deeply buried enough that shielding effects are less of a concern (**Figure 14a**). However, it is possible that this sample was not sufficiently rapidly buried, as the layer of manganese nodules and redox colors higher in the profile suggests a period of surface stability with fluctuating water tables earlier in the site history. However, this layer is at least 5 m above the sample layer, and the presence of undeformed and un-bioturbated cross-bedded sands with little apparent pedogenesis, immediately above the sample layer, suggests a more rapid set of burial condition. Given the age the sample and the consequent uncertainties, burial at several meters depth within a few thousand years of initial deposition may still be considered a “rapid burial”. As the asymmetric 1-sigma uncertainties are in excess of 100ka in either direction, this is a reasonable simplifying assumption to make.

KEN-01, from the colluvial unit Qc7, has a most probable TCN burial age of 0.240 Ma+0.071 / -0.060 Ma (**Fig 14b**) The precise stratigraphic setting of this sample is unclear. Whereas it was collected at a depth of ~10 m below the surface of a gravel pit highwall, the texture of the deposit indicates both fluvial and colluvial reworking. Hence, the exposure history of the sample is poorly constrained. It is possible that the material sampled experienced one or more episodes of exposure, erosion, transport, and burial.

KEN-02 (Qt6) has a most probable TCN burial age of 0.240 Ma, with an uncertainty of +0.071 / -0.060 Ma, was obtained. This finding assumes a simple burial model, which may not be entirely true at this sample site. While the colluvial wedge atop the sample area (see Figure 9) allows for an assumption of zero erosion rate, it is not possible to have full confidence that this sample was rapidly buried the sufficient depth to prevent the effects of incomplete shielding from complicating the age model, expressed in the asymmetry of the probability distribution plot and error ellipse within the banana plot (**Fig. 14c**).

The Mapledale Till sample (VQ-03, **Fig 14d**) has a most probable TCN burial age of 0.304 Ma \pm 0.158 / -0.147. This used a simple burial model, with an assumed a model surface erosion rate of 1 m/Ma, which is taken as a robust age given the upland location of the site still possessing a soil mantle. The maximum possible sample burial depth is estimated be \sim 15m, accounting for recently anthropogenically removed overburden, using alignment with surrounding unmodified terrain as a guide. Even with the most pessimistic assumptions about the pre-Holocene state of the immediate microtopography, yields a the sample burial depth of $>$ 10 m, implying the at the impact of incomplete shielding can be constrained as a source of uncertainty. Based on the well-developed soils at the top of the profile, an erosion rate of erosion of 1 m/Ma was used as a first-order estimate. This is likely an underestimate; but higher erosion rates did not improve model outputs.

Qc6 has a terrestrial cosmogenic nuclide burial age of 0.240 Ma \pm 0.066 Ma (equivalent to MIS 7 or MIS 8) extracted from an abandoned gravel pit exposure at Kennerdell. The presence of the colluvial wedge gives confidence of sufficient shielding, but the presence of 'gretz litee' suggest slope processes that contradict a simple rapid burial model (Heimsath et al., 1999; Van Steijn, 2011). It is therefore unclear what precise process this TCN date for Qc6 should be taken to represent, although an interpretation as a minimum burial age, but not a maximum, is defensible (Suhr, 2019). Alluvium from the modern Clarion River (Qacfu), sampled upstream of the town of Foxburg PA, (FOX-01), has a ^{10}Be concentration consistent with a steady-state basin-wide erosion rate of 29.9 \pm 2.5 m/Ma.

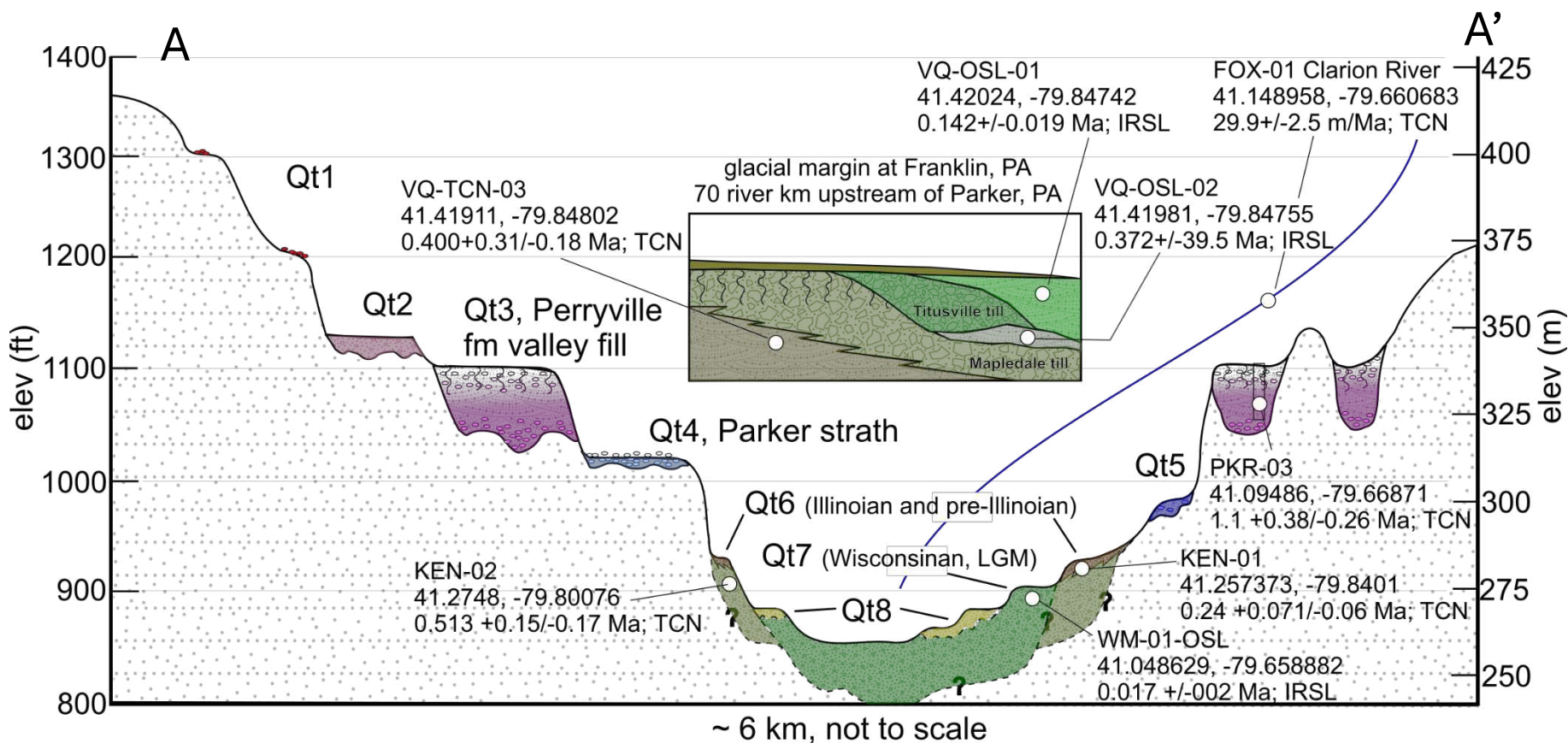


Figure 13.

Synthetic cross section, approximately on line A-A' in Figure 6. Note the that inset is at an equivalent elevation; the curved blue line approximates the long profile of the modern river.

Figure 14.

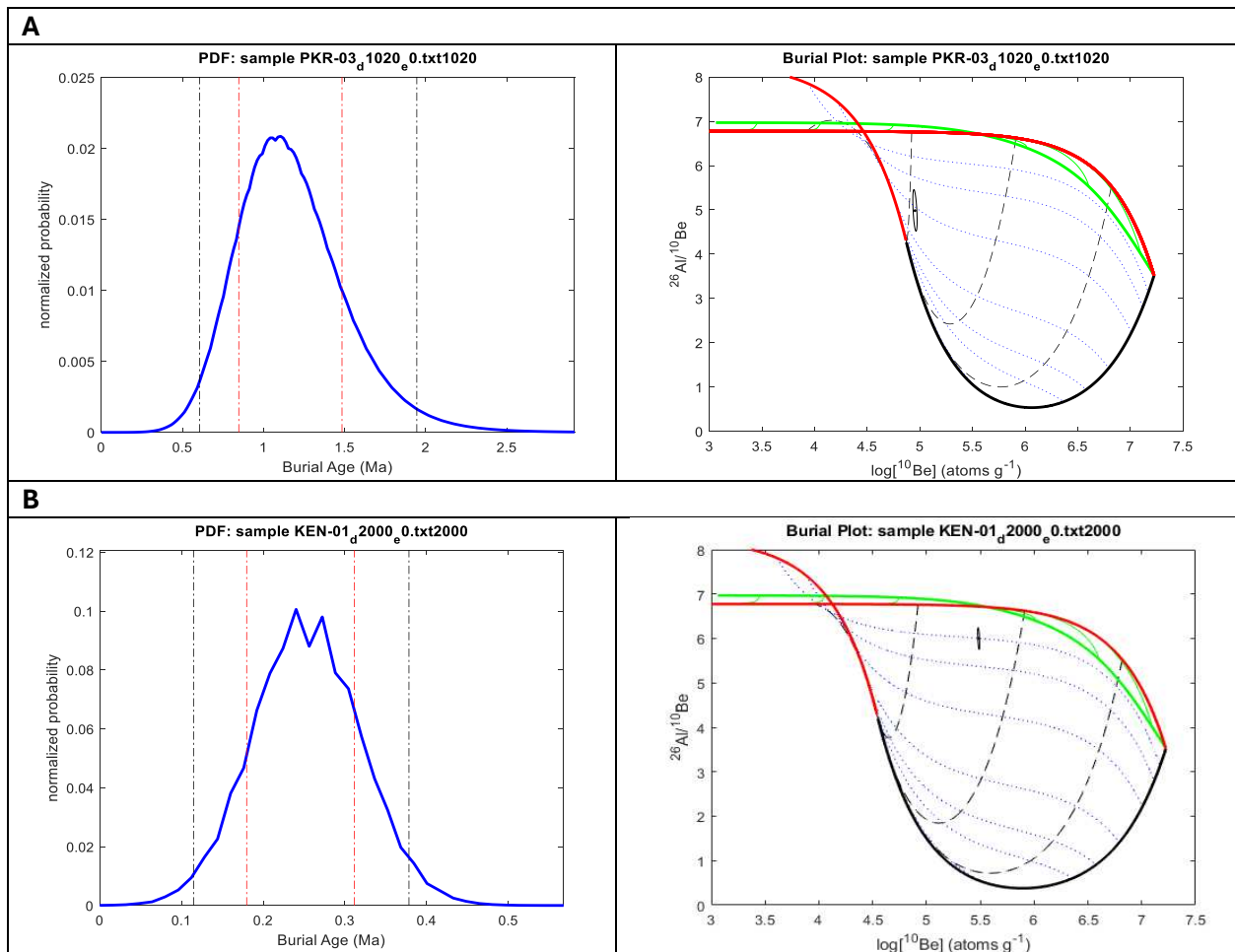
A set of plots relating to the analysis of the TCN samples. On the left is the PDF, the probability density curve of nominal burial age. On the right is the dual-isotope plot of with ^{10}Be concentration on the x-axis and the $^{26}\text{Al}/^{10}\text{Be}$ ratio on the right. The area inside the lines is the possible simple burial histories, while the size of the small ellipse represents the range of possible sample ages. Justifications for sample assumptions are in the main text body above.

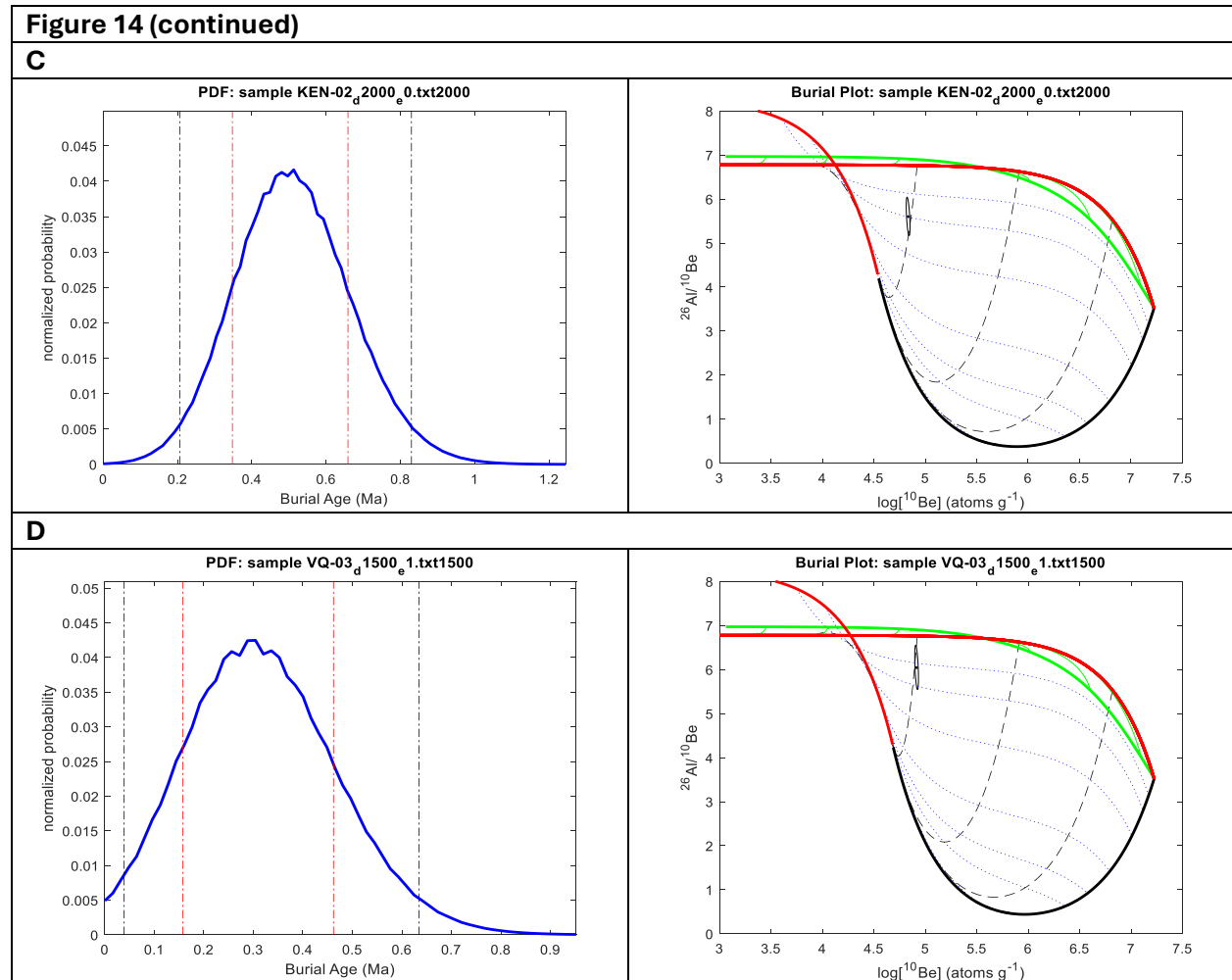
(A) PKR-03 in Qt3; assumes 1020cm of burial and zero erosion;

(B) KEN-01 in Qc6; assume >2000cm of burial, and zero erosion; however, colluvial effects make these assumptions less confident; sample may have a simple burial history

(C) KEN-02-TCN in Qt6; Assumes 2000cm burial depth and $e=0$. This is reasonable because both current conditions and the presence of a substantial colluvial wedge above the terrace deposit from which the sample was collected

(D) VQ-3-TCN in Mapledale; assumes 1500cm of burial and $e=1$ m/Ma;





4.2 LUMINESCENCE DATING

Three IRSL (infrared stimulated luminescence) dates were obtained within or adjacent to the area of study (**Tables 1 and 2**). The WM-01-OSL sample was obtained from within Qt7 at West Monterey PA, at an elevation of 286 m and located ~13m AMRL (above modern river level). This yielded an OSL age of 0.01682 Ma (16.82 ka), with an uncertainty of ± 0.00192 Ma (1.92 ka), making suggesting that the Qt7 unit is very late Pleistocene, after the LGM, but still within MIS 2. The IRSL sample VQ-OSL-01), was obtained from the Titusville outwash unit at the Vincent Quarry locality, northwest of Franklin PA. For this Titusville outwash sample, an IRSL age result was obtained of 0.1419 Ma, and an uncertainties of ± 0.0191 Ma (near the end of MIS 6). The sample VQ-OSL-02, also near Franklin PA, but from within the unit identified as the Mapledale till/kame, yielded an IRSL age result of 0.372 Ma, with an uncertainty of ± 0.0395 Ma. This MIS 9 age is older than the Sangamonian age suggested for the Mapledale by some earlier workers (White, 1968).

4.3 PALEOMAGNETIC DATA

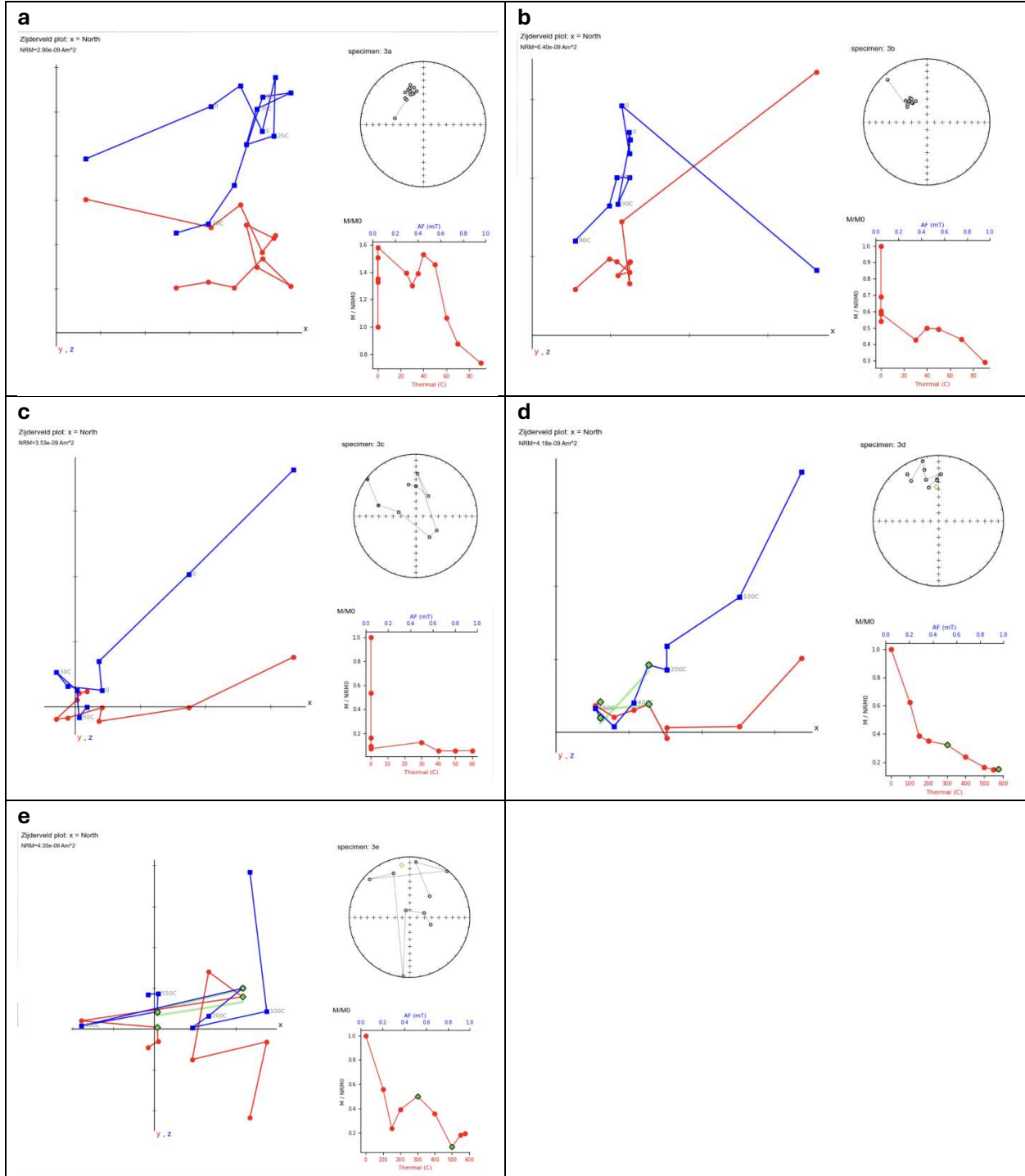
Five oriented specimens, representing one paleomagnetic sample was collected from the PKR-03 site in Qt3 (Perryville Meander). This sample was collected at a stratigraphic depth of 7.8m below the surface, at an absolute elevation of ~227.2m. In this area the local declination is 9.55 deg W. Further raw paleomagnetic data can be found in the supplemental data section. This Qt3 paleomagnetic sample generates complicated and noisy thermal demagnetization plots consistent with a normal polarity but also included a non-trivial reversed overprinting. The summary trend of the three specimens is consistently down and NNW (**Figure 13a-e**). This suggest a paleomagnetic depositional setting during a brief magnetic normal period within a more protracted period of magnetic reversal. As the TCN age for Qt3 suggests a depositional age of approximately 1.1 Ma $+0.38/-0.26$, the most parsimonious interpretation is that this sample was deposited during the Jaramillo normal subchron excursion within the Matuyama reversal. The Jaramillo normal subchron has been variously dated in the literature between 1.11-0.92 Ma (Izett & Obradovich 1992), although other workers have dated it more narrowly to between 1.072 Ma and 0.988 Ma (Kirscher et al 2018). This is within the 1-sigma uncertainty for the TCN results for Qt3, supporting an possible interpretation that Qt3 was deposited between 1.072 Ma and 0.850 Ma. This age would correspond to somewhere between MIS 27 and MIS 30, and therefore more speculatively with pre-Illinoian F (Cohen and Gibbard, 2019), insofar that the official correlation charts based on tills in Nebraska can be appropriately correlative for a fluvial deposit in Pennsylvania (Roy et al., 2004; Balco and Rovey, 2010).

Table 3: Relative Elevations and River Miles of Absolute Geochronology Samples

Sample Name	Surficial Units	Surface Elevation (m), ASL	Nearest River Mile (see Fig 5)	Elevation of River at that River Mile, m ASL	Sample Depth Below Surface (m)	Sample Distance AMRL, m	Age (Ma)	1-sigma uncertainty (Ma)
WM-01-OSL	Qt7, LGM outwash	268.5	79.5	255	1.5	13	0.141	0.0191
PKR-03-TCN	Qt3, Perryville alluvial fill	325	83.5	267	10.2	48	1.1	+0.38 / - 0.26
KEN-01-TCN	Qc6 colluvium	311	108.5	280.5	10	26.5	0.24	+0.071 / - 0.060
KEN-02-TCN	Qt6 terrace	307	105.5	277.5	10	33.5	0.513	+0.15 / - 0.17

Figure 15

Zijderveld plots of pgmag results PKR-03-PMAG from Qt3 at 11.5m depth below surface. Five sub-specimens in total were analyzed. Two of them (b,c) were placed into ceramic boxes and thermally demagnetized. The other three (a,d,e) were subject to AF (alternating field) demagnetization. Both methods, while different, result in similar outcomes. all samples show a result of paleomagnetic normal with a reversed overprinting.



4.5 GEOCHEMISTRY OF SOILS

QT3 CAP SOIL

The Qt3 soil is adjacent to areas mapped by the USDA as the “**Chenango gravelly silt loam**”, and has a structure, color, and texture broadly consistent with that description. This profile and the tau plot of major element geochemistry are depicted in **Figure 16**. The parent material for this soil is a fluvial deposit of mixed sands and gravels, with a 5-10cm loess cap, and a reddish argillic horizon up to 2m thick.

The presence of multiple argillic horizons, with color and texture variations between them, suggest that the profile of undergoing multiple episodes of incipient development, followed by decapitation, and then further deposition of alluvium soil development. The layer at ~375 cm depth contains dark-brownish-purple manganese oxide films on the ped surfaces, which suggests waterlogged reducing conditions at some point in the soil’s history. The ~1.1 Ma age of PKR-03 places an upper limit on the duration of pedogenesis represented by the Qt3 soil. Despite the greater level of precision provided by the sedimentary paleomagnetic results, we cannot say with confidence that the when the final channel abandonment took place and therefore cannot constrain the lower bound of the period of ongoing soil development, beyond that it must have taken place by 513 ka.

The tau plot indicates that the soil has undergone a substantial amount of weathering, but has not reached a steady-state with respect to depletion of even highly mobile elements such as potassium. Most likely this is because of the loess cap material added later in the Pleistocene. This loess cap and materials translocated downwards from it are seen in the positive Ca and Na spikes seen at roughly 60cm depth. The gradual decline in Si relative to Al and Fe between 20 and 300 cm depth suggests a gradual decrease in clay content, while the change in the Al/Fe ratios, despite the lack of variation in K, suggests that there is only a slight to negligible change in the species of clay minerals present within the profile. That spike in Mn at depth presents a layer of encrusted clasts that likely represent strongly reducing conditions, possibly with higher temperatures than is present today. Further geochemical data, including trace elements, is presented in the supplements.

TITUSVILLE KAME SOIL

The Titusville till soil profile is mapped by the USDA as the **Alton Gravelly Loam** (Soil Survey Staff, 2024) and represents a maximum of ~140 ka of pedogenesis. Figure 16 shows the Tau plot of major elements within this soil profile.

Although the Qt3 and Titusville kame soil profiles differ significantly in the relative abundance with respect to depth of both Mn and Mg, it may be observed that the other elemental ratios are similar. This suggests that while the Qt3 soil is ostensibly several hundred thousand years older, a majority of the mineral weathering and soil profile development took place within the first 140 ka of landscape stability.



Figure 16.

Geochemical tau plots of the upper 400cm of the soil developed in the tread of the Qt3 unit at Perryville Meander. Dotted horizontal lines show sample depths. On the left hand side, a partial stratigraphic column sketch and photos of the outcrops are shown.

Titusville VQ-01 soils

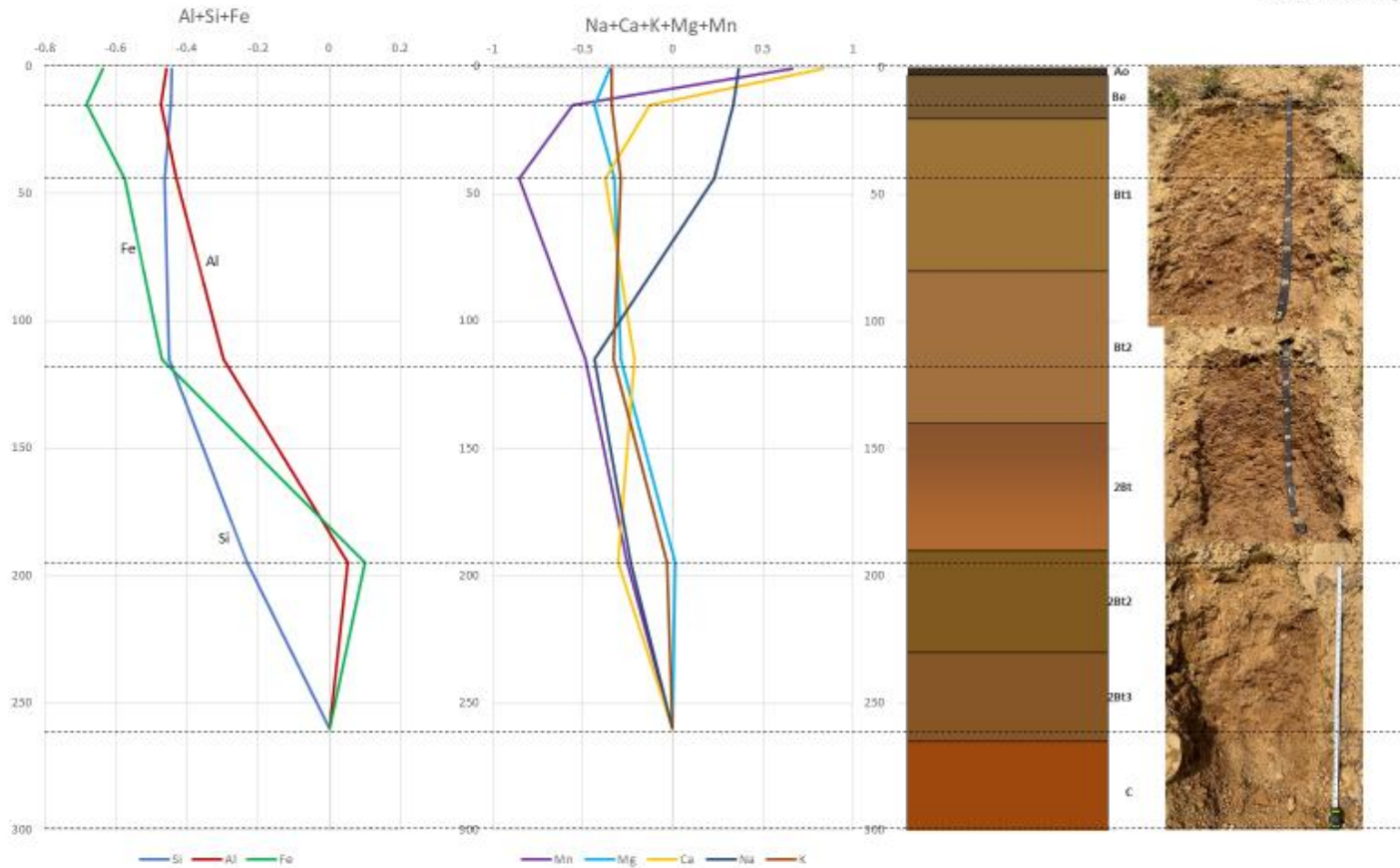


Figure 17.
Soil Tau Plots for the Titusville Kame (VQ-01) deposits near Franklin PA.

5. INTERPRETATIONS AND DISCUSSION

5.1 TOWARDS AN INCISION HISTORY OF THE ALLEGHENY RIVER

The data presented above provide a sketch of the links between glacial cycles, landscape erosion, the formation of the extant terrace architecture, and more tentatively a regional relation between soil profile chemistry and surface stability time. The terrace stratigraphy suggests that the Allegheny River has undergone no fewer than five major cut and fill cycles, over the past 1.5 Ma. But the very scanty preservation of the terraces, especially the scrappy patchy nature of Qt5, suggests that many more cut-and-fill episodes have taken place, the evidence of which is not preserved, or at least not clearly evident at the surface. More usefully, Figure 13 shows a synthetic cross section roughly approximating the A-A' line on Figure 5. The terrace elevations shown in the polygons in Figure 5 can then be extracted to points, via the processes described in Appendix 3. Following this process, a long profile diagram showing the terrace base elevations relative to the modern river along the study reach (**Fig. 18**). This figure allows us to tell a story of the integration and incision histories of the middle Allegheny river across the Pleistocene.

In Qt1 time, pre-integration, there would have been separate drainages draining to the north and south of the integration reach, which is still a regional, if not continental, drainage divide. This pre-integration state may or may not persist into Qt2 time, the evidence is ambiguous. Regardless, this pre-integration state, in Qt1 to Qt2 time, in absolute chronology is in early Pleistocene time, prior to 1.1 Ma, possibly well. In this time, pre-integration state, the main channel of the upper paleo-Allegheny would have been what is today the Clarion River. Next, sometime before 1.1 Ma, but after the deposition of the Qt2, the Allegheny River underwent an episode of incision, creating the entrenched meander loops at the Clarion-Allegheny confluence. It is unclear if there was a specific exogenic driver for this episode of incision, or if it was an authigenic process. This incision is what creates the entrenched meander loops, but may or may not have taken place before the integration reach is breached across the former low divide just upstream of the Allegheny-Clarion confluence.

Then by Qt3 time, the presence of glacially derived exotic clasts implies the integration event has fully taken place, and at least some of the area north of the confluence is now feeding water and sediment into the new Allegheny River. Thus, the integration and breaching of the former drainage divide must have already taken place by the time Qt3 is being deposited and buried ~1.0 Ma. Moreover, the regular but not universal occurrence of the a lightly modified diamict at the base of Qt3, implies the glacial margin at that time must have been close to the modern areas where Qt3

deposits are thickest, near the town of Parker. Perhaps a lobe of one of the mid-Pleistocene continental glaciations extended farther south of Franklin, down the valley of the Allegheny, than had previously been supposed? Speculating how far beyond an active glacial margin a diamict can be transported and still resemble a diamict is beyond the scope of this work. More to the point, the absolute geochronology of the Qt3 fill terrace, which aggrades during Qt3 time, must include the interval $\sim 1.07\text{-}0.990$ Ma, as indicated by the combination of paleomagnetic and TCN data presented in Table 3.

A short digression is in order regarding possible correlations, mentioned briefly in the Background section earlier, between the Qt3 through Qt6 terrace deposits, the Carmichaels formation of the lower Allegheny to upper Ohio Rivers, and ancient Glacial Lake Monongahela. Most intriguingly, the TCN age of the Qt3 unit ($1105 \text{ ka} \pm 379\text{-}258 \text{ ka}$) overlaps with estimates of the first or second incarnation of Glacial Lake Monongahela, which has been dated, depending on how the tentative TCN findings are interpreted, as somewhere between $1810 \text{ ka} \pm 107\text{-}116 \text{ ka}$ at the very uppermost limit of possible isochron ages, down to a young as $1061 \text{ ka} (\pm 98 \text{ ka})$, with a central age estimate of $\sim 1140 \text{ ka}$, very approximately (Kurak, 2021; Kurak et al., 2021). Additionally, paleomagnetic work on putative GL Monongahela sediments has yielded both magnetic normal (post-788 ka) and magnetic reversed (interpreted as pre-788 ka), although these sites would doubtlessly benefit from re-examination with more modern techniques (Jacobson et al., 1988; Marine, 1997). Additionally, many of the “Lake Monongahela” and “Carmichaels” sediments documented and summarized by workers in the late 20th century had sedimentology and geomorphic expressions (Wagner et al., 1970; Marine and Donahue, 2000) not entirely dissimilar to those described for Qt3 in this work. Additionally, there is the matter of the elevations of the constructive surfaces of the high terraces. Even very early workers noticed that the constructive surfaces of the Carmichaels Fm had a common elevation of $\sim 336 \text{ m}$ (White, 1896; Leverett, 1934) and this is similar to both the elevation of the many of high terrace deposits along the valleys of the lower Allegheny and Monongahela Rivers, as well as downstream into the upper Ohio, where a common family of constructive surfaces has been documented between $\sim 334\text{-}340 \text{ m ASL}$, and tending to 60m or more above the modern river channels (White, 1896; Jacobson et al., 1988; Marine, 1997; Kurak et al., 2020). Additionally, the spillover pourpoint at New Martinsville also had an estimated elevation of greater than 325m ASL (Jacobson et al., 1988). It is plausible that Qt3 is in this same family of terraces, with the relatively small amount of variation be attributable paleochannel gradients and ever-confounding isostatic variations. While there is at this time a great deal regarding such a Glacial

Lake Monongahela connection that remains suggestive and circumstantial, the similarities of absolute geochronology age ranges and terrace tread elevations seems too great to be continental. Therefore, this thesis advances the hypothesis that the changes in base level seen by the Middle Allegheny river, discussed more below, likely have some relation to one or more of the stages of filling and emptying of Glacial Lake Monongahela in the early to middle Pleistocene.

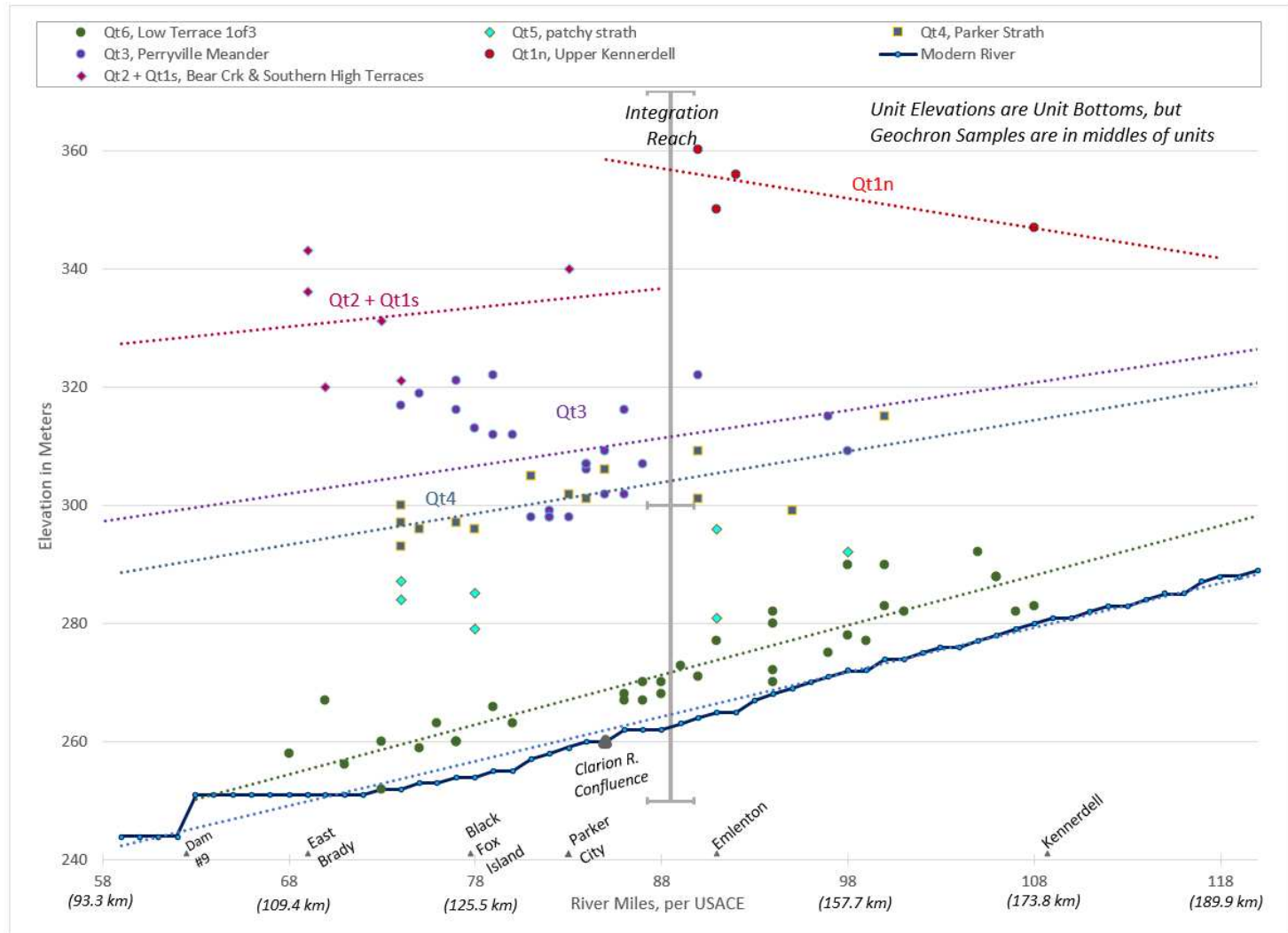
Subsequently, in Qt4 time, the Parker Strath is carved. In absolute chronology, this must be somewhere between ~ 1.0 Ma and ~ 0.5 Ma, but cannot be more precisely constrained. The very existence of a strath terrace implies both a period of base level stability, and an absence of accommodation space. The base level stability, because to carve a bedrock strath as wide as the Parker requires at least a few kiloyears in which the river's relative base level is stable (Fuller et al., 2009) although this is not a universally agreed upon mechanistic inference (Finnegan and Dietrich, 2011). The absence of accommodation space is inferred, because if such space existed when the Parker Strath was being created and deposited, we would find a fill terrace, not a strath terrace.

Then, in Qt5 time, there is a period of renewed incision, creating the unpaired Qt5 straths. This period of incision may conceivably have been caused the arrival of a downstream base level fall signal, perhaps related to the draining of one of the later incarnations of Glacial Lake Monongahela, if not the very final one. Both Qt4 time and Qt5 time must, in absolute chronology, be in the time interval of ~ 1.0 - 0.5 Ma. We know this, because by ~ 0.514 Ma, we are into Qt6 time. During Qt6 time, there is the establishment of a new base level in the inner gorge of the Allegheny River, the river having incised downward 30 m or more in that half-million years. In Qt6, Qt7, and Qt8 time, between ~ 500 ka and the present, there is deposited a series of juxtaposed fill terraces, all within ~ 20 m AMRL, and likely tied to middle and late Pleistocene glacial-interglacial cycles

From the geochronology data in **Table 2** and **Table 3** and the terrace elevation data in Fig.18 , it is possible to construct a diagram, showing the distances AMRL of the known terrace dates, and thereby to infer the rate of main channel incision. (**Fig. 19**). This reveals that the Allegheny River has had a long-term average incision rate over the past million years or more, of ~ 44 m/Ma. Compared to the basin-averaged erosion rate of ~ 30 m/Ma, this helps explain why we see the Allegheny River in deep, steep-sided gorges along much of its length.

Figure 18

Long Profile Graph, depicting the elevations of the mapped terrace units along the Allegheny River, and hypothesized integration reach; vertical axis uncertainty is +/- 1m. The reach graphed on the horizontal axis USACE river miles 58-118, roughly the area shown in Fig. 5; elevations are generally terrace bases, except for unit Qt3, where the vertical lines show the thickness of the fill terrace. Note that while Qt3 has a variable base, there is a common constructive surface around 340m elevation. Qt4 and Qt5 are strath terraces, but the thickness of the other fill terrace units is either unknown or cannot easily be shown to scale.



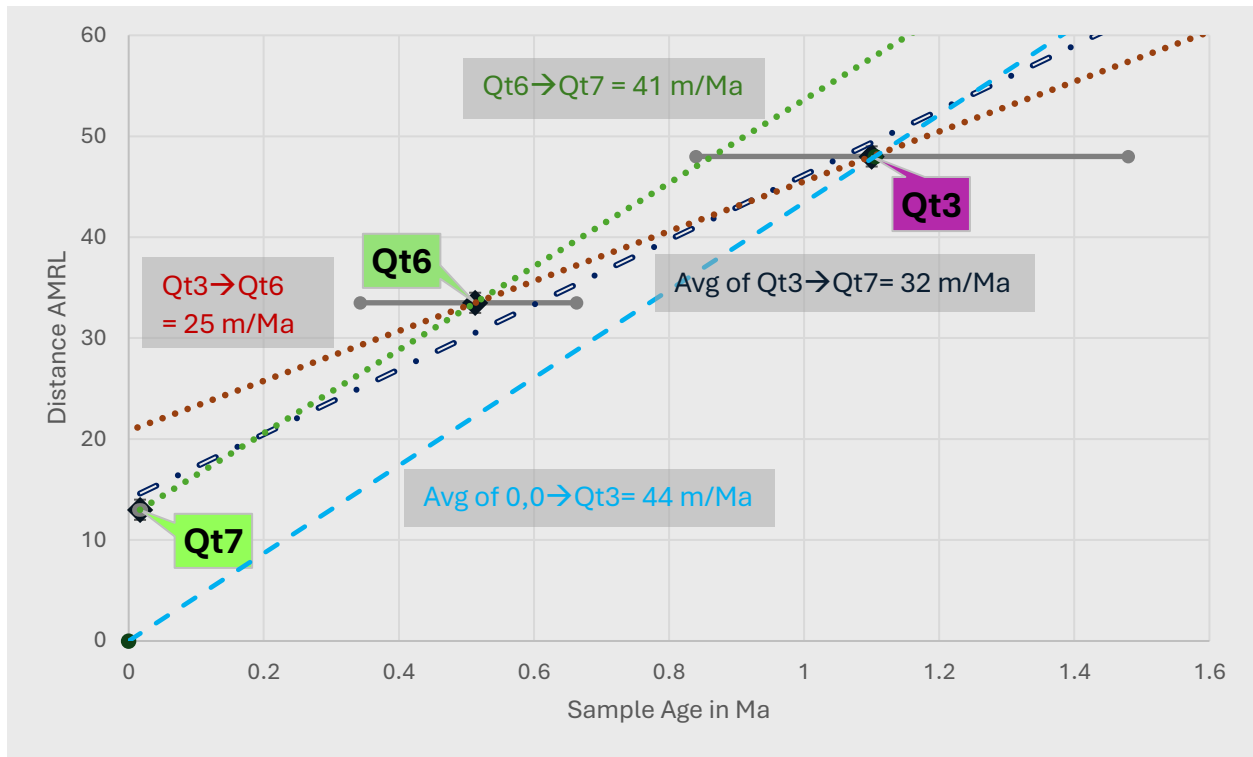


Figure 19

Plot of Sample Ages vs Relative Elevation to Modern River. Ages are in Ma; vertical uncertainties are +/- 1 m. This suggests that the incision rate of the Allegheny has accelerated over the course of the Pleistocene. Alternatively, given the distance between Qt7 and the modern river, these results may instead suggest one or more episodes of rapid incision.

The two soils examined for their profile geochemistry show surprising similarities, given that one is many hundreds of thousands of years older than the other. This suggests that a majority of the depletions of and translocation takes place within the first few hundred years of weathering, after which the rate of soil development slows down to a “steady state”, consistent with idea about “regolith armoring” acting as control on soil weathering (Monteiro et al., 2018).

Evidence has thus been presented for at least five distinct cut-and-fill episodes, of the types described by Pinter (1994). But likely more such episodes took place, but are not sufficiently well-preserved, or at least without obvious surficial expression. The patchy and unpaired nature of the Qt4 and Qt5 strath terraces suggest this to be the case. Relative base level must be changing on kiloyear timescales for these cut-and-fill cycles to take place. While several lines of evidence have been presented strongly suggesting an exogenic (glacial) driver for these river processes, there is some ambiguity regarding the relative role of glacially-driven change in base level via changes in

downstream proglacial lake levels, versus direct glacial impedance causing changes in catchment area, and there in water/sediment supply. One might be tempted to conclude that either GL Monongahela did not extend this far north, or its shoreline and sediments was not preserved. Given the changes in base level and the narrowness of the valleys, the latter explanation seems most probable: that is, Glacial Lake Monongahela did indeed extend as far upstream as East Brady, and Qt3 therefore represents a sort of lake delta deposit, given the presence of well-sorted cross-bedded sands within it. Additionally, that Qt3 generally has a constructive surface close to the ~346m elevation of the Carmichaels formation (Kurak et al., 2023), combined with the similarity in age of the Qt3 formation with reconstructions of the age of the first incarnation of GL Monongahela (ibid), does not prove a relationships between Qt3 and the formation and drainage of GLM. But, the similarity in age and constructional surface elevation strongly suggests a shared origin mechanism, even if the exact causal relationship, remains a goal for future work.

The Allegheny River has experienced an average incision rate of ~45m/Ma over the past half-million years or more, but this may have been as low as 25m/Ma earlier in the Pleistocene. Given that the unglaciated Clarion River basin averaged incision rate was measured as ~30 m/Ma, this suggests strongly that the Middle Allegheny River underwent a period of more rapid incision in the past half-million years than in the half-million years before that. The similarity of the pre-Qt6 incision rate to the unglaciated basin scale erosion rate suggests a possible interpretation, however speculative, that in the very early Pleistocene, the river was in a state of relative equilibrium with respect to the overall landscape erosion rate. Even if this was the case, and the paleo-Allegheny River was dominated by authigenic factors in it's channel behavior, this nevertheless does not preclude the creation of incised meanders or strath terraces even in the absence of clear exogenic forcings (Finnegan and Dietrich, 2011). But it does suggest the possibility that the entrenched bedrock channels in which the Qt3 deposits often sit, may be quite a bit older than the deposits themselves. This raises the possibility that the very highest terraces and their strath surfaces date to the very earliest Pleistocene, before the western Appalachians had experienced direct glacial lobe impingement.

5.2 POSSIBLE AGES OF UNDATED TERRACES

Additionally, projecting the average terrace elevations near the integration reach against the incision rates, we an estimate some possible age ranges for the terraces for which direct geochronology is not available. **Table 4** presents a range of possible inferred ages, for which it may

be reasonable to reconstruct the ages of not sampled Qt units based on simple linear regressions. This data, selected for sanity and plausibility, is then used to create **Figure 19** below. Examining these data, it can be tentatively concluded that Qt4 represents a period of base level stability taking place around 900ka, and that the pre-integration Q1 units are ~2.0 Ma in age; this is consistent with an interpretation of the initial integration taking place in the early Pleistocene, driven perhaps by direct glacial impingement on the earliest drainages during one the very earliest glacial advances, prior to MIS 10.

Which of these hypotheses can be ruled closest to correct? Examining the results in Figure 18 and in Figure 11, it would appear that both H2 and H3 are true at different times. The older higher terraces have a less steep slope than the modern river, and Qt1 has while Qt6 has long profile slope that is slightly steeper than the modern river surface, while Qt3 has a long profile slope that is slightly shallower than the modern river course. This implies that the river today is at a lower gradient than it was in Qt3 time, suggesting the river has experienced a base level fall. However, while in Qt6 time, the river was at a slightly steeper gradient than today, suggesting an ongoing adjustment to the integration event that increased the available drainage area.

Table 4: Possible Inferable Terrace Ages, based on plausible incision rates
Ages and Rates judged most probable in bold, those judged impossible are struck out.

Unit Qt#	Average vertical distance AMRL (m)	Inferred Terrace Age (MA), if assumed incision rate equals...						
		24.7 M/Ma	55.1 m/Ma	35.44 m/Ma	43.636 m/Ma	44.86 m/Ma; Jaramillo Lower	48.48 m/Ma, Jaramillo Upper	46.67 m/Ma, Jaramillo avg
Qt1n	90	3.644	N/A	2.540	2.063	2.006	1.856	1.928
Qt1s	90	3.644	N/A	2.540	2.063	2.006	1.856	1.957
Qt2	80	3.239	N/A	2.257	1.833	1.783	1.650	1.739
Qt4 min	43	1.741	0.780	1.213	0.985	0.959	0.887	0.935
Qt4 avg	46.5	1.883	0.844	1.312	1.066	1.037	0.959	1.011
Qt5	40	1.619	0.726	1.129	0.917	0.892	0.825	0.870
Qt8	5	0.202	0.091	0.111	0.115	0.111	0.103	0.109

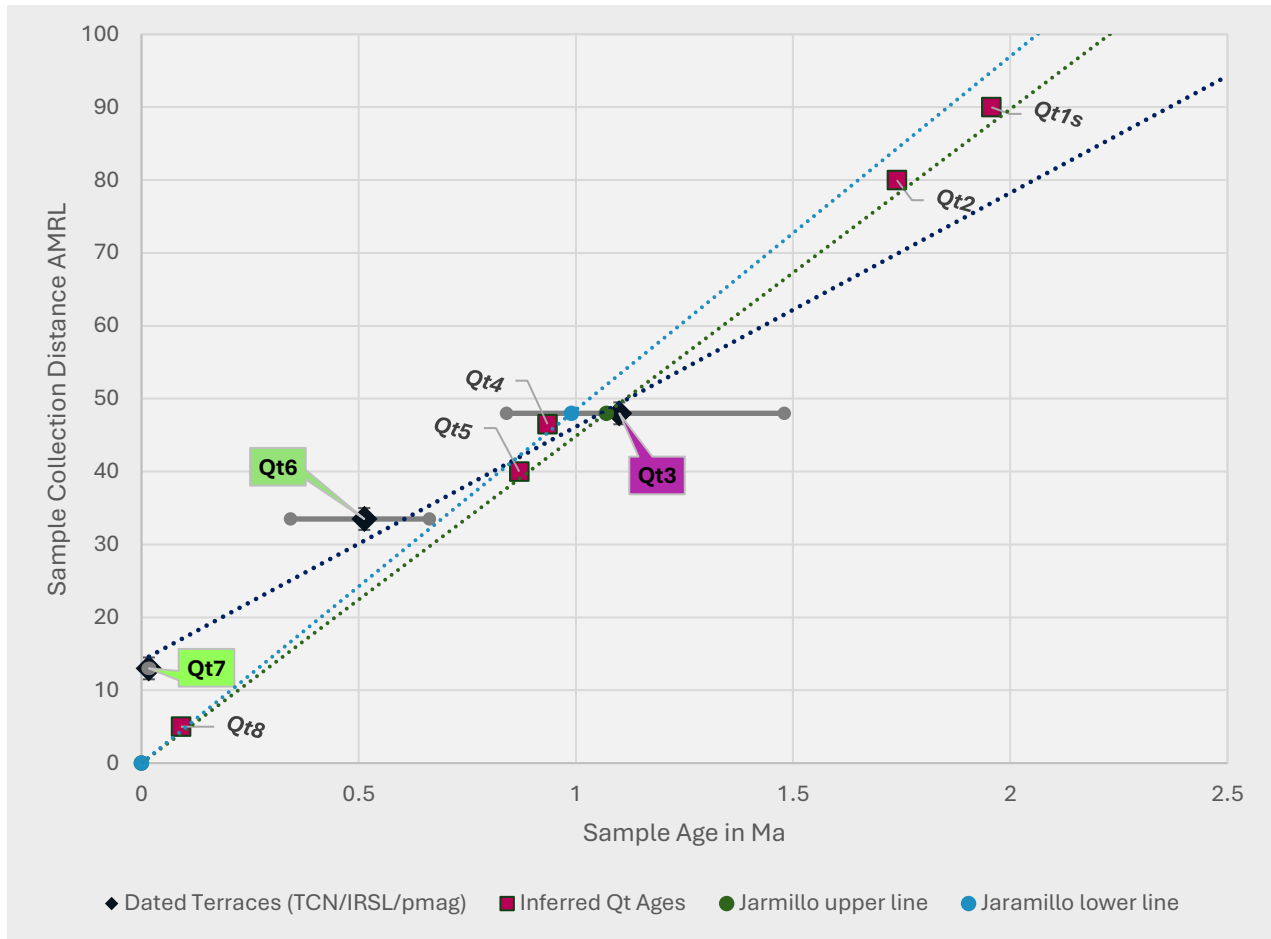
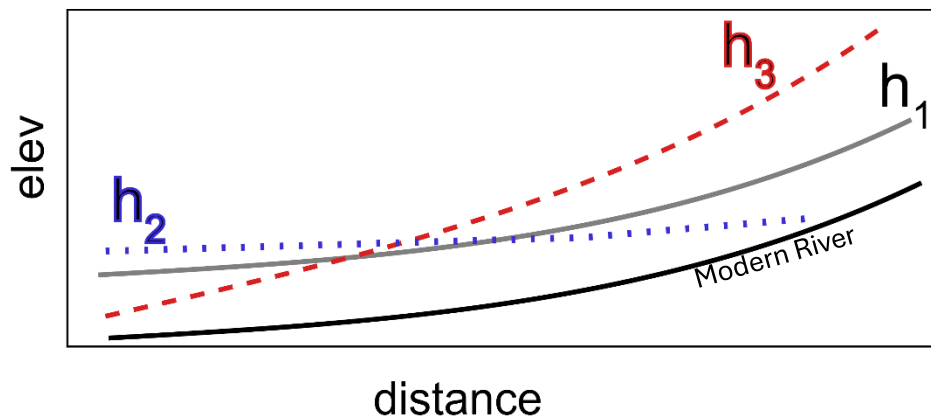


Figure 20.

Range of possible ages for terraces dated by absolute geochronology. Note that the y-axis has an uncertainty of +/- 1m, but the horizontal uncertainties are likely constrained closer to the areas between the dotted lines, very approximately. The green and light blue dotted lines represent the range of the Jaramillo normal excursion between 1070-990 ka, which is the most probable age for Qt3, and therefore the best constraint on long-term incision rate of the Allegheny on mega-year timescales.

Figure 21.

The three original hypotheses of terrace elevations relative to the modern river gradient. Unlabeled thick black line is the modern river. The other three lines are the gradients of the old terrace deposits, which represent a paleo-channel gradient along the former long profile of the river. Colors added for emphasis.



5.4 FINAL THOUGHTS, AND SOME POSSIBLE AVENUES FOR FUTURE WORK

Two obvious next steps for future work in the general avenues addressed in this thesis are: 1) better geochemical and thin-section analysis of the soils that we now have age constraints on; 2) undertaking fluvial inversion modeling of the tributary streams north versus south of the integration reach; including better quantifying the presence of shorter, more deeply incised, and darted tributary streams north of the integration reach. Nonetheless, this is not just a story about one little section of a specific river in Appalachia, but a story about the larger questions of exogenic vs endogenic forcings on geomorphic processes. Having shown above that the incision history of the Allegheny River has been strongly influenced by exogenic climate-related forcing, despite being in a tectonically inactive area, it is my hope that this work not only sheds light on the origins of the modern Allegheny River and its incision history, but contributes to ongoing debates within geomorphology in the role of exogenic vs endogenic processes for divide migration and landscape evolution over kiloyear to megayear timescales.

FIN.

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FIN.

APPENDIX 1: UNPROCESSED XRF GEOCHEMISTRY DATA

Sample PKR-3; Qt3 cap soil

MAJOR ELEMENTS: Results are as a percentage of total sample mass post-ignition

Specimen	PKR-3 3 cm.	PKR-3 20 cm	PKR-3 65 cm	PKR-3 180 cm.	PKR-3 280 cm.	PKR-3 380 cm.	PKR-3 450 cm.
SiO2	82.53	82.09	78.79	70.49	72.82	66.31	69.14
TiO2	0.86	0.84	0.84	0.85	0.95	0.65	0.64
Al2O3	9.89	9.65	11.29	17.14	14.93	17.64	17.74
Fe2O3T	3.25	3.55	4.46	7.82	7.45	6.71	6.48
MnO	0.13	0.02	0.03	0.09	0.13	4.65	1.21
MgO	0.64	0.72	0.85	0.94	0.85	0.90	0.88
CaO	0.30	0.26	0.40	0.19	0.19	0.25	0.34
Na2O	0.77	0.92	1.11	0.29	0.46	0.43	0.65
K2O	1.78	1.92	2.04	1.83	2.02	2.19	2.46
P2O5	0.14	0.06	0.08	0.17	0.17	0.23	0.23
Total	100.29	100.03	99.89	99.81	99.97	99.96	99.77
LOI	9.79	4.08	5.11	9.65	7.82	10.31	8.47

CALIBRATION constants

Constant	Spec1* Constant	Spec2* Constant	Spec3* Constant	Spec4* Constant	Spec5* Constant	Spec6* Constant	Spec7* Constant	
0.0961	7.931133	7.888849	7.571719	6.774089	6.998002	6.372391	6.644354	SiO2
0.3648	0.313728	0.306432	0.306432	0.31008	0.34656	0.23712	0.233472	TiO2
0.0877	0.867353	0.846305	0.990133	1.503178	1.309361	1.547028	1.555798	Al2O3
0.6563	2.132975	2.329865	2.927098	5.132266	4.889435	4.403773	4.252824	Fe2O3T
0.6502	0.084526	0.013004	0.019506	0.058518	0.084526	3.02343	0.786742	MnO
0.0788	0.050432	0.056736	0.06698	0.074072	0.06698	0.07092	0.069344	MgO
0.3314	0.09942	0.086164	0.13256	0.062966	0.062966	0.08285	0.112676	CaO
0.0716	0.055132	0.065872	0.079476	0.020764	0.032936	0.030788	0.04654	Na2O
0.3301	0.587578	0.633792	0.673404	0.604083	0.666802	0.722919	0.812046	K2O
0.1285	0.01799	0.00771	0.01028	0.021845	0.021845	0.029555	0.029555	P2O5
								Total

TRACE ELEMENTS: Results are in parts per million. Uncertainties are +/- 7 ppm

Specimen	PKR-3 3 cm.	PKR-3 20 cm	PKR-3 65 cm	PKR-3 180 cm.	PKR-3 280 cm.	PKR-3 380 cm.	PKR-3 450 cm.
Rb	79.5	77.3	81.0	102.9	101.6	108.2	116.0
Sr	75	76	108	80	83	88	138
Y	37.2	30.5	34.9	29.6	62.1	77.1	59.1
Zr	464	471	473	508	479	296	329
V	69	76	84	124	94	93	96
Ni	19	15	20	45	41	78	121
Cr	55	51	67	75	59	50	50

Nb	15.8	15.3	15.4	13.8	14.2	12.1	12.4
Ga	8.3	8.1	10.2	17.0	15.1	17.4	19.1
Cu	209	82	77	131	140	151	223
Zn	104	63	81	131	145	192	196
Co	9	7	6	15	15	33	36
Ba	469	393	400	420	451	3392	767
La	34	27	29	35	66	56	45
Ce	57	47	60	113	86	<3	138
U	3.8	3.1	3.0	3.8	3.5	2.8	2.1
Th	9.2	9.2	10.2	13.5	15.2	12.2	13.3
Sc	8	8	10	16	15	12	14
Pb	29	21	38	36	55	68	130
Mo	4	4	5	7	5	10	7

Sample: VQ-1; Titusville Kame soil

MAJOR ELEMENTS: Results are as a percentage of total sample mass post-ignition

Specimen	VQ1 1 cm	VQ1 15 cm	VQ1 55 cm	VQ1 115 cm	VQ1 195 cm	VQ1 260 CM
SiO2	81.07	82.43	79.90	78.03	75.38	80.44
TiO2	0.83	0.85	0.85	0.81	0.56	0.46
Al2O3	9.98	9.97	10.77	12.67	13.10	10.22
Fe2O3T	3.71	3.34	4.45	5.29	7.59	5.67
MnO	0.33	0.09	0.03	0.10	0.10	0.11
MgO	0.75	0.67	0.80	0.80	0.79	0.64
CaO	0.43	0.21	0.15	0.18	0.11	0.13
Na2O	0.74	0.74	0.68	0.30	0.28	0.30
K2O	1.74	1.78	1.92	1.73	1.72	1.46
P2O5	0.21	0.14	0.07	0.13	0.22	0.18
Total	99.79	100.22	99.62	100.04	99.85	99.61
LOI	8.84	6.01	5.23	6.97	7.18	5.35

CALIBRATION constants

Constant	Spec1* Constant	Spec2* Constant	Spec3* Constant	Spec4* Constant	Spec5* Constant	Spec6* Constant	Spec7* Constant	
0.0961	7.790827	7.921523	7.67839	7.498683	7.244018	7.730284	0	SiO2
0.3648	0.302784	0.31008	0.31008	0.295488	0.204288	0.167808	0	TiO2
0.0877	0.875246	0.874369	0.944529	1.111159	1.14887	0.896294	0	Al2O3
0.6563	2.434873	2.192042	2.920535	3.471827	4.981317	3.721221	0	Fe2O3T
0.6502	0.214566	0.058518	0.019506	0.06502	0.06502	0.071522	0	MnO
0.0788	0.0591	0.052796	0.06304	0.06304	0.062252	0.050432	0	MgO
0.3314	0.142502	0.069594	0.04971	0.059652	0.036454	0.043082	0	CaO
0.0716	0.052984	0.052984	0.048688	0.02148	0.020048	0.02148	0	Na2O

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0.3301	0.574374	0.587578	0.633792	0.571073	0.567772	0.481946	0	K2O
0.1285	0.026985	0.01799	0.008995	0.016705	0.02827	0.02313	0	P2O5

TRACE ELEMENTS: Results are in parts per million. Uncertainties are +/- 7 ppm

Specimen	VQ1 1 cm	VQ1 15 cm	VQ1 55 cm	VQ1 115 cm	VQ1 195 cm	VQ1 260 CM
Rb	81.3	80.1	84.7	95.2	84.8	64.4
Sr	75	73	69	56	54	50
Y	34.0	37.8	30.5	30.9	27.1	26.2
Zr	464	472	521	424	254	190
V	78	78	90	105	97	82
Ni	19	19	22	31	34	28
Cr	62	60	71	70	52	43
Nb	15.6	15.8	15.8	14.2	9.6	7.3
Ga	8.9	8.3	10.0	12.0	11.2	8.1
Cu	186	130	127	98	451	133
Zn	137	117	97	114	193	109
Co	10	8	9	10	77	66
Ba	429	468	340	358	348	354
La	32	32	25	36	40	29
Ce	63	50	55	94	118	106
U	3.5	2.4	3.5	3.0	2.4	2.9
Th	10.0	9.7	11.8	12.5	11.8	9.2
Sc	9	8	10	13	10	11
Pb	68	40	28	36	39	32

APPENDIX 2: RAW TCN DATA & ALTERNATE INTERPRETION PLOTS

10-Be Name: Pazzaglia Batch ID: 5822
 Atomic Mass of Be: 9.0122

Chemistry Blank: Be-10

Submitter Name	Sample Id	User Identification	9Be Carrier (mg)	Average Current (nA)	Interference (Counts/Sec)	10Be Ratio (x10-15)	10Be Std Dev (x10-15)	Atoms 10Be per mg of 9Be Carrier	Std Dev
Pazzaglia	202301505	Cblk5820-1	0.2639	6454.817464	0.157564854	0.5163909	0.40555	34511.25	27103.83

SAMPLES: Be-10

Sample Id	Aliquot Id	User Identification	Sample Mass (g)	Native Beryllium (mg)	9Be Carrier (mg)	Average Current (nA)	Interference (Counts/Sec)	10Be Ratio (x10-15)	10Be Std Dev (x10-15)
202301510	A	FOX-01-TCN	30.083		0.2632	5493.929932	0.31535429	253.667007	7.33574008

Total 10Be Atoms	Std Dev	Carrier-Corrected Total 10Be Atoms	Carrier-Corrected Std Dev	Cosmogenic 10Be Atoms per gram SiO2	Std Dev	Relative Uncertainty (%)	Uncertainty in the AMS Measurement (%)
446202	129036.	4452941	129233.3	148021.8	4295.89	2.902202	2.891878

CHEMISTRY BLANK: Be-10

WALLACE MS THESIS (2025): Qt Incision Hist. of the Mid. Allegheny R.

Sample Id	Aliquot Id	User Identification	9Be Carrier (mg)	Average Current (nA)	Interference (Counts/Sec)	10Be Ratio (x10-15)	10Be Std Dev (x10-15)	Atoms 10Be per mg of 9Be Carrier	Std Dev
202301516	A	Cblk5823	0.2842	7821.210632		0.433075994	0.193726003	28943.17	12947.02

SAMPLES: Be-10

Sample Id	Aliquot Id	User Identification	Sample Mass (g)	9Be Carrier (mg)	Average Current (nA)	10Be Ratio (x10-15)	10Be Std Dev (x10-15)
202301507	A	GU-8	32.854	0.2848	6813.820041	99.479599	3.089979887
202301508	A	GLD-3	26.522	0.286	7632.835083	10.73600006	0.979860008
202301512	A	VQ-TCN-03	31.426	0.2861	7189.295593	135.6560059	3.751009941
202301513	A	PKR-03-TCN	36.026	0.2858	6698.070038	169.5279999	5.334619999
202301514	A	KEN-02-TCN	33.963	0.2845	7356.226042	122.1269989	3.676870108
202301515	A	KEN-01-TCN	35.6	0.2849	7310.468903	570.5089722	9.21846962

Sample Id	Total 10Be Atoms	Std Dev	Carrier-Corrected Total 10Be Atoms	Carrier-Corrected Std Dev	Cosmogenic 10Be Atoms per gram SiO2	Std Dev	Relative Uncertainty (%)	Uncertainty in the AMS Measurement (%)
202301507	1893460	58813.59	1885217	58929.06	57381.65	1793.665	3.125851	3.106144
202301508	205206.2	18728.89	196928.5	19091.43	7425.1	719.8335	9.694597	9.126863
202301512	2593815	71721.29	2585534	71816.88	82273.72	2285.27	2.777642	2.765089
202301513	3238066	101893.8	3229794	101961	89651.75	2830.205	3.156887	3.146749
202301514	2322074	69910.53	2313839	70007.5	68128.24	2061.287	3.025599	3.010694
202301515	10862680	175522.7	10854434	175561.5	304899.8	4931.502	1.617417	1.615833

26-Al Name: Pazzaglia Batch ID: 5821 & 5823

CHEMISTRY BLANK: Al-26

Submitter Name	Nuclide	Sample Id	Aliquot Id	User Identification	27Al Carrier (mg)	Average Current (nA)	26Al Ratio (x10-15)	26Al Std Dev (x10-15)	Atoms 26Al per mg of 27Al Carrier	Std Dev
Pazzaglia	26-Al	202301516	A	Cblk5823	1.5919	2438.211492	1.292680025	1.237900019	28856.11	27633.27

SAMPLES: Al-26

Sample Id	Aliquot Id	User Identification	Sample Mass (g)	Native Aluminum (mg)	27Al Carrier (mg)	Average Current (nA)	Interference (Counts/Sec)	26Al Ratio (x10-15)	26Al Std Dev (x10-15)
202301507	A	GU-8	32.854	5.519		12367.49501		98.46530151	5.106939793
202301508	A	GLD-3	26.522	4.412		12608.05628		16.05310059	1.596590042
202301512	A	VQ-TCN-03	31.426	5.795		10672.84924		120.7610016	5.835380077
202301513	A	PKR-03-TCN	36.026	5.598		8600.435913		128.798996	7.040709972
202301514	A	KEN-02-TCN	33.963	4.388		6946.490836		132.2779999	6.090620041
202301515	A	KEN-01-TCN	35.6	4.864		11858.95719		599.6480103	14.80840015

Sample Id	Total 26Al Atoms	Std Dev	Carrier-Corrected Total 26Al Atoms	Carrier-Corrected Std Dev	Cosmogenic 26Al Atoms per gram SiO2	Std Dev	Relative Uncertainty (%)	Uncertainty in the AMS Measurement (%)
202301507	12130826	629169.9	12130826	629169.9	369234.4	19150.48	5.186538	5.186538

WALLACE MS THESIS (2025): Qt Incision Hist. of the Mid. Allegheny R.

202301508	1581034	157244.6	1581034	157244.6	59612.17	5928.836	9.94568	9.94568
202301512	15621651	754865.1	15621651	754865.1	497093.2	24020.4	4.832173	4.832173
202301513	16095043	879824.6	16095043	879824.6	446761.9	24421.94	5.466432	5.466432
202301514	12956897	596588.5	12956897	596588.5	381500.4	17565.84	4.604409	4.604409
202301515	65108357	1607861	65108357	1607861	1828886	45164.63	2.469515	2.469515

SAMPLE NUCLIDE RATIOS

Al/Be Ratios Name: Pazzaglia Batch ID: 5821 & 5823

Sample Id	User Identification	Cosmogenic 10Be Atoms per gram		Cosmogenic 26Al Atoms per gram		Al/Be Ratio	Std Dev
		SiO2	Std Dev	SiO2	Std Dev		
202301507	GU-8	57381.64689	1793.665	369234.378	19150.48	6.434712104	0.389664807
202301508	GLD-3	7425.099941	719.8335	59612.1703	5928.836	8.028467055	1.115066426
202301512	VQ-TCN-03	82273.72017	2285.27	497093.19	24020.4	6.04194376	0.336754709
202301513	PKR-03-TCN	89651.75434	2830.205	446761.87	24421.94	4.983303153	0.314571661
202301514	KEN-02-TCN	68128.23831	2061.287	381500.373	17565.84	5.599739287	0.308518858
202301515	KEN-01-TCN	304899.8228	4931.502	1828886.43	45164.63	5.998319109	0.177072824

APPENDIX 3: CLAST COUNTS DATA TABLES

SUMMARIZED DATA TABLES

Qt3 - WEST SIDE PARKER

SIZE CLASS	Number in Class	Number "Exotic" (Ign.+Met.+Congl.)
1 = 32mm to 45 mm	47	18
2 = 45mm to 90mm	34	4
3 = greater than 90mm	21	5
	total clasts counted	percent exotic in this count
	102	26%

Qt3 - EAST SIDE PARKER

Size Class	Number in Class	Number "Exotic" (Ign.+Met.+Congl.)
1 = 32mm to 45 mm	68	17
2 = 45mm to 90mm	20	7
3 = greater than 90mm	12	4
	total clasts counted	percent exotic in this count
	100	23%

Qt6 - ENGLISH PIT NEAR KENNERDELL

Size Class	Number in Class	Number "Exotic" (Ign.+Met.+Congl.)
1 = 32mm to 45 mm	52	19
2 = 45mm to 90mm	30	9
3 = greater than 90mm	17	6
	total clasts counted	percent exotic in this count
	99	34%

[[[the full clast count data is in your field notebooks from the summer of 2023. TRANSCRIBE IT!]]]

RIND THICKNESS LEVEL, REFERENCE

D=4) ROTTEN (TOTAL THICKNESS of clast)

C=3) >2 CM; (more than two cm but not total diameter)

B=2) ~ 1 CM; (about one cm)

A=1) < 1 CM (less than one cm)

ROCK TYPES FOR WESTERN PA SITES =

Limestone or Dolostone (carbonate)

White Sandstone

Grey Sandstone

Red Sandstone (dark / light)

Purple Sandstone

Shale / Coal

Igneous or metamorphic (granite etc)

Other (fossil, conglomerate, etc)

Size classes, based on shortest semi-major axis

0 = well under 4cm, not counted (omitted from data table because I realized I didn't need a size-class analysis as well, partway thru first sampling attempt)

1 = 32mm to 45 mm

2 = 45mm to 90mm

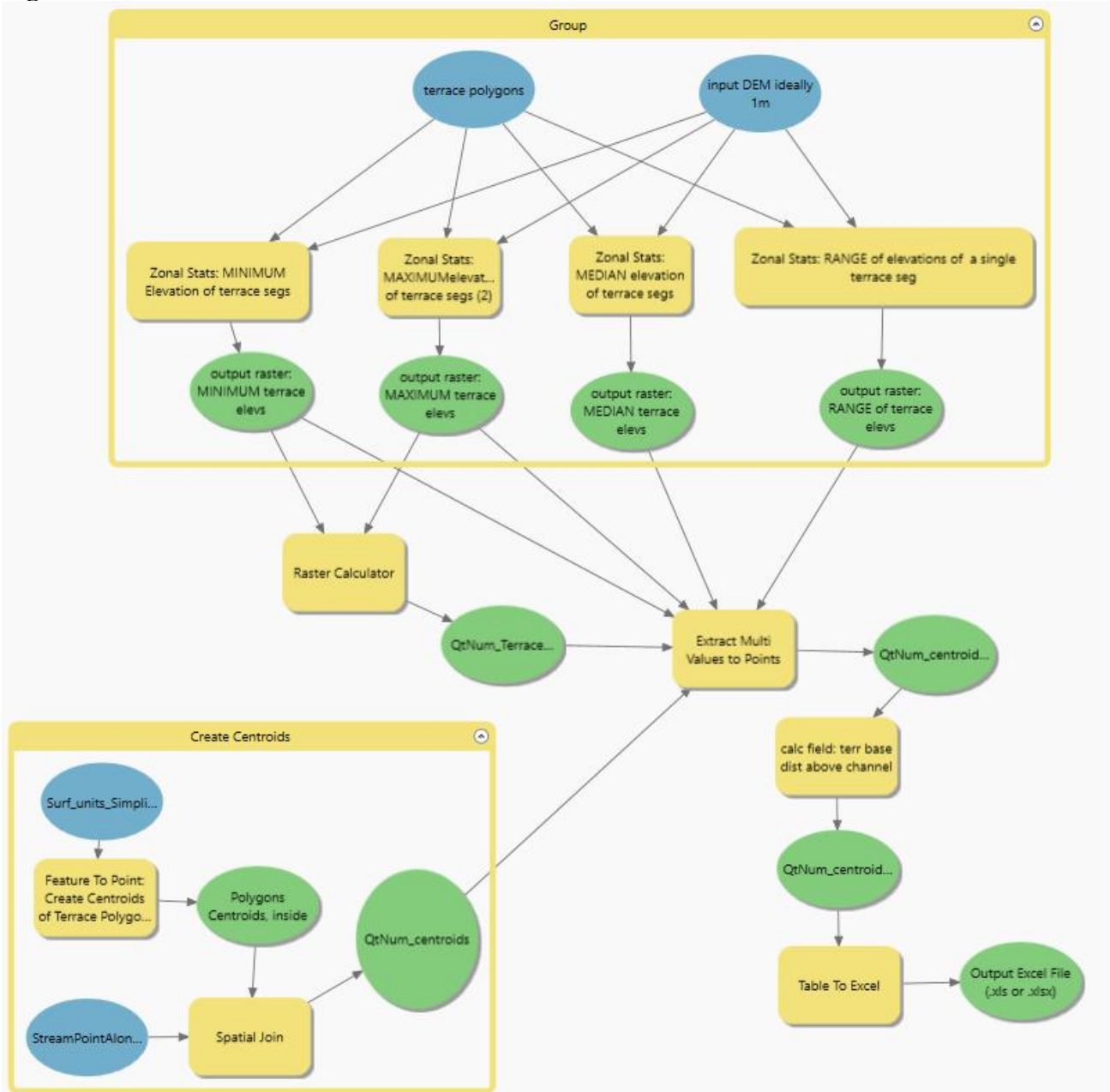
3 = greater than 90mm

APPENDIX 4: SOFTWARE METHODS FOR CREATING LONG PROFILE GRAPHS OF TERRACE ELEVATIONS IN ARCGIS

METHOD: Creating Long Profile Graphs with Terrace Elevations and River Mean Surface Elevations

Related Files and Code can be found at: <https://github.com/j-wallace-geologist/TerraceThickness>

Figure S31



Basic Steps: In ArcGIS Pro 3.3.0

Start with a feature class of the terrace polygons

- Feature to Point of Polygons – this is the centroids of the polygons
 - Creates a point representing the centroid of the polygon
 - Check the “INSIDE” option otherwise the centroid will be outside the polygon, which will cause problems later on
- Add Spatial Join, type CLOSEST,
 - between the Stream Point Elevations and the terrace polygon centroids
 - Include a DISTANCE field as well call it “dist to river”
- Export Features – export the spatial join as a new feature class
 - Keep track of where you save it, you may need it later
 - This step happens automatically as part of the spatial join operation in some newer versions of ArcGIS Pro
- Zonal Statistics, MEDIAN, on the terrace polygons
 - Inputs: the DEM and the terrace polygons
 - Input feature zone data = terrace polygons features class
 - Zone field = OBJECTID
 - because we want stats for each segment of each terrace
 - Input value raster = your DEM of choice
 - Makes a raster with each non-null area the median elevation of the terrace polygon segment
 - Use this if you have low confidence that your terrace base elevations are consistent within the unit, or as an approximation of the upstream terrace base elevation
- Zonal Statistics, MINIMUM, on the terrace polygons
 - Inputs: the DEM and the terrace polygons
 - Input feature zone data = terrace polygons features class
 - Zone field = OBJECTID
 - because we want stats for each segment of each terrace
 - Input value raster = your DEM of choice
 - Makes a raster with each non-null area the minimum elevation of the terrace polygon segment
 - Use this if you have high confidence that your terrace base elevations are consistent within the unit, or as an approximation of the downstream terrace base elevation\
- Extract Multi Values To Points – on centroids, extract from both/all Zonal Stats rasters
 - Modifies the centroid feature point class, so maybe make a copy of it first...
- Table to Excel – export features to an excel file
 - which you will use to make the long profile graph

CURRICULUM VITAE

Jonathan Wallace – jonathan@soil.rocks

EDUCATION

Lehigh University **Master of Science – Earth and Environmental Sciences** **2025**
(expected graduation MAY 2025)

Temple University **Bachelor of Science – Geology** **2019**
Certificate in Geographic Information Systems (GIS)

Brandeis University **Bachelor of Arts – Economics** **2011**

WORK EXPERIENCE

Lehigh University 2022 January – 2025 May (expected)
RESEARCH ASSISTANT / TEACHING ASSISTANT

Lead and co-taught laboratory classes on Introductory Earth Sciences and on Geographic Information Systems; Held office hours and provide academic advising to students; helped prepare course materials, including handouts and quizzes; Graded course assignments and provided feedback to students

Freelance GIS Consulting (occasional, part-time) 2022-2024

Production of Maps and Diagrams for Academic and Non-Profit Clients

React Environmental Professional Services Group (REPSG) 2021 Sept – Nov 2022

ENVIRONMENTAL DATA TECHNICIAN

Producing and Analyzing Environmental Data from Soils and Waters for Compliance with Regulatory; Implementation of Remediation Objectives. Fieldwork for sampling soils, groundwater and surface waters, including site surveying and documenting sample collection and processing protocols; processing groundwater data in Surfer to build contaminant transport models; Communication with environmental laboratories; coordinating project timelines, collaboration for reporting for Phase I and Phase II ESAs; assistance with workplace safety planning and enforcement

Earth Engineering, Inc 2020 May – 2021 July

GEOLOGIST/SCIENTIST I

Fieldwork and consulting for construction of earthworks and foundations, including monitoring and testing of soils; preparation of testing and work summary reports; assistance with Phase I ESAs; assistance with workplace safety planning and enforcement

Sci-Tek Consultants, Inc 2019 October – 2020 April

ENVIRONMENTAL SCIENTIST/GEOLOGIST

Environmental fieldwork including low-flow sampling of monitoring wells, and split spoon sampling of soils and sediments. Report preparation for Phase I and Phase II ESAs.

Freelance Projects 2012-2018

INFORMATIONAL TECHNOLOGY AND MARKET ANALYTICS

Cloud computing setup and tier-1 support; Maintained onsite video Security Systems; deployed and maintained Printer Servers and network infrastructure

A & J Real Estate 2013-2017 (part time after 2014)

CLIENT AND MARKETING ANALYTICS FOR MULTI-FAMILY REAL ESTATE

Multi-family rental real estate marketing and support services, with a focus on creation and

implementation of resident attraction and retention strategies; **learned geographic information systems on the job to allow for better marketing analytics by the firm**

Lindy Properties

2011-2013

JUNIOR PROPERTY MANAGEMENT COORDINATOR

RELEVANT COURSEWORK

- Graduate: Tectonic Geomorphology, Engineering Hydrology
- Undergraduate: Hydrology; Soils and Paleosols; Structural Geology; Geochemistry; Organic Chemistry; Geomorphology; Paleontology and Stratigraphy; Environmental GIS; Spatial Statistics;
- Field Camp at IUGFS (Indiana University Geological Field Station), Summer 2019

PUBLICATIONS & CONFERENCE PRESENTATIONS

Wallace, J., Pazzaglia, F., Germanoski, D., and Peters, S.C., 2025, A NEW AGE MODEL FOR THE GLACIAL REVERSAL, ASSEMBLY, AND INCISION OF THE ALLEGHENY RIVER, NORTHWESTERN PENNSYLVANIA, to be presented 28 March 2025, at NE-NC Regional GSA Conference, Geological Society of America Abstracts with Programs. Vol. 57, No. 3, 2025; doi: 10.1130/abs/2025NE-408964

Wallace, J.F., Pazzaglia, F.J., Fleeger, G., Spencer, J. (2023) *Multiple Pleistocene Cut-And-Fill Episodes Indicated by Surficial Deposits Along the Middle Allegheny River, Western Pennsylvania*. Poster presented at the Geological Society of America (GSA) National Conference, October 2023. Reprinted in Geological Society of America Abstracts with Programs. Vol. 55, No. 6, 2023; doi: 10.1130/abs/2023AM-394205

Wallace, J.F., Terry, D.O., Buynevich, I.V. (2018). *Ichnology, Paleopedology, and Mineral Assemblages of Triassic Stockton Fm Mudstones, SE Pennsylvania: Implications for Paleo-Landscape Reconstruction*. Poster presented at the GSA – National Conference, November 2018.

Wallace, J.F. & Schwarzwald, S. (2017). *Sawgrass to Suburbs: Land-use change over 30 years in exurban Miami directly adjacent to Everglades National Park*. Poster presented at the Annual Temple University Geographical Information Systems Conference, May 2017.

Wallace, J.F., Murray, T.K., Olshevski, S., Sheehan, D., Conley III, W.R, Kopcinski, K., & Buynevich, I.V. (2016). *Dendrogeomorphological Analysis of Slope Processes, Tyler State Park Pennsylvania*. Poster presented at the Geological Society of America-Northeastern Conference, March 2016.