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Pre- and postsettlement depositional processes and environments of the 3rd- to 5th-order White Clay Creek watershed, Piedmont Province, Pennsylvania and Delaware, USA

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ABSTRACT

We extend two hypotheses based on studies of 1st- to 3rd-order Piedmont watersheds of southeastern Pennsylvania, USA, by collecting data in a larger 3rd- to 5th-order watershed nearby. One hypothesis posits that presettlement river corridors were dominated by wetlands, and the other suggests that river valleys were filled by millpond sedimentation following European settlement. Both hypotheses support new river restoration practices, so their generality is important to assess. Ten lithofacies indicate depositional environments, while pedostratigraphic criteria and ^{14}C dating define presettlement and postsettlement stratigraphic units. Basal gravels similar to modern stream bed sediments represent presettlement channels with active bedload transport. Wedge-shaped gravel deposits resembling modern bars further document presettlement bedload transport by channelized flows. Extensive presettlement and postsettlement units of massive, organic-poor, fine-grained sediment formed when overbank flows inundated floodplains. Peat deposits, exposed at a single site (but absent elsewhere), represent a presettlement wetland. Decimeter-thick, discontinuous, massive carbonaceous fine-grained sediments occasionally overlie basal gravels; these may represent localized wetlands adjacent to presettlement channels or hydraulic backwater environments. Laminated sand and mud accumulated behind one 3-m-high mill dam, but these millpond deposits are absent at other sites. Instead of being dominated by wetlands, presettlement river corridors are better described as a complex mosaic of riparian environments including older colluvial landforms, floodplains (some of which may have been seasonally inundated wetlands), primary (and possibly secondary) channels, and depending on geomorphic setting, either localized or valley-spanning wetlands. After European settlement, millponds were important locally, but their deposits represent a minor component of the stratigraphic record.

INTRODUCTION

The perspective of geologic time offers key insights into the evolution of river systems. Rivers respond to drivers such as tectonics and climate that often operate over millennia or longer; understanding how these controls influence river corridor morphology and associated sediment delivery requires studying the stratigraphy and geochronology of sedimentary archives (Armitage et al., 2011; Blum and Tornqvist, 2000; Densmore et al., 2007; Van De Wiel and Coulthard, 2010). Autogenic processes such as meander migration and cutoff (Torres et al., 2017), floodplain sediment storage and remobilization (Huffman et al., 2022), and valley development (Brakenridge, 1984; Jacobson et al., 2016) may also have long time scales that can only be revealed through geological studies. Evaluating the ongoing impacts of humans on rivers and their valleys requires documenting river conditions before disturbance, which in many cases predates historical documentation, leaving geological studies as the only available source of information (Kemp et al., 2020; Wilkinson and McElroy, 2007).

In the mid-Atlantic region of the United States, understanding changes in river corridors since the mid-Holocene has been particularly important to both academic and applied fluvial geomorphology. Many studies have documented an acceleration of upland soil erosion following deforestation and poor agricultural practices soon after European settlement of the region (Costa, 1975; Dearman and James, 2019; Dow et al., 2020; Jacobson and Coleman, 1986; Trimble, 1971; Wegmann et al., 2012), resulting in increased sedimentation in river corridors through overbank deposition and accumulation behind mill dams, leading Merritts et al. (2011) to describe contemporary mid-Atlantic rivers as Anthropocene streams whose morphology is dominantly controlled by the actions of humans. Before European settlement, some river corridors may have been dominated by extensive wetlands (Hartranft et al., 2011; Voli et al., 2009; Wohl et al., 2021). The concept of wetland systems as a predisturbance "stage 0" state of fluvial valleys (Cluer and Thorne, 2014; Wohl et al., 2021) is now being actively promoted as a useful template for stream restoration (Booth et al., 2009; Powers et al., 2019; Voosen, 2020).

Studies documenting the history of mid-Atlantic river corridor sedimentation are also important for contemporary efforts to improve water quality. Current water quality of rivers and estuaries may be impaired as eroding postsettlement deposits supply excess sediment and nutrients to the region's streams (Jiang et al., 2020; Merritts et al., 2013; Miller et al., 2019). Ongoing sediment storage on floodplains, and the millennial residence times of floodplain deposits (Huffman et al., 2022; Pizzuto et al., 2017), imply that best management practices to reduce sediment production may not yield the desired water quality improvements downstream within acceptable time frames. While this "lag" in downstream propagation of benefits has been widely recognized (Meals, et al., 2010; Pizzuto et al., 2014; Science and Technical Advisory Committee, 2005), methods are needed to quantify the time scales involved and include them in watershed management strategies. These time scales often extend beyond available records of stream gages and other observational data sources (Pizzuto et al., 2014), and stratigraphic studies are once again of paramount importance.

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TABLE 1. QUESTIONS ADDRESSED BY THIS STUDY REGARDING PRESETTLEMENT AND POSTSETTLEMENT SEDIMENTATION IN 3RD- TO 5TH-ORDER MID-ATLANTIC PIEDMONT RIVER CORRIDORS, PENNSYLVANIA AND DELAWARE, USA

Research question	Answer from this study	Strength of evidence	Comment
What sediment transport processes deposited fine-grained sediment through time?	Overbank deposition of sand, silt, and clay during flood events	Definitive	Based on comparison with modern overbank deposits
What processes have emplaced coarse-grained gravel facies through time?	Partial bedload transport of streambed gravels, bar sedimentation	Definitive	Gravels likely have diverse origins; Older(?) mass-wasting deposits not studied
Were mill dams a dominant influence on postsettlement valley corridor sedimentation?	No—important locally depending on dam characteristics and setting	Suggestive	Further study focused on mill dam stratigraphy needed
Were wet meadows typical components of presettlement river corridors?	Unlikely, due to absence of extensive organic facies	Suggestive	Further interdisciplinary studies needed
How does stratigraphic data help constrain hydraulic geometry of presettlement rivers?	Lower bankfull depth than present, no other conclusions possible	Strong	No presettlement buried channels found
Were presettlement stream channels anastomosing?	Stratigraphic data provide no evidence	NA	No presettlement buried channels found
Were "wetlands" important components of presettlement river corridors?	Possibly	Uncertain	Further interdisciplinary studies needed

Note: Answers obtained from stratigraphic data, strength of evidence, and comments. NA—not applicable.

While important progress has been made, previous studies of the history of mid-Atlantic river corridors provide an incomplete foundation for progress. For example, presettlement river corridor deposits have been primarily interpreted as floodplains by Dearman and James (2019), Jacobson and Coleman (1986), and Pizzuto (1987), while Hartranft et al. (2011), Merritts et al. (2011), Walter and Merritts (2008a), and Wegmann et al. (2012) interpret presettlement deposits as primarily representing wetland environments. Postsettlement "legacy sediments" (e.g., Wohl, 2015; James, 2018) deposited in river corridors were initially described as floodplain deposits (Costa, 1975; Dearman and James, 2019; Happ et al., 1940; Jacobson and Coleman, 1986; Pizzuto, 1987; Trimble, 1971), but more recently, the influence of ubiquitous mill dams has been emphasized, leading to the hypothesis that legacy sediments primarily accumulated in millponds (Merritts et al., 2011; Walter and Merritts, 2008a). These differences have led to conflicting, and as yet unresolved, visions for restoring contemporary stream channels (Bain et al., 2008; Walter and Merritts, 2008b; Wilcock, 2008).

This study was designed to address some of these data gaps. The following hypotheses of Hartranft et al. (2011) provided a specific focus: "1st to 3rd order Piedmont pre-settlement anastomosing channel valley bottom floodplain systems (ACFS) . . . [were] widespread before European settlement . . . wet-meadow ACFS with organic-rich wetland floodplains existed for thousands of years . . . [but] the majority of once-widespread aquatic ecosystems located in valley bottoms of the mid-Atlantic piedmont . . . [were] ponded and then buried by historic sediment as valleys were dammed for milling." The hypotheses of Hartranft et al. (2011) are supported by studies of headwater valleys in southeastern Pennsylvania, USA, with drainage basin areas of 8–15 km^2 (Elliott et al., 2013; Miller, 2011; Voli et al., 2009), and other studies of the region (Merritts et al., 2011, 2013; Walter and Merritts, 2008a). One of the primary objectives of this study was to determine if the hypotheses of Hartranft et al. (2011), originally proposed for small headwater stream valleys, could be extended to larger, nearby 3rd- to 5th-order watersheds with drainage basin areas of 10–153 km^2. To evaluate these hypotheses, stratigraphic data were obtained from 12 different locations and assembled into geologic sections. These data allow us (1) to identify key depositional processes responsible for storing sediment through time and (2) to document changes in depositional environments from before European settlement to the present. More specific questions derived from these two objectives are highlighted in Table 1.

STUDY AREA

Data were collected from the White Clay Creek and Red Clay Creek subwatersheds of the 6th-order Christina River basin in Pennsylvania and Delaware, USA (https://czo-archive.criticalzone.org/christina/infrastructure/field-area/christina-river-basin/, last accessed 6 February 2023). The area has a moist, subtropical climate (Koppen-Geiger classification Cfa, https://www.noaa.gov/jetstream/global/climate-zones/jetstream-max-addition-k-ppen-geiger-climate-subdivisions, accessed 11 June 2023) with moderately cold winters and warm, humid summers, averaging 1070 mm of annual precipitation (Corrozi et al., 2008). The White Clay Creek, where stratigraphic data were obtained, has a drainage area of 280 km^2, with 153 km^2 of this total in Pennsylvania (where most of the sites are located). Study sites are underlain by Paleozoic gneiss and schist of the Wissahickon Formation and the Cockeysville Marble (https://www.gis.dcnr.state.pa.us/pageode/, last accessed 6 February 2023; Ramsey, 2005), and are located within the Piedmont Physiographic Province (Fischer et al., 2004; Renner, 1927). Land uses in the White Clay Creek watershed include developed areas (38%), agriculture (32%), forest (28%), and wetlands (2%) (Kauffman and Belden, 2010), but within Pennsylvania the watershed is largely rural, with impervious cover ranging from <10% in the west to 10%–20% in the east (Corrozi et al., 2008).

The contemporary White Clay Creek is a sinuous (e.g., non-meandering), gravel-bedded river. For the study sites of Figure 1, Bodek et al. (2021) report sinuosities ranging from 1.02 to 1.74, median bed sediment grain sizes from 19 mm to 90 mm, bankfull widths of 9.9–16.0 m, bankfull depths of 0.8–2.8 m, and slopes from 8×10^{-4} to 6.7×10^{-3}. The channel is mostly single-threaded, but Bodek et al. (2021) report side channels and/or mid-channel bars at five of the 12 study sites. The bed displays well-developed pools and riffles, with occasional alternate and mid-channel bars. Bank sediments are cohesive, consisting of sand, silt, and clay, and the riparian zone alternates between forest and pasture (Sweeney et al., 2004, 2019). Many areas of the riparian zone are classified as wetlands by the National Wetlands Inventory (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/, last accessed 23 February 2023), with PEM1A (emergent, persistent, temporarily flooded), PFO1A (forested, deciduous, temporarily flooded), PFO1C (forested, deciduous, seasonally flooded), and EM5A (emergent, *Phragmites australis*, temporarily flooded) categories most common. Pizzuto et al. (2023) demonstrated that the floodplain of the White Clay Creek is actively accreting vertically by overbank deposition, with fine-medium sand, silt, and clay being deposited at rates of 0–0.75 cm/yr.

Bodek et al. (2021) described frequent exposures of bedrock and colluvium along the margins of the channel. They demonstrated that sediment in modern gravel bars consists primarily of mobile pebble-sized gravels, while the streambed includes immobile cobble and boulder-sized gravels likely sourced from local exposures of bedrock and colluvium. These observations suggest that bars along the White Clay Creek should exhibit sedimentary characteristics consistent

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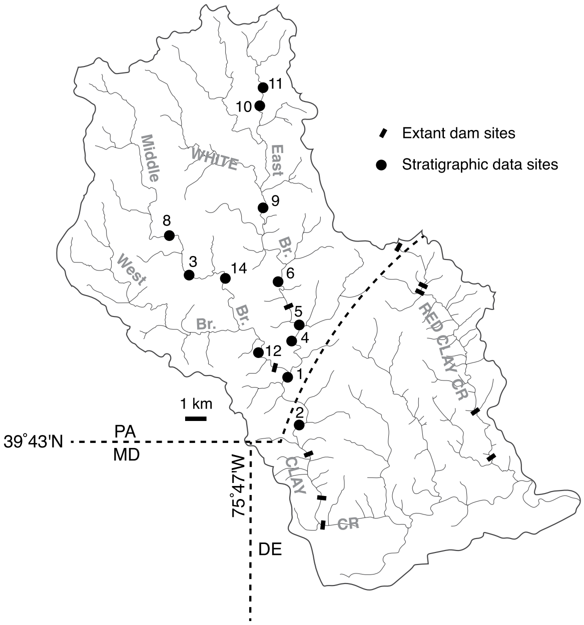

Figure 1. White Clay Creek and Red Clay Creek subwatersheds of the Christina River basin and locations of sampling sites of the Piedmont Province, Pennsylvania (PA) and Delaware (DE), USA, for stratigraphic data and documentation of the effects of extant mill dams. MD—Maryland.

with active fluvial transport such as enhanced roundness, while streambed sediments should be more varied, with some clasts inheriting shapes from local non-fluvial sources and others displaying features consistent with active fluvial transport. Bodek et al. (2021) classified the White Clay Creek as a semi-alluvial river, exhibiting a mix of morphologies characteristic of alluvial, bedrock, and colluvial channels.

Dams have been, and continue to be, important along the White Clay Creek. In total, six low-head run-of-river dams are currently in place along the stream in Delaware (a seventh was removed in 2014), and six dams remain in Pennsylvania (https://www.nps.gov/articles/000/partner-project-spotlight-dam-removal-on-white-clay-creek.htm, last accessed 6 February 2023). Many dams were constructed for milling in the watershed in the eighteenth and nineteenth centuries (http://commondatastorage.googleapis.com/anabranch/ex-pa-chester.html, last accessed 6 February 2023), but few remain in place today. Extant or historic dams have influenced sedimentation at Sites 6, 8, and 12 (Fig. 1; Bodek et al., 2021).

METHODS

Standard stratigraphic methods were followed to infer depositional environments and processes (Dalrymple, 2010; Miall, 1985, 2010). Stratigraphic sections were described at study reaches originally chosen by McCarthy (2018) to infer decadal rates of bank erosion. Exposures were observed along eroding banks or from hand-driven bucket or gouge augers. Sampling locations were selected to highlight deposits formed primarily through vertical accretion (Pizzuto et al., 2023) from the mid-Holocene (e.g., Ramsey, et al., 2022) to the present, a focus that required avoiding (where possible) abundant older colluvial deposits (Costa and Cleaves, 1984; Merritts and Rahnis, 2022), bedrock exposures, and more recent lateral accretion deposits (Jacobson and Coleman, 1986; Pizzuto et al., 2014, 2023; Walter and Merritts, 2008a). Figure 2A provides an illustration of how continuous cross sections were assembled from individual sampling locations.

Sediments were characterized visually in the field according to grain size, fabric, color, lithology, roundness, organic content, and bed thickness and geometry. Selected samples were wet-sieved to determine sand-mud ratios (Lewis, 1984) and loss-on-ignition (LOI) (Ball, 1964). Grain sizes of gravel samples were determined using the Wolman (1954) method; a standard gravelometer (https://www.forestry-suppliers.com/p/53249/22080/wildco-gravelometer, last accessed 16 May 2023) was used to place sampled gravels into size classes in the field. Ground surface topography along stratigraphic sections was extracted from a 1 m horizontal resolution digital elevation model (2015 USGS 3DEP-3D elevation data, https://www.usgs.gov/3d-elevation-program, last accessed 17 January 2023).

Sediments were divided into stratigraphic units representing deposition before and after European settlement using criteria established by previous studies. Dearman and James (2019), Happ et al. (1940), Jacobson and Coleman (1986), Knox (1987), and Pizzuto (1987) used a dark-colored buried A horizon (e.g., a paleosol) to identify the upper surface of presettlement deposits. Where the paleosol is absent, Happ et al. (1940) note that presettlement deposits can be identified by "distinctive bleached colors and hard ferruginous concretions." Jacobson and Coleman (1986) describe presettlement deposits as "gray to light-gray to yellow" with "many distinct mottles and concretions." Jacobson and Coleman (1986) describe post-settlement deposits as "a more uniform, yellowish brown to brown color," with a "very friable" texture.

Pedogenic criteria for defining presettlement and postsettlement stratigraphic units were supplemented by age dating using dendrochronology, ^{14}C, ^{210}Pb, and ^{137}Cs analyses. Details of the dating methods and results have already been published (Pizzuto et al., 2023), but the stratigraphic context for the dates is presented here for the first time (see the Supplemental Material[1] for sample locations and results).

RESULTS

Lithofacies and Lithofacies Associations

Following Miall (2010) and others, sediments were classified into ten lithofacies based on grain size, sedimentary structures, and organic content (Table 2). Lithofacies were provisionally associated with depositional processes based on criteria established by previous studies (Bridge, 2003; Fisk, 1947; Miall, 1985, 1996, 2010; Webb-Sullivan and Evans, 2014), supplemented by our own analyses and observations (detailed later in Results). For example, matrix supported gravels are considered to represent gravity flow deposits. This depositional process could include colluvium, debris flows, and periglacial processes such as solifluction. Stratified, imbricated gravels are interpreted as sediments deposited from fluvial bedload transport. Massive deposits of sand, silt, and clay with little organic material are deposited from overbank flows. If preserved, fine laminations of mud and sand are evidence of deposition in low-energy, subaqueous environments, but other criteria (stratal geometry, for example) may be needed to identify these deposits where post-depositional disturbance is likely. Organic-rich deposits are often associated with wetlands such as "backswamps" (Fisk, 1947; Miall, 1985, 1996; Tye and Coleman, 1989; Webb-Sullivan and Evans, 2014). Some gravel deposits are poorly exposed, and

[1]Supplemental Material. Includes core logs, ^{14}C dates and sample locations, sampling locations for gravels at Sites 1 and 3, measurements of dam and floodplain heights at extant dams, and analyses of percentage silt-clay and loss-on-ignition. Please visit https://doi.org/10.1130/GSAB.S.23601087 to access the supplemental material, and contact editing@geosociety.org with any questions.

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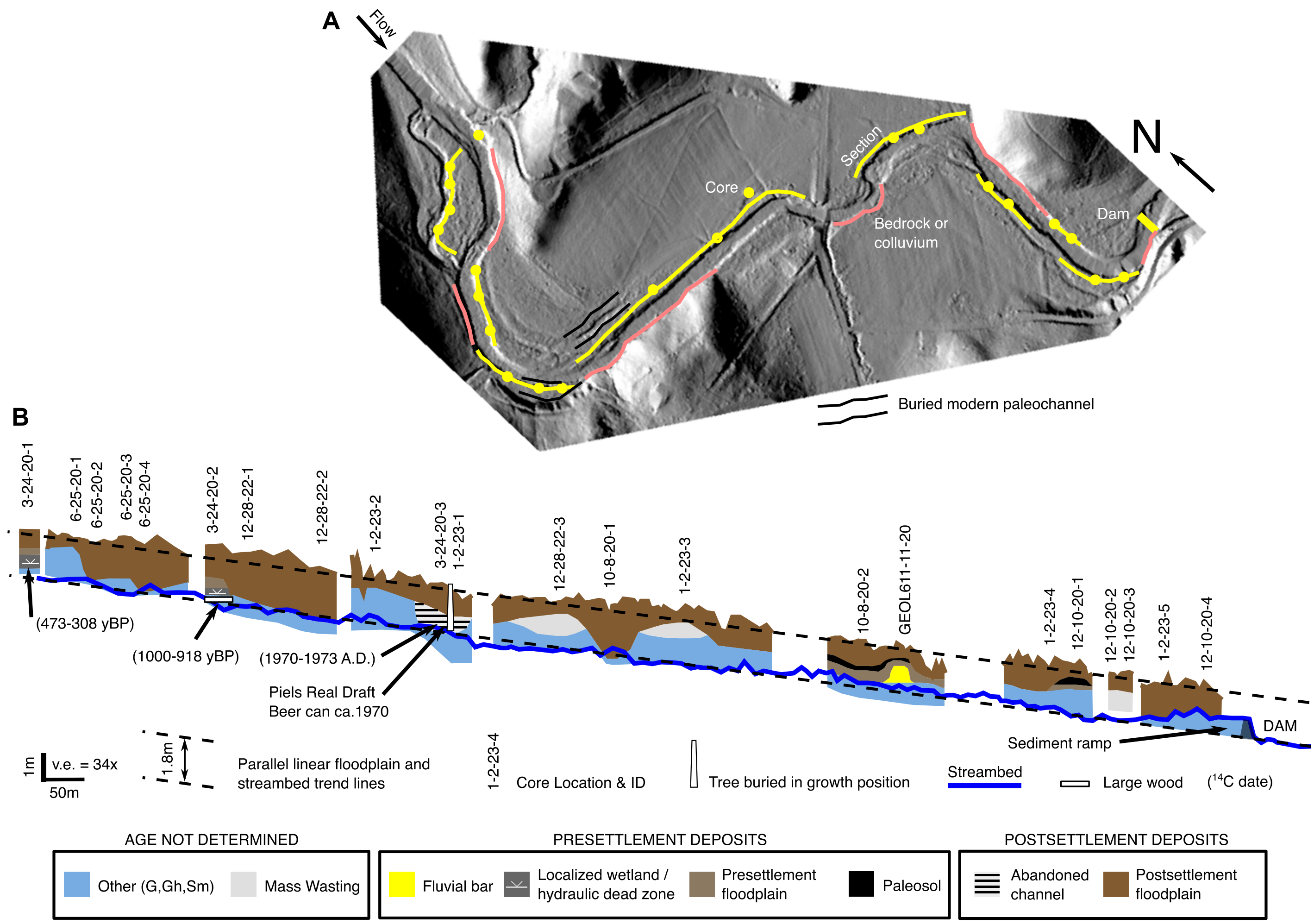

Figure 2. Longitudinal section of Site 12 along the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1). (A) Hillshade map illustrating locations of cores, alignment of the cross section, exposures of bedrock and/or colluvium along the channel, buried modern paleochannels, and an extant low-head mill-dam. (B) Geologic cross section with parallel lines fit to floodplain surface and streambed. G—gravel; Gh—crudely bedded gravel; Sm—massive sand.

sedimentary structures and fabric could not be observed. These were classified with facies code G (Table 2), and no interpretation of the depositional process of these sediments was attempted.

Lithofacies were grouped into eight facies associations and provisional depositional environments were assigned based on previous studies of alluvial stratigraphy in the region (Dow et al., 2020; Jacobson and Coleman, 1986; Walter and Merritts, 2008a; Wegmann et al., 2012) and elsewhere (Brakenridge, 1984; Bridge, 2003; Happ et al., 1940; Knox, 1987; Miall, 1996; and many others) (Table 3). While the sampling strategy of this study was designed to avoid colluvial deposits, some massive, matrix-supported facies (Gmm) were encountered and included in cross sections presented below. Clast-supported, weakly stratified, somewhat imbricated gravel

TABLE 2. LITHOFACIES CLASSIFICATION AND INTERPRETATION FOR RIVER CORRIDOR DEPOSITS OF THE WHITE CLAY CREEK WATERSHED, PENNSYLVANIA AND DELAWARE, USA *

Facies code	Lithofacies	Sedimentary structures	Interpretation
Gmm	Matrix-supported, massive gravel	Massive	Gravity flow
Gh	Clast-supported, crudely bedded gravel	Horizontal bedding, imbrication	Channel lag, bar
G	Gravel	Unknown due to limited exposure	Not interpreted
Sm	Sand, fine to very coarse, maybe pebbly	Massive to horizontally bedded	Levee or bar
Fm	Sand, silt, clay	Massive	Flood (overbank) deposition
Fscm	Silt, clay	Massive	Flood (overbank) deposition
Fl	Sand, silt, clay	Laminations	Low energy subaqueous deposition
Flo	Sand, silt, clay	Laminations of sand, mud, and leaves	Low energy subaqueous deposition
Fmo	Sand, silt, mud with organic material (carbonaceous mud)	Massive	Wetland or hydraulic dead zone
P	Peat	Massive	Wetland

Note: Gmm—matrix-supported gravel; Gh—clast-supported gravel; G—gravel; Sm—sand; Fm—clay, silt, and sand; Fscm—clay and silt; Fl—laminated clay, silt, and sand; Flo—laminated mud, sand, and leaves; Fmo—carbonaceous mud; P—peat.
*Modified from Miall (2010).

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TABLE 3. FACIES ASSOCIATIONS AND THEIR GEOMETRY AND DEPOSITIONAL ENVIRONMENTS OF THE WHITE CLAY CREEK WATERSHED, PENNSYLVANIA AND DELAWARE, USA

Facies association	Lithofacies	Geometry	Width and length (m)	Thickness (m)	Depositional environment or process
Mass wasting	Gmm	Tabular	100 × 100	1–2	Colluvium, debris flow, solifluction(?)
Channel lag	Gh, Sm	Tabular	100 × 1000		Partial bedload transport by channelized flow
Gravel bar	Gh, Sm	Triangular or mounded	10 × 10	1	Bedload transport by channelized flow
Other	G	Tabular?	100 × 100?	?	Gravel deposits with limited exposures; not classified
Clastic floodplain	Fm, Fscm, Sm	Tabular	100 × 1000	1–2	Overbank deposition during floods
Abandoned channel fill	Flo, Fl	Linear	10 × 100	1	Deposition of sand, silt, and mud sediment with intercalated leaves in abandoned channel
Millpond	Fl	Wedge	100 × 1000	<1–3	Subaqueous sedimentation upstream of mill dam
Wetland/hydraulic dead zone	Fmo	Tabular	10 × 10	<1	Accumulation of organic and mineral sediment in localized channel-adjacent wetland or hydraulic dead zone
Wetland	P, Fmo	Tabular	100 × 100	<1	Accumulation of organic and mineral sediment in seasonally or perennially inundated wetland

Note: Gmm—matrix-supported gravel; Gh—clast-supported gravel; Sm—sand; G—gravel; Fm—clay, silt, and sand; Fscm—clay and silt; Flo—laminated mud, sand, and leaves; Fl—laminated clay, silt, sand sand; Fmo—carbonaceous mud; P—peat.

(Gh) and sand (Sm) facies are interpreted channel-lag or bar deposits, depending on their geometry (additional details are provided below). Tabular units of massive sand, silt, and clay (Fm, Fscm, and Sm facies) represent sediments deposited during overbank flows on floodplains. Laminated sand, silt, and clay facies (Flo, Fl) are deposited in abandoned channels and millponds. Peat (facies P) and mixtures of organic material and fine sand, silt, and clay (also termed as "carbonaceous mud," with facies code Fmo) can accumulate in wetland environments (though other possibilities are also considered for the Fmo facies).

To outline more specific evidence for the interpretations of depositional environments in Table 3, we first describe the stratigraphy of the deposits to document their spatial and temporal context. Then, more detailed stratigraphic data for each facies association and depositional environment are presented.

Stratigraphy

Deposits generally consist of laterally extensive basal gravel (mostly facies G and Gh) overlain by finer sediments consisting of sand, silt, clay, and organic matter (Figs. 2 and 3). The thickness of basal gravel deposits is often difficult to assess due to limited exposures, but ranges from 0 m (where bedrock is exposed at the surface) to 1–2 m. Fine-grained deposits range in thickness from 1 m to 3 m.

The most common fine-grained sediments overlying basal gravels are deposits of the Fm and Fmsc facies, which together create laterally extensive tabular units 1–2 m thick (Figs. 2–4). At some locations, surficial sandy Fm deposits transition laterally to silt-clay Fmsc facies with increasing distance from the modern channel of the White Clay Creek (left side of Fig. 4, from cores 8w-5 to 8w-3), but transitions between Fm and Fmsc facies also occur that cannot be readily explained by proximity to a current or former channel.

Pedogenic features and ^{14}C dates provide a clear basis for identifying presettlement and postsettlement deposits at most locations. At Site 3 (Fig. 5), a dark-colored (7.5 YR 2.5/2, very dark

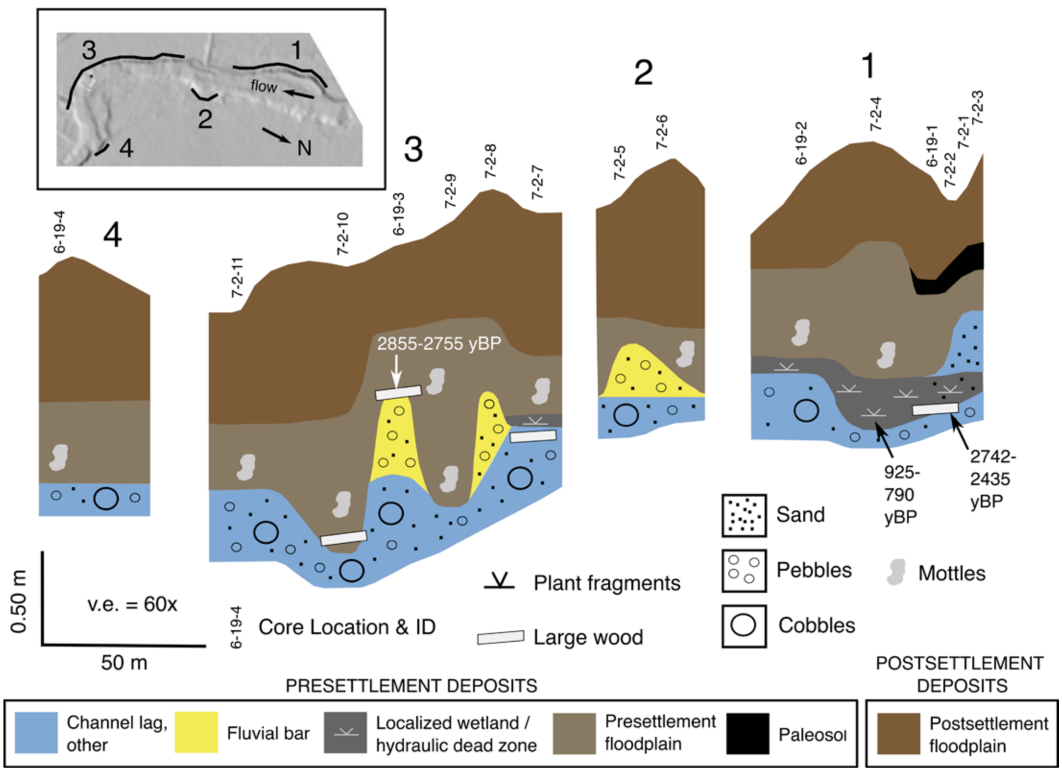

Figure 3. Geologic sections along streambanks at Site 3 on the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1). Lines of sections are indicated in the inset hillshade image.

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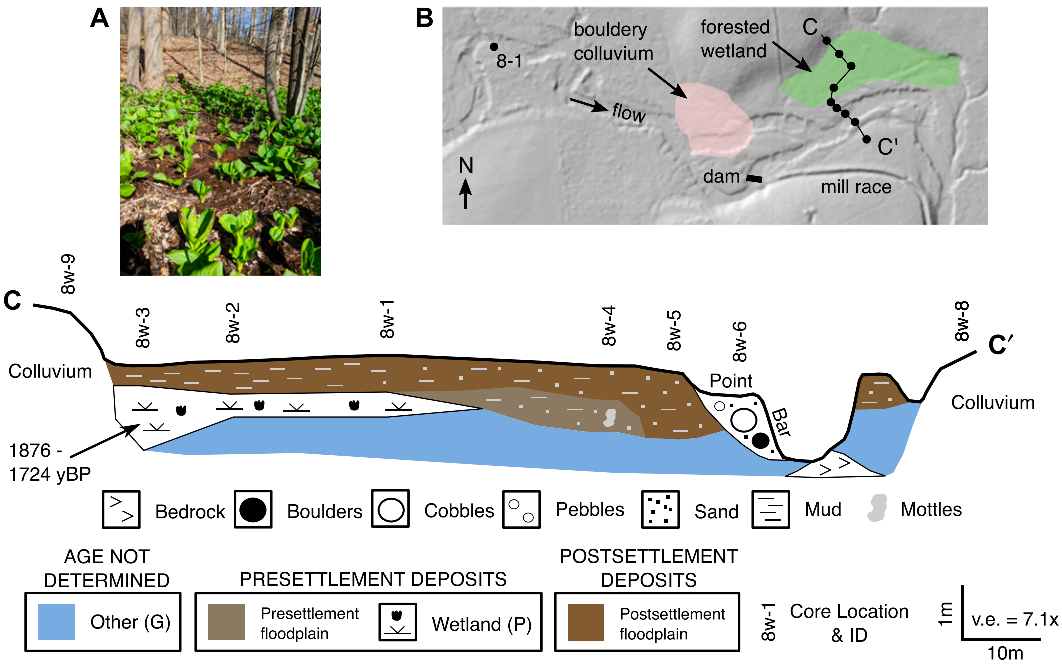

Figure 4. Cross section just downstream of Site 8-1 on the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1). (A) Photo showing forested wetland at location of core 8w-3. (B) Hillshade showing the locations of the cross section, an extant low run-of-river dam, coring Site 8-1, an inferred "apron" of bouldery colluvium extending across approximately half of the valley, and the extent of a forested wetland. G—gravel; P—peat; v.e.—vertical exaggeration.

brown) paleosol is exposed at a depth of 0.7 m, clearly dividing the section into presettlement and postsettlement deposits. This interpretation is supported by ferruginous mottles (Happ et al., 1940; Jacobson and Coleman, 1986) in exposures below the paleosol and a ^{14}C date (calibrated to calendar years) of 2742–2435 yBP (see the Supplemental Material for detailed information describing all radiocarbon dates) on a buried log at a depth of ~1.35 m (Fig. 5). Similar paleosols are available at six (Sites 1, 3, 4, 6, 9, and 12) of nine sites (Fig. 6). At the remaining three sites (5, 8, and 14), paleosols do not occur. Presettlement horizons are identified at Sites 5 and 8 based on well-developed ferruginous mottling, but this criterion is less reliable than paleosol exposures. No

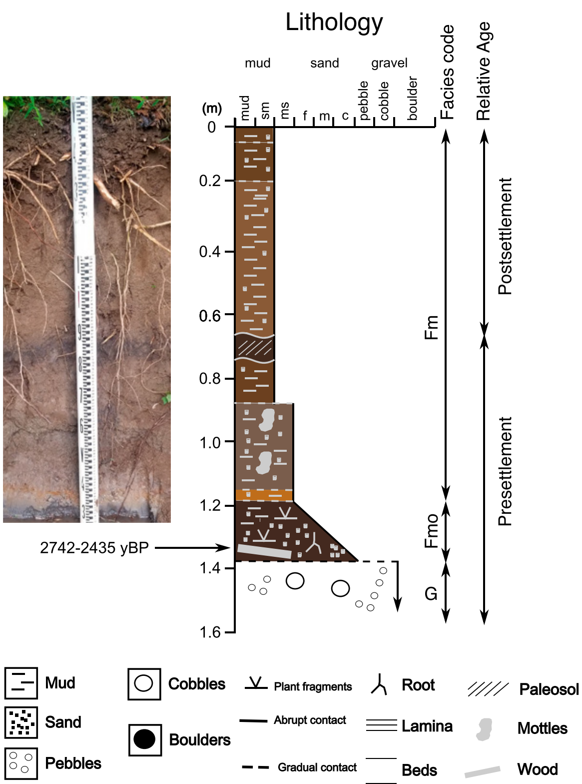

Figure 5. Characteristic vertical stratigraphic sequence from Site 3 on the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1; this section is denoted as 6-19-1 in Fig. 3 and 3-1 in Fig. 6). Colors in the graphic log are the red-green-blue equivalents of the Munsell colors observed in the field (from https://pteromys.melonisland.net/munsell/, last accessed 15 February 2023). sm—sandy mud; ms—muddy sand; f—fine; m—medium; c—coarse; Fm—sand, silt, and clay; Fmo—carbonaceous mud; G—gravel.

features were available at Site 14 to unambiguously identify presettlement deposits.

It is also informative to consider the spatial extent of presettlement and postsettlement deposits documented in cross sections. At Site 3 (Fig. 3), presettlement and postsettlement deposits can be defined along the entire cross section, clearly indicating that the floodplain surface here has been raised an average of ~0.75 m following European settlement. Furthermore, all the gravel and Fmo facies (carbonaceous mud) underlying the presettlement Fm facies at Site 3 must also be of presettlement age, an interpretation that is supported by three ^{14}C dates (Fig. 3). At Site 12 (Fig. 2), fewer paleosols and mottled horizons appear, and thus fewer presettlement deposits can be identified. Presettlement deposits at Site 12 are limited to four locations, two defined by paleosols in the downstream half of the section and two others identified by radiocarbon-dated Fmo facies in the upstream half of the section. At Site 8, presettlement deposits occur on the northern half of the cross section between cores 8w-4 and 8w-3, based on pedogenic features observed in core 8w-4 and a radiocarbon date from organic material sampled by core 8w-3. In the vicinity of the modern channel (between cores 8w-5 and 8w-8), no presettlement deposits can be defined.

Description and Interpretation of Lithofacies and Facies Associations

Clastic Floodplain Deposits—Fm and Fscm Facies

Massive deposits of sand, silt, and clay (facies Fm and Fscm) are the most abundant depos-

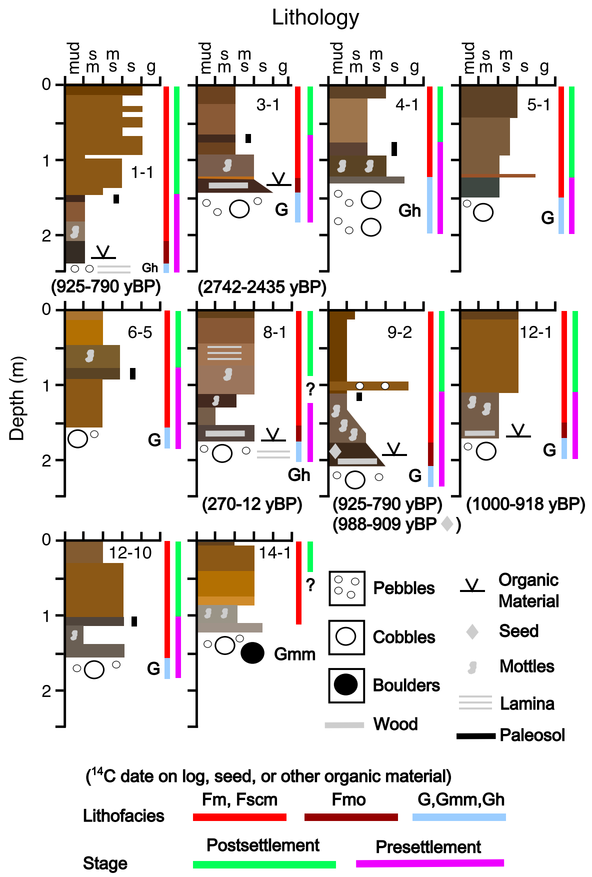

Figure 6. Vertical stratigraphic sequences from nine different study sites from deposits along the White Clay Creek in Pennsylvania and Delaware (Fig. 1). The site number for each core is indicated as the first number in the core ID number. Colors in graphic logs are red-green-blue equivalents of Munsell colors observed in the field. sm—sandy mud; ms—muddy sand; s—sand; g—gravel; Gh—crudely bedded gravel; Gmm—matrix-supported gravel; Fm—clay, silt, and sand; Fscm—clay and silt; Fmo—carbonaceous mud.

its of the White Clay Creek riparian corridor (Figs. 2–6). They have a wide range of silt-clay percentages, and very low organic content (as measured by LOI) (Fig. 7). Presettlement and postsettlement clastic floodplain deposits cannot be distinguished based on % silt-clay and LOI values (Fig. 7), as has been noted in previous studies (Dearman and James, 2019; Coleman, 1982), but these two units often differ somewhat in color though with considerable overlap. Presettlement fine-grained deposits tend to have relatively low Munsell (Munsell Color, 1994) chromas between 1 and 4, values from 4 to 6, and hues of 7.5–10 YR (Fig. 8), yielding colors such as dark gray, brown, and dark brown. The paleosol, where present, is darker-colored (hues of 2.5Y and 2.5YR-10 YR, chromas 1–3, values from 2 to 4), with colors of very dark gray, dark brown, and very dark brown. Post-settlement deposits are typically shades of dark yellowish brown, with higher chromas (e.g., 1–8), values of 2.5–5, and hues of 7.5YR and 10YR (Fig. 8). These deposits do not display “gleyed” colors of the Munsell classification typically associated with wetlands, but 43% of samples from the presettlement Fm facies can be classified as wetland soils based on chromas of 1–2 and the presence of mottling (Tiner, 1998, 1999) (Table 4).

The interpretation of these fine-grained, massive, organic-poor sediments as overbank deposits is consistent with previous studies in the mid-Atlantic region (Jacobson and Coleman, 1986; Pizzuto, 1987) and elsewhere (Aslan and Autin, 1998; Brakenridge, 1984; Bridge, 2003; Miall, 1985, 1996, 2010; Webb-Sullivan and Evans, 2014). Pizzuto et al. (2023) demonstrated that vertical accretion during overbank events is an ongoing process that continues to raise the elevation of the upper surface of the post-settlement floodplain at significant rates. The similarity between presettlement and postsettlement deposits, and the continuity of presettlement deposits at some of our sites (e.g., Site 3, Fig. 3) provide compelling evidence that overbank deposition on presettlement floodplains was an important process before European colonization.

Localized Wetland Deposits—Fmo Facies

Fine-grained clastic deposits with significant amounts of organic matter (facies denoted Fmo) can be found at some sites, typically exposed immediately above basal gravels (Figs. 5 and 6). These deposits have silt-clay contents similar to overbank deposits, and LOI values of less than 20%, slightly higher than the overbank facies but still relatively low (Fig. 7). These deposits contain plant and leaf fragments, seeds, and occasionally display buried wood and a few tree stumps in growth position. Munsell colors have hues of 5YR-10YR, values from 2 to 5, and chromas of 1–2 (Fig. 8), resulting in gray, dark gray, and black colors. 44% of the localized wetland deposits have soil properties typical of wetlands (Fig. 8; Table 4).

Exposures of the Fmo facies are not extensive, and all appear to predate European settlement. They occur at five (Sites 1, 3, 8, 9, and 12) of the nine sites (Fig. 6) and are limited to decimeter thick units that extend for ~1 to >10 m (Figs. 2 and 3). Most of the exposures have been dated using ^{14}C, yielding ages that predate European settlement (Figs. 2, 3, 5, and 6), except at Site 8, where an age of 270–12 yBP was obtained from a buried log.

Based on their enhanced organic content, previous studies have concluded that these basal, primarily clastic sediments represent presettlement wetland deposits (Elliott, et al., 2013; Hartranft et al., 2011; Miller, 2011; Voli et al., 2009; Walter and Merritts, 2008a; Wegmann et al., 2012). This interpretation seems reasonable, but their limited spatial extent suggests that such environments were not extensive, valley-spanning depositional environments. Rather, the Fmo facies likely accumulated in more localized environments such as small wetlands adjacent to presettlement channels, or perhaps simply in hydraulic backwater settings (caused, for example, by side channel confluences, large wood accumulations, or local irregularities in channel geometry) where wetland plants might flourish and where organic detritus and fine sediment could accumulate.

Wetland Deposits—Peat (P) Facies

Initial coring revealed no deposits consisting primarily of organic material. Further field reconnaissance revealed a promising location downstream of coring Site 8-1 (Fig. 4B). An apron of bouldery colluvium, consisting of abundant boulders >1 m in diameter in a matrix of sand, silt, and clay, extends across approximately half of the White Clay Creek valley (Fig. 4B). Somewhat farther downstream, the valley widens into a prominent reentrant. The modern environment of this reentrant is classified by the National Wetlands Inventory (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands-mapper/, last accessed 23 January 2023) as PFO1A: palustrine (i.e., non-saline), forested (broad-leaved deciduous woody vegetation taller than 6 m), temporarily flooded (surface water is present for a few days to weeks during the growing season, but the water table lies well below

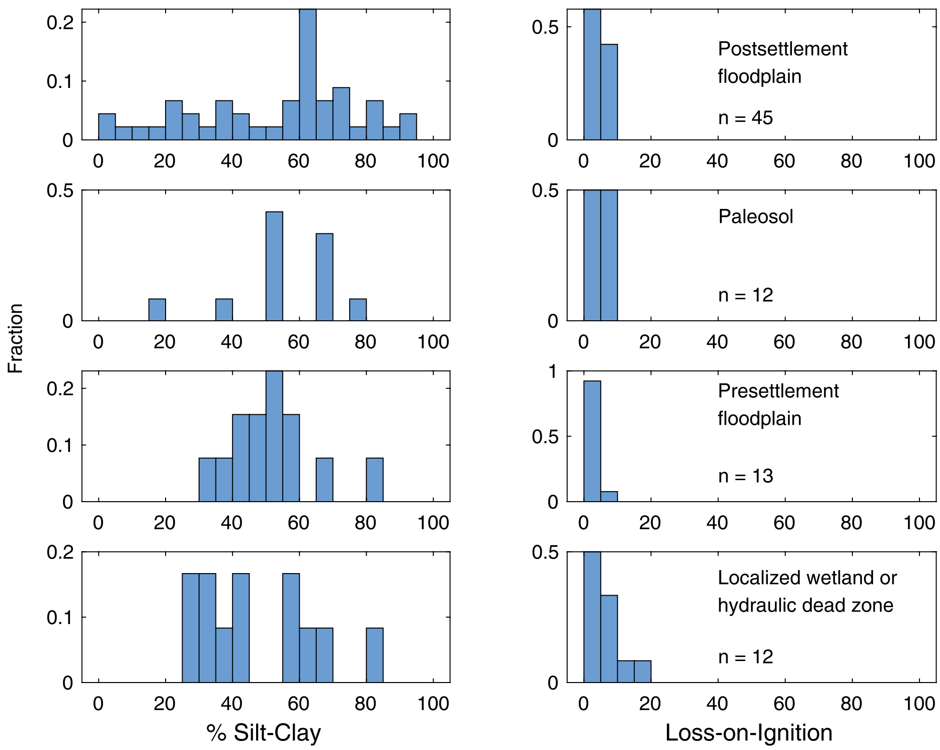

Figure 7. Histograms of percentage silt-clay and loss-on-ignition for samples from the postsettlement floodplain, paleosol, presettlement floodplain, and localized wetland/hydraulic dead zone sediments. Numbers of samples for both analyses are indicated in the right panels. Samples were obtained from Sites 1, 2, 3, 5, 6, 8, 9, and 12 (site locations are illustrated in Fig. 1). Results for individual samples are presented in the Supplemental Material (see text footnote 1).

the ground surface for most of the season) (Fig. 4A). Observations during repeated visits to the site from 2019 to 2022 confirmed this classification.

Sediments along the cross section at this site (Fig. 4) consist of a basal sand and gravel unit overlain by presettlement (inferred from color and mottling) and postsettlement overbank deposits. Peat deposits (P) are preserved underlying postsettlement overbank deposits along the northwestern half of the cross section. These deposits, observed only in narrow 2–5-cm-diameter core samples, consist primarily of poorly preserved leaves, stems, and twigs in a muddy matrix. The deposits are somewhat greater than 1 m thick in core 8w-3, and gradually thin toward core 8w-1. A ^{14}C date of 1876–1724 yBP from core 8w-3 demonstrates that the peat deposits predate European settlement. Laboratory measurements of LOI and % silt-clay demonstrate that these highly organic sediments are unlike other deposits sampled during this study (Fig. 9).

Consistent with conclusions from previous studies (Walter and Merritts, 2008a; Webb-Sullivan and Evans, 2014; and many others), the peat deposits of Figure 4 are interpreted as representing a wetland depositional environment.

Laminated Millpond and Channel Fill Deposits—Fl and Flo Facies

Significant laminated deposits were only observed at Sites 6 and 12. At Site 6 (Fig. 10), a wedge-shaped deposit of laminated fine sand, silt, and clay (facies Fl) accumulated behind a nearly 3-m-high mill dam established at this location in the early nineteenth century. The deposits consist of mm- to cm-thick, continuous horizontal laminations of clay, silt, and fine sand. Bulk grain sizes consist primarily of silt and clay, with some samples comprised primarily of sand (Fig. 9). Organic content is very low, with LOI values mostly between 1% and 5% (Fig. 9). Laminated sediments overlie the paleosol capping the presettlement overbank deposits near their upstream terminus, where they gradually pinch out. Upstream portions of the cross section are also noteworthy for the absence of Fmo facies (Fig. 10).

Laminated fine sediments are also observed at Site 12, but these deposits are not associated with the 1-m-high extant run-of-river mill dam at the downstream end of this reach (Fig. 2). Rather, laminated sediments are exposed along a short ~75 m section of the right bank of the White Clay Creek (facing downstream), more than 1 km upstream of the dam and ~3 m above its crest. These deposits occupy the lower half of the exposed bank. In addition to layers of sand and mud generally similar to those at Site 6, many of the laminations here are created by cm-thick accumulations of leaves, hence their designation as Flo facies. A ^{14}C date yields a date of A.D. 1970–1973. This chronology is supported by the discovery of a beer can ("Piels Real Draft Beer") manufactured ca. 1970 at the base of the deposit. This exposure also features an entire tree trunk buried vertically in growth position, indicating that that the base of this deposit was subaerially exposed at the time the tree germinated.

Laminated sediments at Sites 6 and 12 have different origins. The lithology and geometry of Fl facies at Site 6 are consistent with accumulation in a millpond behind the relatively high dam once located at this site. This interpretation is supported by observations of similar deposits located behind mill dams along rivers broadly similar to the White Clay Creek (Dow et al., 2020; Evans, et al., 2000; Walter and Merritts, 2008a). Flo facies deposits at Site 12, however, are not spatially related to an existing milldam, and their young age precludes being related to any former mill dam. The local extent of these deposits, their proximity to several current and former channels of the White Clay Creek (see existing side channel upstream and buried former channel illustrated in the hillshade of Fig. 2), and their geometry and lithology (Bridge, 2003; Fisk, 1947) all suggest that these sediments represent the filling of an abandoned channel.

Bar Deposits—Gh Facies

Presettlement-age bar deposits (facies Gh) occur at Sites 3 and 12 (Figs. 2, 3, and 11). They consist of clast-supported pebbles and sand in beds typically a few tens of meters in length and a few decimeters in thickness. These units are often triangular in cross section (Fig. 11B) and overlie coarser gravel deposits. Pebble clasts of the downstream bar deposit in subsection 3 of Figure 2 (near core 6-19-3 of Site 3) are weakly imbricated, and indicate flow downvalley at the time of deposition (Fig. 11A and 11B). A ^{14}C date from a log lying on the upper surface of this now-buried bar has an age of 2755–2655 yBP, clearly demonstrating that these deposits predate European settlement (Fig. 3). The bar deposit of Site 12 (Fig. 2) is exposed below a paleosol, also suggesting a presettlement age.

Figure 12 compares the grain-size distribution, roundness, and lithology of presettlement bar deposits from Site 3 with those from a nearby modern bar. Samples of the presettlement bar were obtained from the downstream deposit in subsection 3 (near core 6-19-3) and also from the deposit in subsection 2 (near cores 7-2-5 and 7-2-6) (Fig. 3), while modern bar samples were obtained just upstream of subsection 4 (see the

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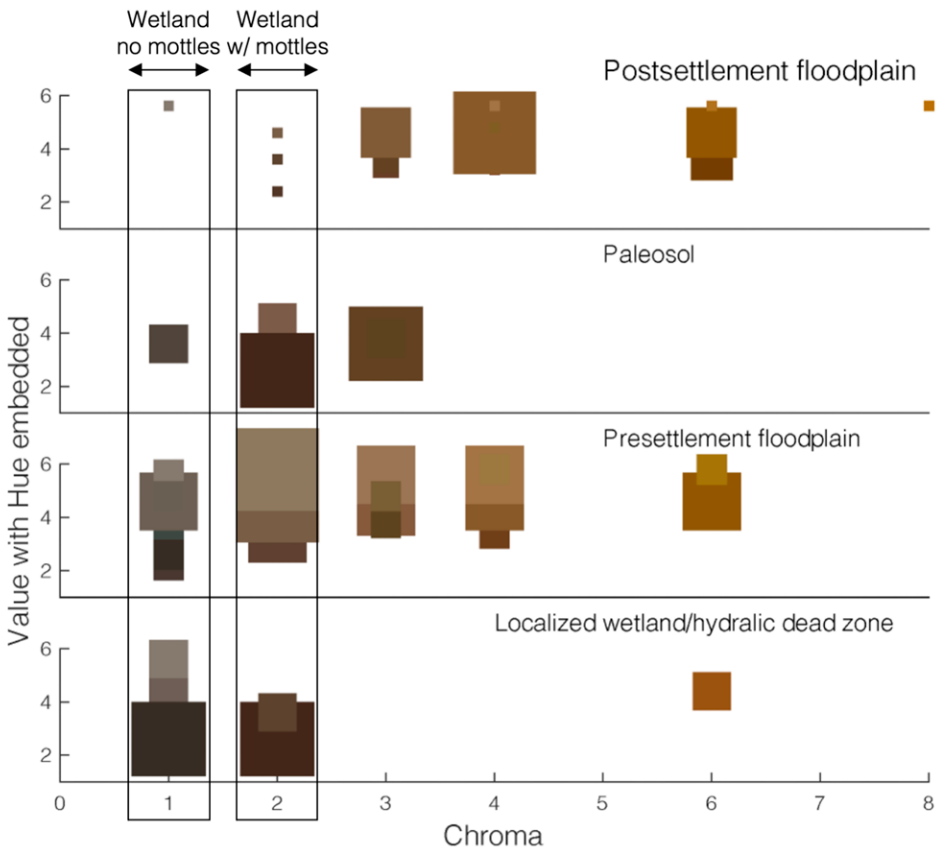

Figure 8. Colors of four stratigraphic units, plotted in sequence from bottom (oldest) to top (youngest), from deposits along the White Clay Creek in Pennsylvania and Delaware (Fig. 1). Symbol size is proportional to the frequency of observations of each color. Colors are plotted as red-green-blue equivalents to Munsell Colors (from https://pteromys.melonisland .net/munsell/, accessed 15 February 2023). Colors indicating wetland conditions for samples with and without mottles are indicated (Tiner, 1998). Hue values of 10y Gley, 5YR, 7.5YR, 10YR, and 2.5Y are plotted in decimal increments of 0, 0.2, 0.4, 0.6, and 0.8 for each value (for example, a 5YR Hue with a value of 4 is plotted at 4.2).

Supplemental Material for detailed sample locations). The lithology, roundness, and grain size distribution of the presettlement bar samples are very similar to those of the modern bar, providing additional evidence that these deposits represent buried gravel bars of the presettlement White Clay Creek.

Channel-Lag Deposits—Gh and Sm Facies

While basal gravel deposits are often poorly exposed, focused sampling and analyses of deposits at Site 3 provides additional useful data. Figure 12 compares sediment characteristics of potential colluvial and tributary sediment sources with presettlement gravel deposits (“Channel lag”), deposits of the modern streambed, and those of presettlement and modern bar deposits of Site 3. The grain-size distributions of colluvium, tributary deposits, channel-lag deposits, and the modern streambed are generally similar, with gravel sizes ranging from the smallest granules and pebbles to the largest cobbles. Small differences in the grain-size distributions between samples can largely be attributed to sampling issues; sand-sized sediments of channel-lag deposits and colluvium were not analyzed, so these sizes are not included in the data of Figure 12. Boulders are likely present in all these environments but were not encountered due to limited areas of exposure of the basal gravels and the tributary sampling site. Tributary and colluvial gravels are mostly angular, while samples from other deposits are primarily subangular or subrounded. Most of the samples consist primarily of quartz with lesser proportions of metamorphic and other lithologies, while samples of colluvium primarily reflect the local metamorphic bedrock of the Wissahickon Formation (https://www.gis.dcnr.state.pa.us/pageode/, last accessed 10 February 2023).

The data of Figure 12 suggest the following conceptual model for these deposits. Potential local sediment sources to the streambed of the White Clay Creek include colluvium and tributaries, as well as the upstream channel itself. Colluvium and tributary sources would include sediments that have experienced little fluvial transport, so these deposits should be more angular and reflect local bedrock lithologies. Samples of the streambed should reflect at least some fluvial transport, resulting in increased rounding of locally supplied angular clasts, resulting in the observed subrounded and subangular clasts of the modern streambed samples. Fluvial transport would also promote increased prominence of resistant lithologies such as quartz. More readily mobile fractions of the streambed could be moved by competent streamflows and stored in bar deposits, which would therefore lack the largest grain sizes stored on the streambed.

These observations suggest that gravel characteristics of the modern streambed can be explained by sorting and rounding through bedload transport processes of locally sourced gravel clasts. Because modern streambed sediments are very similar to those of presettlement basal gravels (at least at Site 3), this conceptual framework should not only apply to the modern White Clay Creek, but also to the White Clay Creek prior to European settlement.

Additional details are provided by exposures from an eroding streambank at Site 1 (Fig. 13) (sampling locations are documented in the Supplemental Material). Weakly stratified, subrounded, clast-supported sand and pebbles (facies Gh) suggest fluvial deposition of these basal gravels. Furthermore, the gravels are interbedded with localized wetland (Fmo facies) deposits, indicating active deposition of both units simultaneously. A ^{14}C date from the Fmo facies of 652–537 yBP indicates that these sediments were deposited just a few hundred years before European settlement.

TABLE 4. NUMBER OF SEDIMENT SAMPLES WITH WETLAND CHARACTERISTICS IN SELECTED STRATIGRAPHIC UNITS AND FACIES OF THE WHITE CLAY CREEK WATERSHED, PENNSYLVANIA AND DELAWARE, USA

Unit	No. of samples	No. of gley	No. of chroma 1	No. of chroma 2 with mottles	% wetland soils
Postsettlement overbank	60	0	1	0	2
Paleosol	9	0	1	0	11
Presettlement overbank	43	1	8	10	43
Localized wetland (Fmo facies)	9	0	4	0	44

Note: Fmo—carbonaceous mud.

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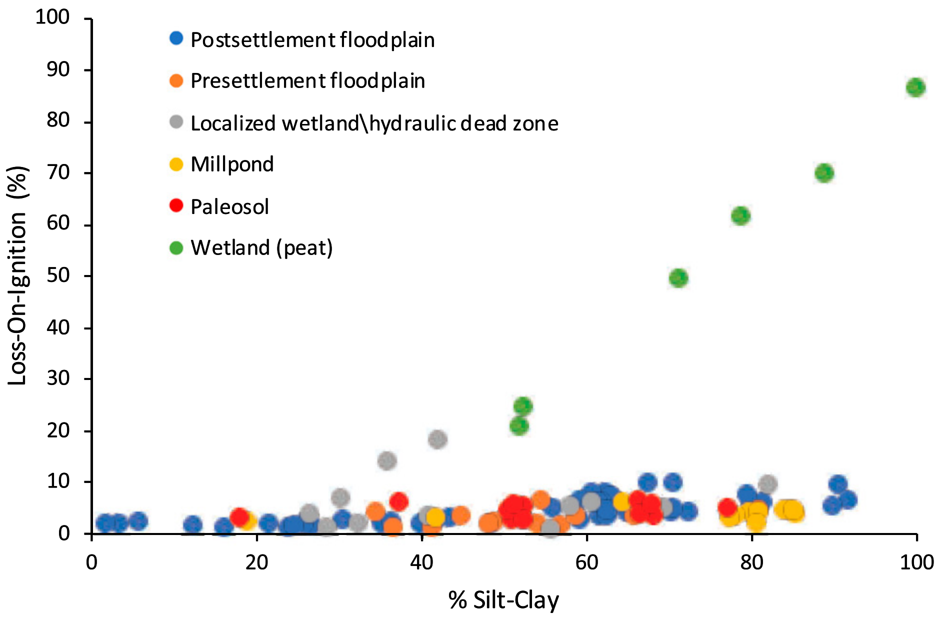

Figure 9. Scatterplot of percentage silt-clay and loss-on-ignition for White Clay Creek stratigraphic units and depositional environments.

DISCUSSION

Holocene–Present Sediment Transport Processes of the White Clay Creek

Fine-grained deposits, which represent most of the preserved stratigraphy, consist of fine-medium sand and mud, with little organic material. The similarity between presettlement deposits and modern overbank deposits suggests a similar origin: deposition from suspension during overbank flows on presettlement floodplain surfaces. This interpretation is supported by the occurrence of buried A horizons, which likely form on subaerially exposed floodplain surfaces subject to episodic inundation. Thus, overbank deposition has been the primary process for storing sediment in the riparian corridor of the White Clay Creek from before European settlement to the present.

Gravel was transported as bedload and deposited by the White Clay Creek before European settlement. Presettlement basal gravels are more rounded and compositionally sorted compared to local colluvial and tributary sources at Site 3 (Fig. 12), suggesting modification by active bedload transport. Presettlement wedge-shaped Gh facies exhibit sediment characteristics and morphology similar to modern gravel bars (Figs. 11 and 12), providing additional evidence of active bedload transport by the presettlement White Clay Creek. Furthermore, bedload transport of gravel-sized sediments requires competent, focused flows, implying that the presettlement White Clay Creek exhibited at least some active channels, rather than consisting of unconcentrated shallow flows within a river corridor of unchannelized wetlands.

Radiocarbon dating clearly indicates that fluvial bedload transport was active along the White Clay Creek throughout the late Holocene. Dates from a log deposited on top of a buried bar at Site 3 provides evidence of bedload transport 2855–2755 yBP (Fig. 7), while interbedded fluvial gravels and localized wetland deposits at Site 1 indicate active bedload transport a few hundred years before European settlement (Fig. 13).

Bodek et al.'s (2021) conceptual framework of bedload transport processes of the modern White Clay Creek is consistent with characteristics of gravel deposits described here, with bar deposits composed of sediments slightly finer than the streambed deposits, and streambed deposits composed of sediments that appear to represent weak fluvial reworking of clasts locally sourced from tributaries and colluvium. This implies that bedload transport processes of the White Clay Creek prior to European settlement were broadly similar to those of the modern channel.

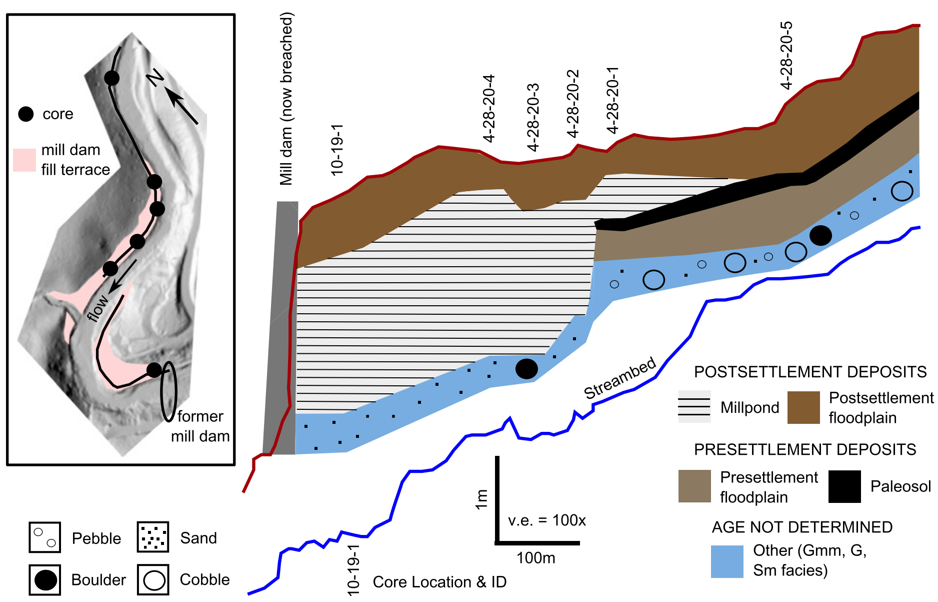

Figure 10. Longitudinal section at Site 6 upstream of the location of a former mill dam along the East Branch of the White Clay Creek in Pennsylvania (Fig. 1). Hillshade indicates the locations of cores, cross section, site of the former mill dam, and spatial extent of the fill terrace created by deposition upstream of the mill dam. v.e.—vertical exaggeration; Gmm—matrix-supported gravel; G—gravel; Sm—massive sand.

The Influence of Mill Dams on Postsettlement River Corridor Sedimentation

Laminated fine sediments representing millpond sedimentation are well-developed at Site 6 (Fig. 10), and extend upstream in a wedge-shaped deposit consistent with the expected extent of an impoundment created by the nearly 3-m-high dam. Laminated sediments are not represented in other deposits of our field sites, with the exception of the channel fill deposits at Site 12 (Fig. 2) and some weakly laminated deposits at Site 8 (core 8-1, Fig. 6), which may reflect the influence of the small run-of-river

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Figure 11. Mounded bar deposits of Site 3 along the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1). (A) Close-up of the more southerly (core 6-19-3) of the two bar deposits in panel 3 of Figure 3 showing subrounded clasts and weakly imbricated texture. (B) Wider view of the deposit in panel A. (C) Bar deposit in panel 2 of Figure 3.

dam downstream of the coring location at Site 8-1 (Fig. 4).

Sedimentation upstream of run-of-river dams is likely not limited to subaqeuous sedimentation in millponds: dams can increase water levels upstream, enhancing overbank sedimentation on floodplains adjacent to millponds. The potential for overbank sedimentation upstream of millponds can be at least provisionally assessed by measuring the height of floodplain surfaces adjacent to extant milldams relative to millpond water levels, since millpond deposition, by definition, cannot raise the floodplain. Data from nine sites along the White Clay Creek and Red Clay Creek in Delaware and Pennsylvania (Fig. 1), representing extant run-of-river dams with a mean height of 1.6 m, indicate that modern floodplain surfaces average 1.3 m above the level of low-flow water passing over the dams (Fig. 14). These data suggest that overbank deposition can continue to increase floodplain elevations above millpond water levels after dam construction. Further studies are needed, however, to better define the geometry of these deposits and to further clarify processes that control their development and occurrence.

The influence of the small, 1-m-high mill dam at the downstream end of Site 12 on river corridor sedimentation is documented in Figure 2. No laminated deposits are found that represent millpond sedimentation. Furthermore, linear trend lines fit to the channel and bank tops are parallel and separated by a constant interval of 1.8 m for the entire length of the cross section, indicating that the dam has not created a "wedge" of overbank deposits by raising water levels upstream during high flows. The only influence of the dam on river morphology at Site 12 is the development of a "gravel ramp" immediately behind the dam, a landform created to facilitate continuity of coarse bedload transport through the impoundment and over the top of the dam (Pearson and Pizzuto, 2015).

Sites 6 (Fig. 10) and 12 (Fig. 2) may represent two end-member scenarios. Site 6 had a high dam in a steep, narrow valley, likely creating a relatively deep impoundment that readily trapped fine sediment, resulting in a well-developed, wedge-shaped, laminated millpond deposit. The small dam at Site 12 is located in a

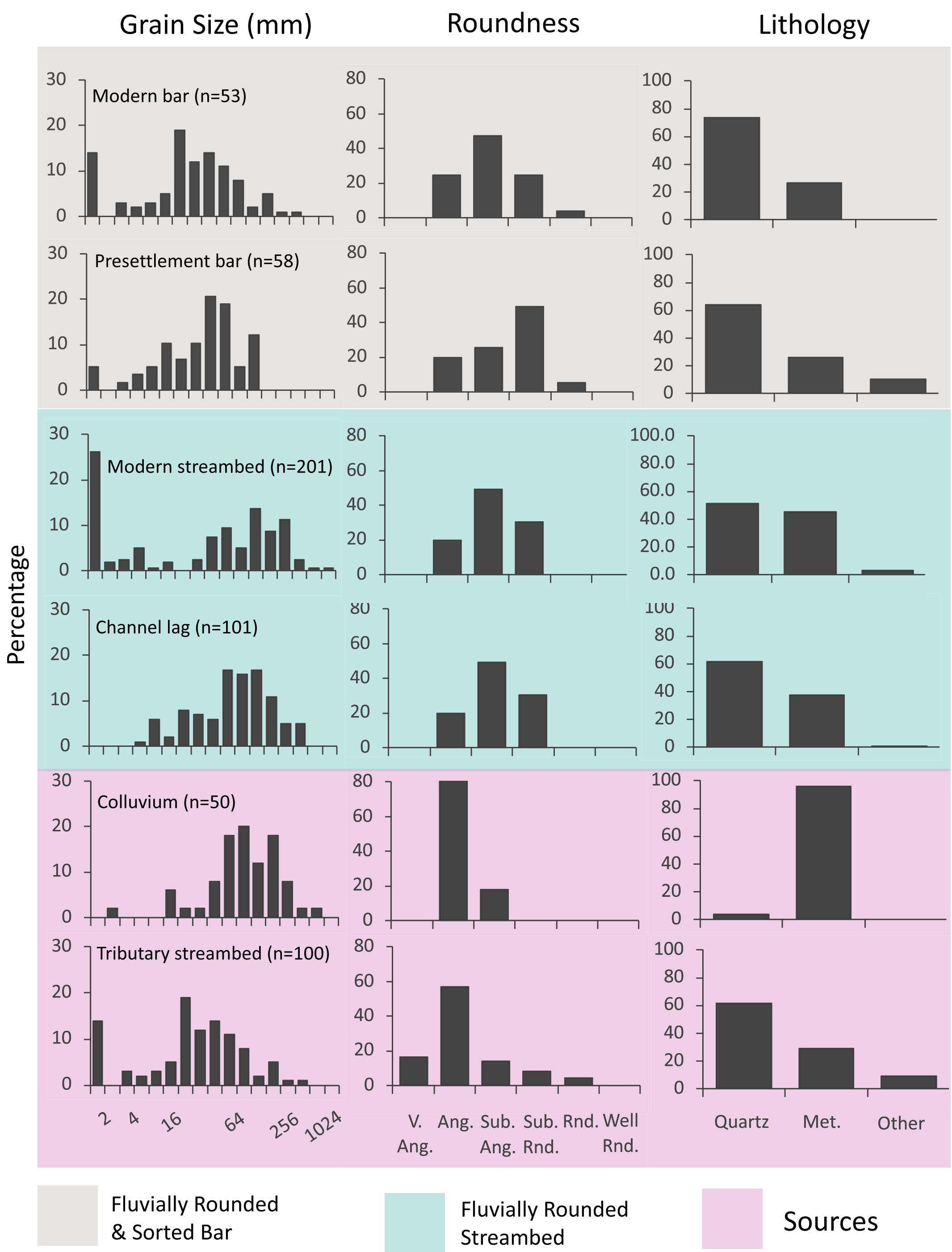

Figure 12. Grain-size distribution, roundness, and generalized lithologic composition of coarse sediments from tributary streambed, colluvium, channel-lag, modern streambed, presettlement bar, and modern bar deposits of Site 3 along the Middle Branch of the White Clay Creek in Pennsylvania (Fig. 1). Shading divides sampling locations into potential sediment sources and fluvially modified streambed and bar deposits. "Met." denotes metamorphic rock lithologies. V. Ang.—very angular; Ang.—angular; Sub. Ang.—sub-angular; Sub. Rnd.—sub-rounded; Rnd.—rounded; Well Rnd.—well rounded; n—number of samples.

reach with a much lower slope and wider valley, and apparently had negligible influence on river corridor sedimentation beyond the localized gravel sediment ramp developed immediately upstream of the dam.

These observations, combined with the general absence of laminated sediments in our field area, suggest that sedimentation related to mill dams may be localized, and should vary according to valley width and slope, and dam height and lifespan. Absence of mill dam sedimentation impacts, cited in 2nd- to 5th-order mid-Atlantic watersheds by Hupp et al. (2013) and Pizzuto (2014), also suggest that the influence of mill dams may differ systematically with varying drainage areas, with stronger impacts in headwater reaches and lesser impacts farther downstream (again, depending also on dam height and geomorphic setting). While a conclusive assessment should await further study specifically focused on mill dam sedimentation, the stratigraphy of our sites is generally aligned with the conclusions of Donovan et al. (2015), who found that erosion of mill pond deposits increases contemporary sediment yields by ~15%, a relatively modest contribution to the background sediment yield provided by upland soil erosion, gully erosion, and streambank erosion of floodplain deposits unrelated to mill dams.

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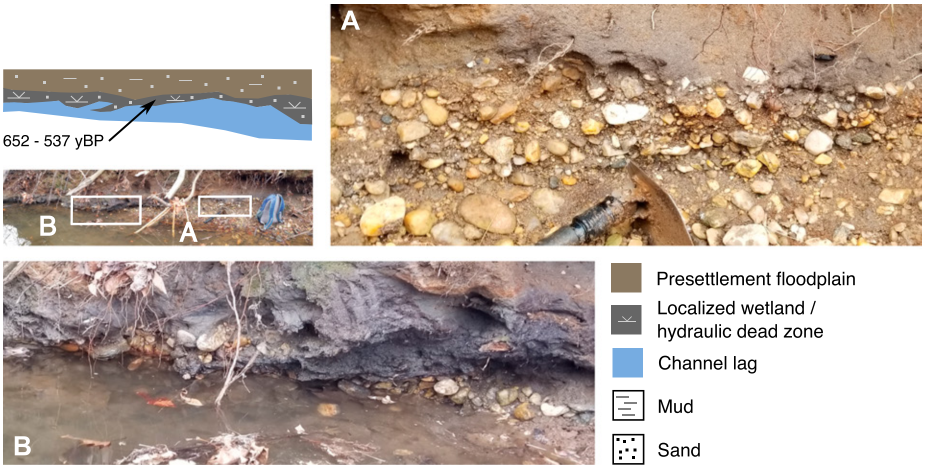

Figure 13. Subrounded (occasionally subangular), weakly stratified, clast-supported pebbly channel-lag deposits interbedded with massive, organic-rich, sandy localized wetland deposits. These sediments are exposed in an eroding bank at Site 1 (location documented in the Supplemental Material [see text footnote 1]). The ^{14}C date was obtained from wood fragments sampled from the localized wetland layer.

Wetland Depositional Environments

Two facies have been identified along the White Clay Creek that could represent wetland depositional environments: peat (P) and carbonaceous mud (Fmo) deposits. Based on their fine grain size (predominately clay, silt, and some fine sand), abundant preserved organic material, and tabular geometry, interpreting the peat deposits of Site 8 as representing an extensive presettlement wetland depositional environment is consistent with previous studies (Bridge and Demicco, 2008; Brierley and Fryiers, 2005; Coleman, 1969; Fisk, 1947; Tye and Coleman, 1989; Walker and Cant, 1984; Webb-Sullivan and Evans, 2014). Interpreting the primarily clastic Fmo deposits, which are of limited spatial extent, is less straightforward.

Presettlement Fmo facies immediately overlying basal gravels have been described previously in the mid-Atlantic region (Wegmann et al., 2012; Voli et al., 2009; Walter and Merritts, 2008a), though mostly from lower (1st to 3rd) order watersheds. Wegmann et al. (2012) interprets similar deposits as a "buried wetland or waterlogged soil layer." Voli et al. (2009), Elliott et al. (2013), Hartranft et al. (2011), and Merritts et al. (2011) present the most detailed interpretation of these deposits, focusing on data from the 2nd-order Big Spring Run in southeastern Pennsylvania (Voosen, 2020). Citing paleobotanical data of Hilgartner et al. (2010), who identified seeds representing emergent herbaceous wet meadows in Fmo deposits, Hartranft et al. (2011) postulate that 1st- to 3rd-order, presettlement river corridors consisted of anastomosing channel valley bottom floodplain systems with "shallow vegetated channels" and an "organic-rich wetland floodplain." The Great Marsh of Chester County, Pennsylvania, (Martin, 1958; https://greatmarshinstitute.org/, last accessed 26 January 2023) is offered as a modern analogue.

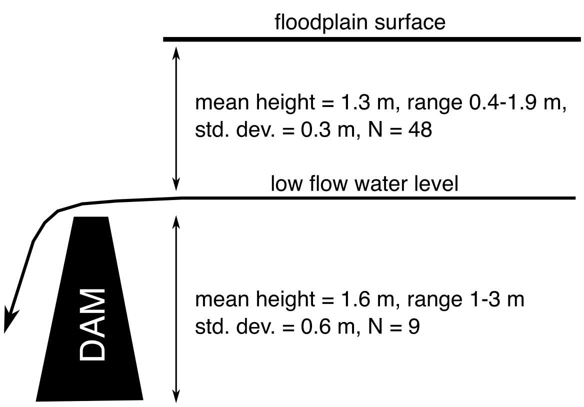

Figure 14. Graphical summary of measurements of dam height and floodplain height above low water level. Locations of the nine dams are indicated in Figure 1. All data are available in the Supplemental Material (see text footnote 1). std. dev.—standard deviation; N—number of samples.

The Great Marsh, a large, valley-spanning, km-wide complex of ponds and herbaceous wetlands, is a poor candidate for the depositional environment of the Fmo facies of this study. Although its deposits are not extensively characterized, Martin (1958) presents analyses of organic content ranging from 20% to 25%, equivalent to LOI values of ~50% (Ball, 1964), indicating that the Great Marsh deposits have very high organic content, as would be expected for these frequently saturated wetland environments. Although peat deposits of Site 8 (Fig. 4) could represent a wet meadow such as the Great Marsh, the limited spatial extent of the Fmo facies and its low organic content suggest an alternative depositional environment. Smaller wetlands adjacent to active channels, or hydraulic dead zones such as side channels or the downstream ends of alternate bars, seem like more reasonable depositional environments of the Fmo facies observed in this study. This does not, of course, negate conclusions of other studies describing similar deposits elsewhere.

Peat and carbonaceous mud facies, however, may not be the only deposits that represent wetland environments along the White Clay Creek. The modern floodplain, underlain by post-settlement overbank deposits with little preserved organic material, has numerous areas classified as wetlands by the National Wetlands Inventory. The northwestern segment of the cross section at Site 8 (Fig. 4) is a typical example, where mud-rich Fmsc facies represent deposits of a modern forested wetland (Fig. 4A). This suggests the possibility that some presettlement floodplains, represented by clastic overbank deposits, could have been wetland environments based on criteria related to hydroperiod even though they do not preserve deposits consisting of peat or muck (Tiner, 1998, 1999). This hypothesis cannot be evaluated without additional data, but studies of fossil leaves from presettlement Fmo facies by Miller (2011) (who studied deposits near Site 10) and Elliott et al. (2013) (who studied deposits near Lancaster, Pennsylvania) demonstrate that forested wetlands were prominent along presettlement river corridors.

Presettlement Fluvial Geomorphology of the White Clay Creek

Stratigraphic data provide some insights into the morphology of the White Clay Creek before European settlement. Because the elevation of basal gravels has not varied through time, it is likely that streambed elevations before settlement were similar to those of the present channel. Reconstructing floodplain elevations before

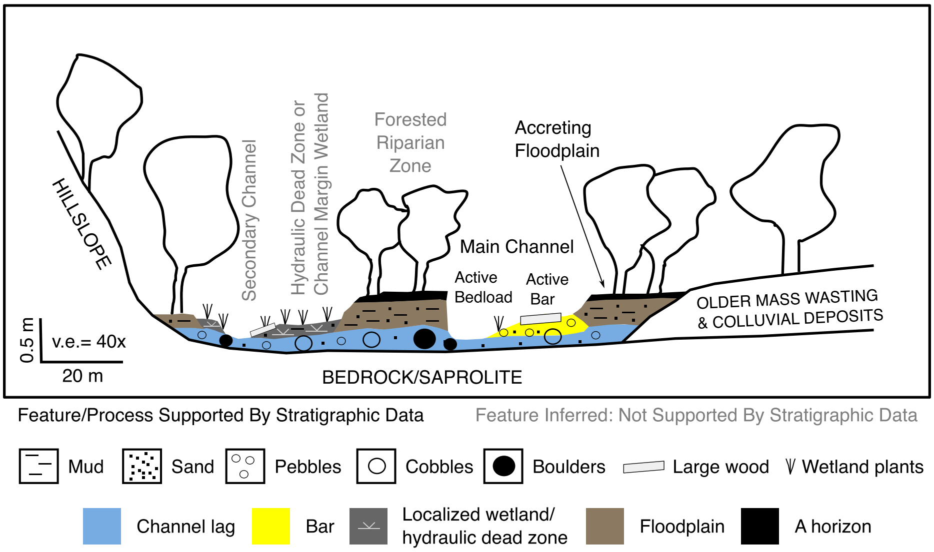

Figure 15. Conceptual model of the presettlement riparian zone of the White Clay Creek in Pennsylvania and Delaware, based primarily on data from Sites 12, 3, and 6 (Figs. 2, 3, and 10). A reconstruction of presettlement riparian environments of Site 8 based on data of Figure 4 would contain fewer floodplains and would feature a more extensive wetland environment. Shaded lettering indicates features and environments whose presence is inferred from indirect evidence rather than being directly supported by stratigraphic data. v.e.—vertical exaggeration.

settlement requires removing ~1 m of post-settlement alluvium, indicating that bankfull channel depths before settlement should have been considerably lower than those of the present channel (Fig. 15), a result that has also been emphasized in other studies (Jacobson and Coleman, 1986; Walter and Merritts, 2008a).

Few other conclusions can be derived from the available stratigraphic data. Presettlement cross sections are not preserved, and therefore, the widths of presettlement channels cannot be reconstructed. Data are also not available to reconstruct presettlement channel planforms, which might be accomplished by mapping directions of paleocurrents (Galeazzi et al., 2021) (only possible if cross-bedding or other useful sedimentary structures are available), by analyzing the morphology and character of preserved bars (Miall, 1977) (rarely available in deposits of the White Clay Creek), or by documenting the morphology of buried channels (not preserved along the White Clay Creek) (Bridge, 2003; Ghinassi et al., 2018). Demonstrating anastomosis from the stratigraphic record is particularly difficult, requiring not only the preservation of multiple channels, but also demonstrating that more than one channel was active simultaneously. Makaske (2001) concludes: "in most cases, anastomosis (coexistence of channels) cannot be demonstrated in the stratigraphic record."

Because sediment transport processes of the presettlement White Clay Creek appear to have been broadly similar to those of the modern channel, it seems reasonable to attribute some features of the current channel form to the presettlement channel. As noted above, Bodek et al. (2021) cite secondary channels at five of 12 study sites, and they suggest that the modern White Clay Creek has a tendency toward anastomosis. This is the motivation for including a side channel in the conceptual model of the presettlement riparian corridor (Fig. 15). It is important to realize, however, that this interpretation is not supported by stratigraphic data, but rather is an inference based on the modern channel morphology and its likely (though uncertain) extrapolation into the past.

Applications and Research Needs

Pizzuto et al. (2023) present a conceptual framework for watershed sediment routing in the Mid-Atlantic region that accounts for sediment storage. They argue that sediment storage imposes millennial time scales on sediment delivery and propose developing sediment routing models that begin in the late Holocene, with predictions continuing into the present and future. The results presented here demonstrate that suspended sediment deposition during overbank flows has been the dominant process of sediment storage since the late Holocene, and therefore, this is the key process that must be represented in sediment routing models over these time scales.

Our results also highlight the diversity of presettlement river corridor sedimentary environments. The valley of the presettlement White Clay Creek consisted of a mosaic of older colluvial landforms, floodplains, and, depending on geomorphic setting, either localized or extensive forested or herbaceous wetlands. Presettlement environments of the region likely also varied systematically with valley width, slope, drainage basin area, and other variables; the role and influence of these controls should be understood through regional stratigraphic studies before developing guidelines for restoring specific sites. Current studies of modern river corridors recognize their diversity and variety (Iskin and Wohl, 2023); it is only reasonable to expect past environments to be equally complex.

While obtaining more stratigraphic data will be essential, using the stratigraphic record to define reference conditions for restoration design will require resolving fundamental differences between knowledge and classification of modern environments and our ability to identify and classify environments of the past from the geologic record. Modern wetlands are defined by hydroperiod and are mapped based on vegetation and soil characteristics (Tiner, 1998, 1999). As noted above, significant areas of the modern floodplain of the White Clay Creek consisting almost entirely of clastic sediment are mapped as wetlands. In the stratigraphic record, these environments lack preserved pollen or plant fossils (Bain and Brush, 2005), and soil criteria (Aslan and Autin, 1998; Happ et al., 1940; Wright, 1999) may not be useful, and therefore, they are difficult or impossible to identify in presettlement deposits as wetlands. Wetlands that preserve muck or peat, however, are readily identifiable. Similarly, modern river channels are classified in part based on their planform and geometry, but these attributes are also difficult to identify in fluvial deposits. Restoration, however, requires specific information: which plants should be introduced, what hydroperiod should be created, and what is the specific size and geometry of river channels to be installed at a specific location? These questions will always be difficult to answer using reference conditions derived from the stratigraphic record, despite the development of novel paleoecological methods (e.g., using fossil beetles as indicators of past wetland environments) (Baker et al., 1993; Brown, 2002) and improved dating methods.

At least two related initiatives can advance our ability to use presettlement reference conditions to improve restoration practice. The first is to collect new and more complete stratigraphic data, relying on interdisciplinary teams of geologists, paleoecologists, and geochronologists. The second is to begin a conversation among stratigraphers, wetland scientists, and restoration practitioners to clarify, recognizing the limitations of stratigraphic data, the specific knowledge of past environments that will be needed to productively inform future restoration designs.

CONCLUSIONS

Ten lithofacies grouped into eight facies associations provide the basis for interpreting Holocene–present depositional environments and sediment transport processes of the 3rd- to 5th-order White Clay Creek river corridor. While basal gravel deposits are highly varied and are likely of diverse origin, some basal gravels are similar in grain size, shape, and lithology to gravels of the modern streambed; these deposits, therefore, represent presettlement channel facies subject to episodic bedload transport. Some basal gravels are overlain by wedge-shaped deposits of pebble-sized gravel resembling modern bar deposits, providing further evidence of active bedload transport by channelized flows before European settlement. Massive fine-grained deposits overlie gravels at nearly all sites. These deposits can be divided into presettlement and postsettlement facies based on pedogenic features and radiocarbon dating, but they are lithologically indistinguishable based on grain size and sedimentary structures. Pizzuto et al. (2023) demonstrated that these sedimentary units are actively accreting by overbank deposition, and because of their lithologic uniformity, it is reasonable to conclude that all of these sediments were deposited on vertically accreting floodplains.

Three other, less abundant, fine-grained facies can be defined. Peat facies are observed at only one cross section, where they occupy approximately half of the river corridor. These sediments were likely deposited in a seasonally or perennially flooded wetland (possibly herbaceous). Decimeter thick, laterally discontinuous beds of carbonaceous mud occasionally overlie basal gravel deposits (and are buried by younger overbank deposits). These sediments, interpreted to represent extensive wetland deposits by previous studies of 1st- to 3rd-order river corridors of the mid-Atlantic region, may represent small, localized wetlands adjacent to presettlement channels or hydraulic backwater environments at our 3rd- to 5th-order sites. Laminated mud and sand deposits accumulated behind a now-breached, 3-m-high mill dam at one site; these deposits pinch out upstream, defining the limit of the impoundment in which they were deposited. Millpond deposits are not present at any other sites, including those with extant or former milldams.

Stratigraphic data suggest that the predisturbance river corridor of the White Clay Creek was a mosaic of diverse riparian environments, including older colluvial landforms, floodplains, primary and possibly secondary channels, and, depending on geomorphic setting, either localized or extensive wetlands. The stratigraphy does not allow reconstruction of channel width or planform, but bankfull depths were probably much lower. These interpretations can provide an initial template for restoration, but more detailed studies to document the spatial and temporal variability of past river corridor environments are needed.

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