Stratigraphic Reconstruction of Holocene Paleogeography and Paleoclimate, Little Falls, MD

Elizabeth Cranmer
Earth and Environment Department
Franklin and Marshall College

Advisor: Dorothy Merritts, Earth and Environment
Franklin & Marshall College
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Honors Thesis Defense Committee:
Noel Potter, Retired from Geology Department, Dickinson College
Roger Thomas, Earth and Environment Department, Franklin & Marshall College
Chris Williams, Earth and Environment Department, Franklin & Marshall College
# TABLE OF CONTENTS

ABSTRACT ................................................................................. 3
INTRODUCTION ........................................................................... 4

BACKGROUND .................................................................................. 4
  Location ...................................................................................... 4
  Geology ...................................................................................... 5
  Modern and Past Climate ................................................................. 5
  Modern and Past Vegetation and Inferred Climate-Vegetation Response .................................................................................. 7
  Historic Landuse: Dams and their Local Impacts ........................................... 9
  General Description of Sediments Exposed along Stream Banks in the Little Falls Valley Bottom .................................................................................. 11

METHODS ......................................................................................... 12
  LIDAR & Aerial Photographs and Field Mapping ........................................ 12
  Characterizing the Site and Sedimentary Units ........................................ 13
  Magnetic Susceptibility ........................................................................... 14
  Radiocarbon Dating ................................................................................ 14
  Size and Imbrication Analysis for Quartzose gravels ................................ 15
  Distribution of Fine-grained Sediments .................................................. 15
  Seed Analysis .................................................................................... 16

RESULTS ....................................................................................... 16
  Characterizing the Site ........................................................................ 16
  Magnetic Susceptibility ........................................................................ 18
  Radiocarbon Dating ............................................................................. 19
  Quartzose Gravels Grain Size and Imbrication Analysis .......................... 20
  LIDAR & Aerial Photographs ................................................................. 21
  Seed Analysis .................................................................................... 22

DISSCussion .................................................................................. 22
  Interpretation of the Origin of Stratigraphic Units .................................. 22
  Reconstruction of Paleostratigraphy and History of Little Falls .......................... 27
  Inference of Landscape Response to Climate Change ................................ 29

CONCLUSION .............................................................................. 30
ACKNOWLEDGEMENTS .................................................................. 30

REFERENCES ........................................................................... 32
APPENDIX OF FIGURES & TABLES .................................................. 35
Abstract

In the Appalachian piedmont region of the eastern United States, the proliferation of milldams and their ponds greatly altered the landscape during early American settlement. Widespread upland deforestation coupled with other land clearing processes increased sedimentation behind the milldams. This sediment, referred to as legacy sediment, buried the original valley bottom topography, soils, plants, and deposits. The focus of this research is to reconstruct the Holocene landscape that existed in part of the Little Falls watershed, northern Maryland, before it was buried by millpond sediment. The stratigraphy, sedimentology, and spatial relations of sedimentary units exposed in stream banks along Little Falls, now a deeply incised channel due to 20th-century milldam breaching, are the basis for this reconstruction. Radiocarbon dates from organic material in the sediment provide age control, while magnetic susceptibility indicates whether or not sediments were disturbed by anthropogenic activities. Historic and recent air photos, combined with light detecting and ranging (LIDAR) data, reveal the incision and subsequent stream bank erosion that have occurred since 1952.

Five distinct sedimentary units overlying bedrock are exposed along Little Falls. From bottom (oldest) to top (youngest), these are: 1) late Pleistocene (?) cobble- to boulder-sized rubble of angular to sub-angular schist with some quartz; 2) a thin (0.2 to 0.6-m) layer of late Pleistocene sandy cobble gravel that consists predominantly of oxidized, sub-angular to sub-rounded quartz; 3) a Holocene organic-rich loam that contains wetland seeds (primarily sedges) and varies in thickness from 0 m near valley margins to 1 m in the lowest parts of the valley bottom; 4) a mid- to late-Holocene(?) light grey sandy loam with occasional angular pebbles and cobbles that fines upward and varies in thickness from 0 to ~1 m; and 5) historic laminated silt loam that coarsens upward to sandy loam. The quartz-rich sandy cobble gravel is older than ~10,500 yrs based on two radiocarbon dates of wood at the top of the gravel. The organic-rich loam is a wetland soil with radiocarbon ages that range from ~5000 yrs BP to 1700 AD. The sandy loam is rich in kaolinite and thickest near valley margins, supporting the interpretation that it is derived from upslope erosion of saprolite. In places, this transported saprolite merges down slope with the mid- to late-Holocene wetland soil. The laminated silt loam has a high magnetic susceptibility, indicating that the sediment has been extensively disturbed by anthropogenic activity. This sedimentary unit has in-filled the pre-existing topography, supporting the interpretation that it is mill pond sediment upstream of a milldam. In places, it overlies Holocene wetlands, whereas in others it overlies the saprolite-derived deposits that mantle the toes of hill slopes. The origin of the rubble layer between bedrock and the sandy cobble gravel is uncertain, but it is likely to be Pleistocene in age, and possibly related to full-glacial climatic conditions. It is proposed here that this rubble might have formed as a result of late Pleistocene para-glacial conditions, whereas latest Pleistocene peri-glacial conditions mobilized the overlying sandy cobble gravel. It also is proposed here that cyclical episodes of cold, dry conditions throughout the Holocene led to intermittent deposition of clay-rich sand derived from eroded saprolite along the toes of hill slopes. Intervening warm, wet intervals resulted in thin brown soils on these clay-rich sands.

Results of this work indicate that Holocene wetlands began to form and spread along the Little Falls valley bottom after the Younger Dryas (~12,900 to 11,500 yrs BP). For most of the Holocene, the Little Falls valley bottom was occupied by wetlands, and part of it remained a tussock sedge meadow for the entire mid- to late-Holocene.
Introduction

This paper is the culmination of a year-long independent research project with Professor Dorothy Merritts as the advisor. The research focuses on geomorphic response to climate variation during the late Pleistocene through Holocene Epochs, and to human activities since European settlement in the 18th century AD. The field site is a 2 km reach of Little Falls near the town of White Hall in Baltimore County, Maryland. The landforms, stratigraphy, and temporal and spatial relationships of sediments exposed along the present-day stream banks of Little Falls are the basis of the reconstructions and inferences of geomorphic processes that have occurred along the Little Falls valley during the past approximately 25 ky.

Background

Location

Little Falls, a third-order tributary of Gunpowder Falls, flows from north to south in the Upland Piedmont physiographic region of northern Baltimore County, Maryland (Figure 1). The field area is an approximately 2-km length of the stream that begins just downstream of the small, historic mill town of White Hall. (Figure 2). At this location, the watershed has a drainage area of approximately 134.7 square km (United States Geological Survey, 2007). The region has moderate relief, with a minimum elevation of 90.01 m and a maximum elevation of 180 m, as determined from high-resolution LIDAR data (Figure 3). Compared with the western coast of the United States, the piedmont region has very low relief (Figure 4). Hillslope gradients typically range from 25 to 60 percent, and the stream gradient generally is 0.0024 m/m (Figure 5).

The United States Geological Survey (USGS) stream gage station # 0158200 (Little Falls at Blue Mount, MD) is located 1.3 kilometers downstream from the research area. The mean annual discharge at this station is 1.95 m$^3$/s (with a drainage area of 137 square kilometers); the
maximum mean monthly discharge is 2.66 m³/s in March and the minimum is 1.33 m³/s in October (United State Geological Survey, 2008).

**Geology**

The field site is located in Maryland’s upland Piedmont Plateau Physiographic Province. From the Phoenix and Hereford geologic quadrangles, the bedrock consists of four formations of the Wissahickon Group, for which ages range from Proterozoic to Ordovician. From oldest to youngest, these formations are the Loch Raven, the Piney Run, the Pleasant Grove, and the Prettyboy Schist. The predominant bedrock in the study area consists of the Piney Run and Pleasant Grove Formations. The Pleasant Grove Formation is fine-grained schist containing epidote, chlorite, muscovite, and quartz (Muiller, 1985). The Piney Run Formation can be coarser grained. It is a garnet porphyroblastic mica schist with some vein quartz (Muiller, 1985). This formation also contains lenses of amphibolites and undifferentiated ultramafic and mafic rocks.

**Modern and Past Climate**

The modern climate of northern Baltimore County is humid and temperate. In the nearby city of Baltimore, the annual precipitation is 40.76 inches per year (Northeast Region Climate Center, 2000). The winters are typically mild, with a January mean high temperature of 4.556 °C and low of -4.778 °C (Northeast Region Climate Center, 2000). The mean July high temperature is 30.667 °C, while the mean low is 19.333 °C. Pizzuto and O’Neal (2009) report up to 13 annual freeze-thaw cycles in the nearby Virginia Blue Ridge Physiographic Province and Valley and Ridge Province (Pizzuto & O'Neal, 2009). Given that about 273 kilometers separate White Hall, MD, from the South River, VA, and that the elevation of the two areas is similar, the Little Falls area probably experiences a similar number of annual freeze-thaw cycles during the winter.
Prior to the Holocene warm interglacial period, the paleoclimate was significantly different along the eastern seaboard. The last glacial maximum occurred ~18,000 BP in central Pennsylvania. During this late Pleistocene full-glacial maximum, stream incision occurred along the lower reaches the Susquehanna and Potomac Rivers (Reusser et al., 2004). South of the ice margin, periglacial conditions existed throughout the Appalachian Mountains and piedmont of Pennsylvania, Maryland, and Virginia. The colder conditions allowed frost action to destabilize upland slopes, thereby enabling mass movement to take place and resulting in alluvial fan deposition at tributary junctions (Whittecar & Duffy, 2000; Ritter et al., 2002). Periglacial conditions have been documented in the Pine Barrens, New Jersey and the Piedmont Upland of Lancaster County, Pennsylvania (Potzger & Otto, 1943; Pollack et al., 2000). The period between the Wisconsin glacial maximum and the Holocene is the para-glacial interval, in which rapid deglaciation was associated with warming temperatures (Prentice et al., 1991).

Para-glacial conditions in British Columbia provide a modern example of the types of cold-related geomorphic processes that might have occurred in the Pennsylvania Piedmont during the late Pleistocene. In British Columbia, sediment and water supply are the key characteristics in fan deposition, with the debris supply coming from frost shattering, while the water supply is from ice melting (Ryder, 1971a). The alluvial fan sediments are deposited both by mudflow and fluvial processes. The para-glacial fans have a steeper gradient than the typical deposition pattern of arid fans, along with a lower correlation between “basin parameters and fan gradient” (Ryder, 1971b). These alluvial fans are a transitional deposit, where “the body of detritus in the fan represents an intermediate stage of storage of material removed from the fan basin but not yet entirely removed from the area” (Ryder, 1971a, p. 298). One could hypothesize that fans remain as landforms during the warmer inter-glacial period, but during the onset of the
next cycle of glacial conditions, increased rates of erosion might flush the remnant fans from the basins.

Various indicators of paleoclimate, including ice cores, pollen records, and deep-sea records, indicate that the climate became warmer and moister during the Pleistocene-Holocene transition. Warmer temperatures of the Holocene, following the para-glaciation conditions, have been interpreted as the cause of cessation of sedimentation along Appalachian alluvial fans (Whittecar & Duffy, 2000). Vegetation grew on the alluvial fan surfaces, while the sediment and water supply decreased (Ryder, 1971a). A brief but intense pulse of cold conditions occurred 12,700-11,500 years ago, during the Younger Dryas, according to the pollen record (Leigh, 2008). The $\delta^{18}$O record from the Camp Century ice core confirms this stadial event (Figure 6) (Dansgaard et al., 1971). In the coastal plain sedimentary record of Georgia, Leigh did not find evidence of this pulse; the Younger Dryas climatic extreme could have been moderated by the temperature gradient existing at the onset of the Holocene. After the Younger Dryas, the climate warmed. Further warming occurred about 4,000 to 7,000 years ago (Leigh, 2008). Sedimentary deposits in lakes in eastern North America and offshore in the northern Atlantic indicate that within the Holocene, 1,500-year moisture cycles (Bond cycles) occurred (Bond et al., 1997; Li et al., 2007). The record of variation in these sedimentary records has been used by Li et al. (2007) to discern climatic oscillations between cold, dry and warm, wet conditions that occurred with a temporal period of about 1500 years (Li et al., 2007). This work also indicated that a major drought occurred about 4,400 years ago in the Mid-Atlantic region (Li et al., 2007).

Modern and Past Vegetation and Inferred Climate-Vegetation Responses

The vegetation in this region changed somewhat from early to mid-Holocene, but the primary types of ecosystems established by the mid-Holocene persisted until European
settlement, about 1700 AD (pers. comm., Dr. William Hilgartner, 2008). Native vegetation cover on the uplands surrounding Little Falls today consists of oak, chestnut, hickory, and tulip trees (Brush et al., 1980). The terrace surfaces adjacent to the stream are vegetated by grasses, sycamore trees, and invasive species, particularly multiflora rose. Some sedges occur along the fine-grained margins of inset gravel point bars. Logging occurred throughout the region after European settlement, but many hill slopes in northern Maryland, including in the Little Falls watershed, have become wooded again since the mid-20th century.

For the Maryland region, vegetation at the last glacial maximum based on pollen studies was >20% spruce, 5-20% birch, >20% northern pines, 1-5% prairie forbs (flowering plants with broad leaves), >2% alder and 1-0.5% sedge (Prentice et al., 1991). By 9,000 BP, the spruce and northern pines had thinned to 1-5%. Prairie forbs increased to 5-20%, while oak, hickory and elm appeared (>20%, >2%, and >2%, respectively) (Prentice et al., 1991). The modern climate supports 5-20% birch, northern pines and prairie forbs, 1-5% spruce, >2% hickory and elm, 1-0.5% sedge and alder, and some beech (Prentice et al., 1991).

Prentice et al. (1991) modeled Pleistocene to Holocene vegetation response to climate for the eastern USA at 3,000-year intervals using the pollen record (n = 982 surface pollen and n = 328 fossil pollen sites) from two sets of six or seven taxa. The modern pollen record was used to create isopoll maps for modeling climate (Prentice et al., 1991). Their test case of six taxa (northern pines, southern pines, spruce, birch, oak, and prairie forbs) produced the inferred climate isopolls, showing annual precipitation and mean temperatures for January and July (Prentice et al., 1991). These data imply that the winter temperature gradient shifted from north-south during the Pleistocene to the modern northwest-southeast direction between 12,000 and
9,000 years ago, while the summer gradient shifted northeast-southwest 15,000 to 12,000 years ago (Prentice et al., 1991).

**Historic Landuse: Dams and their Local Impacts**

In Baltimore County District 10, one of the first documented water-powered mills was built in 1735; 48 such mills are known to have existed in the district (McGrain, 2007). In 1669, the Maryland colonial legislature passed a Mill Act which mandated that 80-year leases for ten acres of flooded land could be obtained for water-powered mills (Hart, 1995). Some form of compensation would be provided for farmland inundated by slackwater in the millpond. With European colonization and intensive milling, exploitation of stream power was maximized by valley-spanning dams located about every one to two miles along stream corridors (Walter and Merritts, 2008). Lancaster County had over 400 mills by 1840, while Baltimore County had 365 known mills in 1820 (Walter & Merritts, 2008; McGrain, 2007). Based on a compilation of mills from US Census data undertaken by Mike Rahnis (United States Census Bureau, 1841), Baltimore County had 117 mills in 1840. Base-level changes produced by these milldams altered stream corridors substantially.

When dams are built on a stream, they act as a local high point, or base-level control, that alters the stream’s long profile. Upstream from the dam, the water is calm and fine sediments are deposited in the slackwater. As sediments are deposited, the slackwater effect migrates upstream and the available water storage area is decreased. Eventually, the millpond fills with sediment (Figure 7). These sedimentary deposits have been characterized as legacy sediments.
When dams are removed, deep incision occurs, thereby decreasing the wetted perimeter and increasing the shear stress along the channel. As a result, incision spreads laterally, quickly eroding the banks (Cantelli et al., 2004; Doyle et al., 2003). Rates of 0.5 to 1 m per year are common for bank retreat (Walter et al., 2007). The conventional paradigm of fluvial geomorphology in the mid-Atlantic region supposes that during storm events, meandering streams deposit bed load on point bars and fine-grained sediment on the adjacent, elevated floodplain (e.g., Leopold, Wolman, and Miller, 1964). Ongoing research calls this interpretation of benches identified as floodplains in the mid-Atlantic region in question, because the majority of these features are previously unrecognized historic millpond terraces (Walter & Merritts, 2008; Wohl & Merritts, 2007). In essence, they are fill terraces.

Pizzuto and O’Neal (2009) investigated bank erosion rates along a 30-km reach of the South River in Virginia’s Blue Ridge and Ridge and Valley Provinces. They related this erosion to the locations of fourteen mill dams (Pizzuto & O’Neal, 2009). Potential causes of the accelerated erosion rates observed in the 20th century assessed by Pizzuto and O’Neal include an increased number of freeze-thaw cycles, greater storm intensity, lower density of tree coverage, and the effect of dam removal and incision of historic (i.e., legacy) sediment. Statistically, the first three factors did not explain the high bank erosion rates – leaving legacy sediment as the
primary cause. For nine of the fourteen historic dams within the study area, higher rates of bank erosion were “unambiguously explained by the loss of mill dams (Pizzuto & O’Neal, 2009).”

General Description of Sediments Exposed along Stream Banks in the Little Falls Valley Bottom

A general description of the sediments exposed along Little Falls is provided here as background in order to establish terminology and place names that are used in subsequent sections. The two-meter high stream banks expose clastic sediment that are largely of sand or finer grain size, but the basal section consist of sandy gravel that contains abundant cobbles and small boulders. These sandy gravel deposits within the stream bank are interpreted to here as quartzose gravels. Historic incision upstream of a breached mill dam since the mid- to late-20th Century has enabled Little Falls to erode and transport some of this quartzose gravel, which is commonly re-deposited on modern point bars that are set within the older deposits exposed along the banks. These recent gravel deposits are referred to here as reworked quartzose gravels. The quartzose gravels overlies a coarser-grained unit that consists mostly of cobbles and boulders in grain size, and rests directly on bedrock with a sub-planar erosional surface. This unit is referred to here as a rubble layer. The uppermost part of the sedimentary section along the stream banks typically consists of one to two meters of historic sand, silt, and clay that were deposited upstream of an 18th-century mill dam during a period of rapid soil erosion induced by widespread land clearance for agriculture, iron mining, and charcoaling (Jacobson & Coleman, 1986). This historic sediment is referred to as legacy sediment, using the terminology of Cronin et al (2003). Throughout the study area, a 0.5- to 1-m thick, dark organic-rich deposit typically occurs between the historic sediment and cobble- to boulder-sized gravel at the base of the incised stream banks. This unit is referred to as the “organic-rich” sediment. Near valley margins, another sedimentary unit occurs between the organic-rich and historic sediment. This unit is
distinctively light in color and relatively clay-rich. It also includes a thin but prominent (<6 cm) brown soil. This unit is referred to as the “light-grey sandy loam”, although its texture is variable, as discussed below. All sediments below the historic sediment are referred to collectively as pre-settlement sediments.

The modern Little Falls stream channel is generally located close to the valley margin within a relatively wide valley bottom (Figure 3). The wide valley bottom is the result of deposition of historic sediment in a shallow (~2 m) millpond upstream of a milldam during the 1700s to early 1800s. A 2.2-m rock embankment bearing the Northern Central Railroad line, which connected Baltimore, MD, to York, PA, was built atop this historic sediment along the valley corridor in the mid-1830s. This was extended across the valley bottom at numerous points between hillslope spurs (Figure 3). The embankment consists of large boulders of various rock types, including types not local to the area. Today, the rail line has been converted to a trail and park, but the embankment remains, so the modern stream is pinned between the embankment and bedrock valley margins in several places. As a consequence, it is unable to migrate laterally, resulting in deep incision and erosion. Deep incision along the stream channel has produced the unusually well-exposed stratigraphy that is the basis of this investigation.

**Methods**

**LIDAR & Aerial Photographs and Field Mapping**

Field data are plotted on a variety of images and databases that include LIDAR and digital orthophotos. Light-detection and ranging (LIDAR) data were obtained from Baltimore County (Baltimore County, 2008). LIDAR is generated from an instrument that emits pulses of electromagnetic energy and can be carried in a low-lying airplane flying over the earth’s surface. Travel time for the reflected pulses to the airplane-mounted sensor is processed to produce
digital topographic data of the elevation of the Earth’s surface. These data are combined with
Global Positioning System (GPS) horizontal position locations acquired by a GPS unit mounted
in the airplane. From these three coordinates—the z (elevation), x (longitude), and y (latitude)—a
digital topographic map can be created of the earth’s surface. The resolution of this LIDAR data
is ~10 cm in the vertical direction, and 15 cm in the horizontal. A digital terrain model is
constructed from these data. For the Little Falls digital terrain model, the pixel resolution is 1.83
m. In ESRI’s ArcGIS, the LIDAR data can be used to create a long profile and cross sections of
the valley using the 3D Analyst extension.

In the GIS environment, orthorectified digital airphotos (i.e., orthophotos) from 2005 and
2007 were added to the spatial database. In addition, aerial photographs for 1952, 1971, and
1981 were georeferenced to the 2005 dataset. These older air photos are not orthorectified.

During field work, exposures of the pre-settlement organic-rich deposits were mapped
onto the 2005 digital orthophoto, and in some places a GPS point was surveyed (Figure 3). The
goal of this effort was to determine the distribution of the organic-rich sediment. GPS survey
points were collected for all sample sites as well as for other significant features, such as the
stump of a very large tree in the pre-settlement organic-rich sediment along the left bank of First
Mine Branch Run. Gravel imbrication directions for the gravel lobes were plotted in the GIS
environment as well.

*Characterizing the Site and Sedimentary Units*

Deep incision and eroding stream banks along the entire length of Little Falls in the study
area provide cross-sections of the landscape at different orientations with respect to the valley
and hillslopes. Along these vertical stream bank exposures, the different sedimentary units were
identified, described and sampled at three primary sites (Figure 2). A complete stratigraphic
section was described and sampled from the right bank at the furthest upstream site, referred to herein as the “Site 1”. A stratigraphic section of the pre-historic sediments was described and sampled from the left bank at an exposure below the railroad embankment, a site referred to herein as the “Site 3”. A core sample of pre-settlement organic-rich soil was taken from right bank at a site referred to herein as the “Site 5”. At a tributary junction on right bank immediately downstream of the core site (Site 4), quartzose gravel adjacent to and stratigraphically lower than the pre-settlement organic-rich soil was described. At each primary field site, field sketches were drawn and photographs were taken and later made into panoramic mosaics using Nikon software. The moist color was recorded using a Munsell soil color chart.

**Magnetic Susceptibility**

Magnetic susceptibility was measured for 10-cm increment samples at sites 1 and 3 (Figure 2). A Bartington Model MS2 Magnetic Susceptibility Meter was used. The readings are volume specific $\kappa$, which is dimensionless. Three measurements were made on each sample and averaged. The results were graphed in Excel.

**Radiocarbon Dating**

Organic samples from the organic-rich sediment were collected for radiocarbon dating (Table 1). At Site 3, samples were collected from the base (immediately above the gravel) and middle of the unit. From the core at the Site 5, samples were collected from the base and from 4 cm below the top of the unit. A small tree in growth position was sampled from the top of this unit (base of historic sediment) at the mouth of First Mine Branch Run, where it flows beneath a railroad bridge and enters Little Falls (Site 4).

The organic-rich sediment samples were examined in the lab for plant remains. Large pieces of wood and seeds were removed, and smaller organic matter was extracted while
examining samples under a microscope. The organic matter selected for radiocarbon dating was washed with distilled water in the lab, oven dried at 90 °C for 3 hours, and weighed. The dried samples were sent to Beta Analytic Inc. to be analyzed by either the Accelerator Mass Spectrometry (AMS) or the conventional radiometric process, depending on the sample mass.

Size and Imbrication Analysis for Quartzose gravels

At Site 3, fifty pebbles and cobbles from the stream bank were randomly sampled from the basal, quartzose gravel that underlies the organic-rich dark sediment. The three axes of each clast were measured with a tape measure in the field. These axial dimensions were used to calculate the “volume” of each clast based on the generalized shape of a rectangular prism.

At Sites 1 &3, the quartzose gravel occurs in a sedimentary unit with an undulatory upper boundary. The relief of these undulations was measured with a stadia rod at the gravel lobe site and with a tape measure at the Site 3. The crest of each undulation (equivalent to the period of a wave) was surveyed as GPS points at the gravel lobe site, and these points were used to calculate the approximate distance between the highest parts of each gravel “hump”, or lobe. The imbrication orientation of these gravels was measured with a Brunton compass at Site 1, and the axis lengths of the five largest pebbles were measured at each gravel lobe.

Distribution of Fine-grained Sediments

Grain size was measured using a standard sieve analysis in the laboratory for all 20 samples from the gravel lobe site. The samples were sieved using the following sieving sizes: 1) gravels and larger, greater than 12 mesh (1.70 mm, -0.75 Φ); 2) coarse sand, 12-35 mesh (1.70 mm-500 μm, -0.75-1.0 Φ); 3) mediums sand 35-80 mesh (500-180 μm, 1.0-2.5 Φ); 4) fine sands, 80-230 mesh (180-63 μm, 2.5-4.0 Φ); and 5) silt and clay, less than 230 mesh (63 μm, 4.0 Φ). Samples were taken from the top of the outcrop, at the terrace surface, down to the top of the
quartzose gravel. Each sample was 10 cm in thickness. For air-dried samples, sieves were used to separate pebbles, coarse sand, medium sand, fine sand, and silt/clay. These fractions were weighed and the weights were used to calculate percent of each size fraction.

Seed Analysis

In collaboration with Dr. William Hilgartner, a new coring device for sampling bank sediments was developed by Dr. Dorothy Merritts and Dr. Robert Walter. In May, 0.8 to 0.9 m of 25.4 cm diameter flu piping was used to form an open cylinder. A plastic lid was secured to one end of the half-cylinder. These attached parts were the sampling apparatus. At the wetland seed site, the coring device was gently pushed into the bank and a long-bladed shovel was used to separate the filled half-cylinder from the bank. The ~0.9-m thick sample was wrapped in plastic for transport to the lab. Dr. Hilgartner, an expert on Holocene seeds, divided this core into 2-cm intervals and extracted seeds from each interval. He identified these seeds to the genus, and sometimes species level.

Results

Characterizing the Site

Five distinct sedimentary units overlying bedrock are exposed along Little Falls. From bottom (oldest) to top (youngest), these are: 1) rubble--cobble- to boulder-sized rubble of angular to sub-angular schist with some quartz; 2) quartzose gravel--a thin (0.2 to 0.6-m) layer of sandy gravels to cobbles that consists predominantly of oxidized, sub-angular to sub-rounded quartz; 3) organic-rich sediment--an organic-rich loam that contains obligate wetland seeds and varies in thickness from nothing near valley margins to 1 m in the lowest parts of the valley bottom; 4) light-grey sandy loam--a light-colored loamy sand to sandy clay loam with occasional angular pebbles and cobbles that varies in thickness from 0 to ~1 m and has an undulatory
surface with a thin (~6-cm) soil; and 5) historic sediment--laminated sandy loam that coarsens upward. For Site 1, these stratigraphic units are depicted in Figure 8.

Bedrock underlies the basal rubble unit, and appears to have a beveled surface. The rubble unit rests with angular unconformity on the bedrock. Sub-rounded to sub-angular gravels to large cobbles (predominately schist clasts) are weakly cemented together within this friable and iron-stained unit. The rubble typically occurs just below the water level, and its maximum thickness is about 0.4 m. The unit also appears to be clast-supported.

The quartzose gravel overlying the rubble is predominately quartz at Site 1, and about 67% quartz at the Site 3. The other clasts present are mica schist. Most clasts are sub-rounded. More information about these gravels is discussed below.

The organic-rich sediment that overlies the quartzose gravel ranges from dark grey to dark greyish brown in Munsell color. The soil texture is predominately silt clay loam, but coarsens upward. The lower contact with the quartzose gravel is undulatory, with a maximum amplitude of 0.3 m and a wavelength of 30 m. Woody material found near this contact was radiocarbon dated, and will be further explained in the radiocarbon subsection. The organic-rich sediment fills in the low spots between the gravel lobes at both the multiple gravel deposits and Site 3s. It sometimes does not occur above the highest parts of the gravel lobes.

The light grey sandy loam also fills the low spots between the gravel lobes, and is thickest at the lowest points between the lobes. This unit fines upward from sandy loam and loamy sand to mixed silt-clay loam. The Munsell colors are mostly in the grey hues. X-ray diffraction analysis indicates this unit consists of quartz, muscovite, and kaolinite. In addition, localized iron and manganese oxide layers occur in lenses that interfinger with the fine sediment
These lenses are more common near the valley wall, and a stone line sometimes occurs above the interfingered layers.

The uppermost sedimentary unit is a finely laminated fine sand, silt, and clay. The soil texture is predominately sandy loam or loam sand, while the Munsell color is dark yellowish brown to dark greyish brown. This unit fines-upward and is about a meter thick, forming the top of the fill terrace that exists along the Little Falls valley bottom.

Two stratigraphic columns illustrate the quartzose gravel unit, organic-rich unit, and the thin brown soil at the top of the light grey sandy loam (Figures 10 & 11). The Munsell color is included in the stratigraphic columns, along with soil texture. At Site 3, massive slumping and erosion during storms in the late fall to early winter prevented characterization of the upper section of the bank. Particle size for samples from Site 1 was determined by sieving (Figure 12). The light grey unit lies just above the quartzose gravel and fines-upward from gravel to fine sands. This unit is topped by a very dark greyish brown soil that is slightly coarser than the sediment below it. Above this layer, the sediments coarsen upwards, becoming sandier at the top.

At Site 3, a crude road consisting of logs, boulders, and cobbles is present at the top of the organic-rich sediment. Just upstream at site 2, on left bank, a similar structure is found at the same stratigraphic position (Figure 13). Both sites are close to the western valley margin. The logs have ax marks and cut ends, and some of the cobbles are of non-local rock types. This road was perhaps built to enable horses, people, and wagons to cross the original marshy valley bottom. It was buried by the laminated sediments.

**Magnetic Susceptibility**

In an effort to document the anthropogenic influence on Little Falls, magnetic susceptibility is used as an approximate distinction between pre-settlement and post-settlement
sediment. Magnetic susceptibility focuses primarily on the cation nature of iron. Divalent iron is found in reducing conditions, like wetlands, while the trivalent iron occurs in oxidizing conditions. Thus, higher magnetic susceptibility values represent aerobic soils, while the lower values are wetland anoxic soils (Grimely & Vepraskas, 2000). Several works attribute these high magnetic susceptibility values in post-settlement sediments to be from human-induced magnetic enhancement of soil properties, such as widespread burning (for charcoal or land clearing) and tilling of the landscape (Oldfield et al., 1989; Grimely & Vepraskas, 2000; Ketterings et al., 2000; Walter & Merritts, 2008). The magnetic susceptibility of samples taken from two stratigraphic sections is illustrated in Figures 10 & 11 (Table 2). A graph of depth versus magnetic susceptibility reveals that the pre-settlement organic-rich sediment has low values of magnetic susceptibility. The post-settlement historic sediments maintain high magnetic susceptibility values to the top of the section.

Radiocarbon Dating

From Site 3 three samples were radiocarbon dated (Table 3). The 95% confidence interval is reported for each radiocarbon date, and the date is presented as the calibrated date. In some cases the curve has local minima, which are not included with the intercept data for the confidence intervals. (This is why multiple intercepts appear in some cases.) BetaAnalytic did the calibration. An acorn sampled approximately 1.97 m below the top of the terrace dates between 3160-2920 BP or 2900-2890 BP (two intercepts). The tree stump near the base of the organic-rich sediment dates from 4970-4810 BP or 4750-4710 BP (two intercepts). A small piece of wood at the base of the organic-rich sediment, resting directly on the relict sandy gravel, dates from 5040-4850 BP. At site 4, an in-place tree stump from the base of the stream bank yields a young radiocarbon age with multiple intercepts. The 95% confidence interval for the possible
dates are 1690-1730 AD, 1810-1930 AD, and an open-ended minimum of 1950 to present. The railroad embankment at the top of this outcrop was built atop the laminated historic sediment connecting Baltimore, MD, and York, PA, between 1831 and 1838, so the tree had to be buried before about 1831. As a result, the sample is interpreted to be either 1690-1730 AD or 1810-1831 AD. The latter of these is unlikely, because it allows only ~ 21 years for the deposition of nearly 2 meters of laminated historic sediment.

Downstream from these sites the organic-rich sediment at Site 5 was radiocarbon dated. As at the upstream sites, this organic-rich sediment is overlain by about 2 m of laminated sediment. A beaver-gnawed log from the base of the organic sediment, resting directly on the quartzose gravel, yielded a date of 5280-5160 BP, 5130-5100 BP, or 5080-4860 BP while a second sample taken about 4 cm below the top of the unit yielded an age of 1660-1960 AD. The 68% confidence interval for this date gave the following four intercepts: 1660-1770 AD, 1800-1880 AD, 1910-1940 AD, and 1950-1960 AD. Using the same reasoning as for the in-place tree stump regarding the railroad built on top of the laminated sediment between 1831 and 1838, the youngest three dates are considered improbable. Upstream, at Site 1, two pieces of wood were sampled at the top of the quartzose gravel. One sample was 1.97 m below the top of the sedimentary section, just above the top of the quartzose gravel, and yields a 95% confidence interval date of 11,250-11,100 BP. The other sample was from the base of the wetland sediment just above the gravels. It dates to 10,580-10,250 BP.

Quartzose Gravel Grain Size and Imbrication Analysis

The histogram of pebble to cobble volumes (using the three axial lengths to form a rectangular prism) is plotted as Figure 14. This plot shows the grain size of these larger clasts, in an effort to understand their depositional history. For Site 1, the five largest clasts were measured
at five separate gravel lobes. In contrast, at the Site 3 fifty random clasts were sampled. Two-thirds of the clasts at the gravel lobe site were quartz and the remainder was mica schist, except for one clast which was quartzite with casts of Skolithos linearis burrows. The largest clasts at Site 1 are larger than those at Site 3. For Site 1, imbrications orientations indicate movement from the valley wall towards the center of the valley if assuming fluvial deposition (Table 4, Figure 15).

**LIDAR & Aerial Photographs**

The LIDAR was used to generate long profiles and valley-wide cross-sections. The stream long profile for all of Little Falls shows the relation between fill terraces and historic milldams (Figure 5). Between First Mine Branch Run and the downstream railroad crossing, a small early 20th century dam remains in place (Figure 2). This dam was built within the incised Little Falls stream channel. The LIDAR data was used to form a simple cross-section for a typical reach of Little Falls is as shown in Figure 15.

The banks of Little Falls in the field reach were mapped from historic aerial photographs and 2005 digital orthophotographs. From 1952 to 2005, as much as 45.72 m of erosion occurred at the outermost parts of meander bends. Even as the stream migrated laterally, the low-flow channel maintained the same approximate width. The stream bend adjacent to the railroad embankment has undergone about 91.44 m of erosion and lateral migration (Figure 16). Field observations of these sites indicate that the high banks of historic fine-grained sediment have been removed from these eroded stretches of the stream. Coarse sand and gravel bars have been deposited at elevations lower than the original fill terrace. At high flow, the stream tops some of these gravel surfaces, so the high-flow channel is much wider than it was prior to hundreds of feet of lateral erosion.
Seed Analysis

At Site 5, the core sample of organic-rich sediment at the wetland seed site reveals a sequence of “subtle compositional changes within a relatively constant hydrologic regime (pers. comm., Dr. William Hilgartner, 2008)” that spans 5 millennia. Seeds of Carex stricta (tussock sedge), Carex stipata and several other herbaceous obligate wetland species are present throughout the organic-rich sediments. Samples below the top 10 cm of the organic-rich sediment do not contain seeds of alder and other shrubs, whereas alder is present at the top of the core. This core can be interpreted to represent a stable tussock sedge meadow into which alder began to grow during the latter part of its history. The radiocarbon sample from 4 cm below the top of this core yielded a probable age of 1660--1770 AD (see discussion above), so it is likely that alder appeared within the past ~1000 yrs.

Discussion

Interpretation of the Origin of Stratigraphic Units

The rubble layer is an interesting conundrum. How was it deposited and what conditions triggered this response? No organic matter was found in the rubble layer for age dating. The overlying quartzose gravels have a minimum age of ~10 ka and must be younger than the rubble layer. The rubble layer thus also has a minimum age of ~10 ka. Given that most of the weathered clasts are mica schist, the clasts are derived from local bedrock. This unit varies in thickness laterally and is not continuous, though where it occurs it appears to be planar. Our working hypothesis is that following the Wisconsin glacial period (circa 18 ka to 14 ka) the rubble layer could have been deposited during the ensuing rapid para-glacial warming. Para-glacial conditions can destabilize slopes and transport clasts with the increased water supply from melting permafrost. The mudflow portions of para-glacial fans have thick beds of gravels and cobbles that fine-upwards into silt (Ryder, 1971a). The distal portions of debris flows also have
the same features. The rubble layer shows similar features, if one assumes that the fines were eroded away subsequent to deposition.

The quartzose gravel deposits vary in clast grain size in relation to their proximity to the valley wall. At Site 1, the imbrication directions show that the gravels moved from the valley walls towards the valley bottom. Imbrication is normally associated with a fluvial setting, as the clast becomes aligned parallel to the stream flow. Imbrication can also occur in debris flows and under periglacial conditions. In debris flows, the clasts become aligned either parallel or perpendicular to the flow in the distal portions of the flow (Major 1998), particularly when the flow is deposited in incremental pulses. Millar notes that on moderate slopes, periglacial mass movement causes the clasts to align parallel to the hillslope (2006). Given their spatial distribution, Little Falls’ quartzose gravels are unlikely to have been deposited as channel bars, despite the fact that they fine upward. A better interpretation would be that these gravels were deposited as mass movement from the footslope. Colluvium also generally fines upward, but commonly has a pronounced stone line at the upper boundary of the deposit (pers. comm., Dr. Frank Pazzaglia, 2009). These deposits at Little Falls might have been transported as a result of para-glacial conditions after the last glacial maximum, but prior to earliest Holocene time. As with the rubble layer, the rapid shift from extreme cold to warmer temperatures at the end of the Younger Dryas might have led to melting permafrost that destabilized gravels and moved them from the uplands into the valley bottoms.

The organic-rich sediments gradually covered the gravels as wetlands expanded during the warm Holocene. Similar buried Holocene wetlands in Pennsylvania were described by Walter and Merritts (2008). Unpublished seed analysis from Site 5 show (in 2 cm increments) sedge seeds throughout the whole stratigraphic unit, with some alder towards the top (pers.
comm., Dr. William Hilgartner, 2008). Radiocarbon dates indicate that wetlands existed from ~10,500 BP to as late as ~1660-1830 AD. The aforementioned distribution of seeds suggests that the climate was fairly consistent during the wetland sediment deposition. Disconformities may be present within the wetland unit, but they are not readily observed. At Site 4, the upright tree dated to 1690 to 1730 A.D. further indicates that these wetlands were present at the beginning of European settlement. Large tree trunks, possibly of the Atlantic White Cedar, have been exhumed from the banks of First Mine branch. Today this wetland tree is rare. The seed analysis is consistent with the inferred late Holocene vegetation cover presented in Prentice et al. (1991).

Around 5,000 BP, the wetlands of Little Falls were tussock sedge meadows bordered by alder shrub-scrub, and had relatively low stream velocities. The wetlands covered the valley bottoms, with vegetation-stabilized islands and multiple “channels” among them. As described by Dr. William Hilgartner (pers. comm., 2008), “The tussock sedge meadows are obligate wetlands too wet for most tree growth but upstream they may give way to alder wetlands as the hydroperiod decreases” (pers. comm., Dr. William Hilgartner, 2008). A modern analog exists in a 2-mile reach of Marsh Creek located in Chester County, PA (Figure 17). Another type of wet, low-energy environment that provides a modern analog for this organic-rich deposit is a wet meadow, in which the entire area is vegetated, yet water freely moves through the system (Figure 18).

The light-grey layer above the organic-rich sediment is sandy and fines-upward, yet iron and manganese oxide lenses also occur in this unit. This layer also has variable thickness, with thicker portions near the valley margins. A stone line is common at its upper boundary. Kaolinite, quartz, and muscovite are the dominant minerals in this unit. The initial hypothesis for this unit was that it could be an eroded and re-deposited loess or E-horizon deposit. The loess
hypothesis is unlikely because loess consists primarily of silt-sized particles, but this unit consists mostly of sand and clay. If it were an eroded and re-deposited E-horizon, it would have to have been washed from the surrounding uplands in order to have variable thickness in outcrop. This seems unlikely because E-horizons typically are less than 0.1 m thick, while the observed deposit can be up to 0.7 m in thickness. In addition, neither hypothesis explains the presence of the iron and manganese oxide lenses.

An alternative option is that this unit is derived from saprolite. In southeastern Pennsylvania, the “saprolite formed from metaquartzite is very uniform and is composed entirely of gray, quartz sand” (Sevon, 2000). This description is consistent with the observed color and particle size of the light-colored sediment from the banks of Little Falls. Research on nearby uplands suggests that saprolite was eroded and transported downslope into the valleys during Pleistocene and Holocene time, becoming what has been referred to by others as pseudo-saprolite (Pollack et al., 2000; Sevon, 2000; Cleaves, 2000). This interpretation is consistent with the variable thickness of this unit across the field site. Pazzaglia and Cleaves’ field work on the Delta Quadrangle in Maryland showed that this /pseudo-saprolite layer has similar characteristics to the light-gray unit described here (“the same coloration, manganese and iron cementation, and induration of the deposit”), including the unusual strongly oxidized layers within the light grey unit (Pazzaglia & Cleaves, 1998). Dr. Frank Pazzaglia observed the Little Falls sediment in March, 2009, and later observed the following (pers. comm., 2009): “On the hillslopes, these deposits are always buried by coarse-grained colluvial diamictons, [just] as the Little Falls deposit was beneath that boulder stone line (Pazzaglia & Cleaves, 1998)”. In addition, the cross sections from Pollack et al.’s work show two different colored colluvia overlying the transported/pseudo-saprolite layer. A notable feature of these cross sections is that the colluvia
pinch out toward the valley bottoms. Furthermore, loess may be incorporated within the colluvium (Pollack et al., 2000). The red and brown colluvia observed by Pollack et al. (2000) do not appear in the bank outcrops of Little Falls. It is possible that this colluvium was too coarse to be moved into the valley bottoms. Another possibility is that colluvium was moved, but has weathered to lighter colored minerals. Potassium feldspar and muscovite are present in schist in the Little Falls area, and weathering of potassium feldspar yields light-colored kaolinite (Deer, Howie, & Zussman, 1971). The environmental conditions were not conducive to weathering of muscovite (Pavich, pers. com. 2009). The light grey unit at Little Falls probably is the kaolinite clay and mica residue from weathering of colluvium. As the colluvium moved downslope into the valley, it accumulated along the edges of the wetlands and sometimes buried them. In some places, this colluvium appears to have been partially buried by subsequent upward growth of the wetlands (Figure 19).

Supposing the light grey unit is the residuum of clays, quartz, and mica from colluvia, Pollack et al (2000) proposed two possible transport mechanisms for moving it downslope. The first mechanism is slopewash and the second is mass movement (e.g., creep or gelifluction), both of which might be enhanced by freeze-thaw processes (Pollack et al., 2000). Given the age of the contact between the quartzose gravel and wetland sediment of ~10 ky, the overlying light grey unit must be Holocene in age. The slopewash hypothesis is consistent with formation of a stone line; the observed variable thickness could come from winter’s freeze-thaw cycles. A possible forcing factor for the light grey unit’s transportation is the ~1.5 ky Holocene moisture cycles.

The uppermost stratigraphic unit consists of fine brown sediments that coarsen upward. This unit also shows fine lamina when naturally eroded by the stream. Radiocarbon dates reveal
that the contact between the former wetland and this unit dates to the late early 18\textsuperscript{th} Century. This date is consistent with the advent of the proliferation of mill ponds.

A prevailing hypothesis for the origin of this brown sediment has been that a meandering stream overloaded by historic sediment aggraded rapidly during early European land clearance, but the data presented here is not consistent with this interpretation of the terraces along Little Falls. One would expect a fining-upward sequence with some evidence of channel facies (Blatt \textit{et al.}, 1972). Instead, the observed coarsening upward sequence and finely laminated beds are more consistent with a lacustrine or deltaic setting. The interpretation here is that these fill terraces were formed from sedimentation in a mill pond, then incised in response to milldam breaching (Walter & Merritts, 2008).

\textit{Reconstruction of Paleogeography and History of Little Falls}

Conventionally, valleys like Little Falls produce well-defined, meandering channels. Such a channel should migrate back and forth between the valley walls, leaving a record of its movement. Point bar gravels are deposited on the lower energy side of a meander, while erosion occurs on the outside of the bend where the higher velocity is present. In high-flow events, fine sediment spills over the channel and is deposited on the floodplain. This is the traditional view for Little Falls during the Holocene, as interpreted by Jacobson and Coleman (1986) and others (Forest Encyclopedia Network, 2008). However, this model appears to be inconsistent with field observations.

From other outcrops in Pennsylvania, Walter and Merritts’s work paints a different picture for the Holocene. Valley-wide wetlands existed with many, smaller, lower velocity channels. These meadows contained “stable vegetated islands and multiple small channels. … In particular, logjams blocked channels and led to the formation of side channels and floodplain
sloughs, producing multiple anabranching channels and riverine wetlands that are stark contrast to the large, single channels that exist in these streams today (Walter & Merritts, 2008).

Leigh refutes this Holocene interpretation of streams before mill pond filling. He insists that meandering channels are the natural past conditions for the whole of the southeastern US (Leigh, 2008). Yet, his work focuses on the coastal plain in Georgia and the Carolinas, while Walter and Merritts have worked in streams from the piedmont of the mid-Atlantic. Leigh’s work is on the lower relief alluvial section of higher order rivers. Little Falls and its counterparts in Pennsylvanian are high relief areas in lower order streams. Generalizations for one type of waterway may not hold true for the other.

The abundance of pre-Holocene gravel deposits lends itself to the consideration of wandering gravel beds – an intermediate between meandering streams and anabranching streams – as a stream classification for Little Falls. This type of stream contains many branching channels with banks that are somewhat stabilized by vegetation (Wooldridge & Hickin, 2005). Braided streams can move the same sediment supply as wandering gravel beds, but the stream channels shift frequently. Meandering streams have stable banks, but have a single channel. Modern examples of wandering gravel-bed rivers exist in British Colombia, which is suggestive of the environmental conditions necessary for such rivers to exist (Wooldridge & Hickin, 2005). In a flume study designed to model the generation of meandering channels, initial vegetation of the flume and a repeated pattern of flood conditions formed stabilized banks and a dominate, irregular, sinuous channel with some, smaller branches (Tal & Paola, 2007). If Little Falls was a wandering gravel-bed stream, the water would flow between the gravel deposits with vegetation growing on the banks. The wetland would grow, filling in the depressions between the banks. Once buried by legacy sediment, one would expect to find paleo-channels. However, such
channels are not exposed along the banks of Little Falls, nor do the imbrication directions of the quartzose gravel deposits suggest any water transportation as exhibited by wandering gravel-bed rivers.

Inference of Landscape Response to Climate Changes

The rubble layer is thought to have originated under possibly para-glacial conditions, immediately after the Last Glacial Maximum. This layer could have been deposited through mass movement. The quartzose gravels are alluvial and colluvial lobes from nearby valley walls. These clasts were possibly moved during para-glacial conditions, most likely the melting following the Younger Dryas. Conditions of the earliest Holocene are unclear due to the contact between the light grey sandy loam and the wetland. The outcrops do not reveal if the light grey sandy loam truncates the organic material nor has anything been found to date in the upper sections of this layer. The light grey sandy loam comes from saprolite-derived colluvium, moved though slopewash or frost-creep/gelifluction as upland material migrated to the valley bottoms. The iron and manganese oxides come from geochemical interactions with this layer at springs along valley margins. Wetlands began to flourish, especially towards the mid-Holocene. Little Falls did not have well-defined stream banks. There was no sharp delineation between the sedge wetland and the stream. Relatively stable climate conditions existed during the late Holocene. Sometime during early European colonization, a road was built across Little Falls. Bog iron was mined from nearby tributaries, and by the early 18th century, the proliferation of water-mills caused fine-grained sediment to be deposited in the slackwater behind its dams. In the 1830’s a railroad was built on the legacy sediment. The confluence of First Mine Branch with Little Falls changed, while downstream a second dam was built between within the lower reaches of the
field site. By 1952, both dams had breached – causing the high rates of bank erosion observed since that time.

**Conclusion**

Deposition of the sediments now exposed along the banks of Little Falls has been influenced by numerous factors that include bedrock geology, climate, vegetation, topography, and land use. Both climate and vegetation changed significantly during latest Pleistocene and Holocene time. Vegetation and land “use” have changed especially during the past three centuries since European settlement.

The distribution and stratigraphy of sediments exposed in the stream banks along Little Falls suggest that as a result of permafrost thawing after the Last Glacial Maximum (~18,000 BP) clastic material moved into the piedmont valley bottom. The time of origin of these lower deposits is not well-defined. After the Younger Dryas (12,700-11,500 BP), tussock sedge wetlands were established. From 5,000 BP to the early 18th Century, these wetlands were stable. The light grey sandy loam’s relation to the wetland is complex. In some places, this layer is above the wetland soil, while in others it is below the organic material (Figure 20). However, it clearly is a hillslope colluviums deposit. After the early 1700’s, mill dams and their ponds irrevocably changed the landscape – causing today’s two-meter banks and high erosion rates.

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University aided and explained during several work days. Thank you Karen Mertzman ‘01 for doing the XRD analysis on samples from the Site 1. Among my peers, I would also like to thank Stacey Sosenko ‘09, Franklin Dekker ’10, Laura Kratz ‘11, and Katie Datin ‘11 for their help in processing samples in the lab. Stacey did exceptional magnetic susceptibility work. Laura did the sieving for the grain size analysis, while Katie worked with me on the rough estimate of soil textures and Munsell colors for Site 1. Franklin did the soil textures and Munsell colors for the Site 3. Thank you to Dr. Frank Pazzaglia, Dr. Craig Kochel, Allen Gellis, others who attended the March field trip to Little Falls, and Milan Pavich; without your lively discussions and feedback, the conclusions about the saprolite would not have been drawn. Finally, thank you to my parents for their love, support and proof-reading of the thesis.
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Appendix of Figures and Tables

Figure 1. Location map for Little Falls, MD. 36
Figure 2. 2005 Orthophotograph with field sites, 1952 stream banks, and cross-section line. 37
Figure 3. LIDAR image of Little Falls with wetland outcrops noted. 38
Figure 4. Tectonic comparison of the east coast and west coast. 39
Figure 5. Long profile of Little Falls, MD. 40
Figure 6. Camp Century ice core δ¹⁸O as a temperature proxy. 41
Figure 7. Mill pond filling. Figure drawn by Franklin Dekker ’10. 10
Table 1. Samples collected for potential radiocarbon dating. 42
Figure 8. Figure of all the stratigraphic units. 43
Figure 9. Iron and manganese oxides lenses. 44
Figure 10. Stratigraphic column for Site 3. 45
Figure 11. Stratigraphic column for Site 1. 46
Figure 12. Grain size analysis from the multiple gravel deposits trench. 47
Figure 13. Photograph of buried road, presumed to be colonial. 48
Table 2. Magnetic susceptibility data for Site 1 and Site 3. 49
Table 3. Radiocarbon dates for organic samples during the 2008-2009 academic year. 48
Figure 14. Histogram of quartzose gravel volumes. 50
Table 4. Imbrication directions from Site 1. 51
Figure 15. Plotted imbrications directions. 51
Figure 16. Representative cross section for Little Falls. 52
Figure 17. Stream bank erosion since 1952. 53
Figure 18. Marsh Creek, modern analog for pre-settlement Little Falls. 53
Figure 19. A wet meadow from New Jersey, another possible analog for Little Falls. 54
Figure 20. Contact between the saprolite-derived unit and the wetland, Big Spring Run. 54
Figure 21. Complied stratigraphic column for Little Falls. 55
Figure 1. General location map for Little Falls. (Images created in Google Earth.)
Figure 2. Detailed location map for the Little Falls field site using the 2005 orthophotograph. Included are the field site labels, location of representative cross section, and the 1952 stream banks.
Figure 3. LIDAR data (color-relief with warm colors as highs, and cool ones as lows) of Little Falls field area. The 1952 stream banks represents the top edge of the stream bank on 1952 aerial photos.
Mid-Atlantic Piedmont Tectonic Setting:

Figure 4. Relief of the east and west coast of the US. The west coast transect is from the San Francisco Bay across the Sierra Nevada Mountains. The east coast transect is along Mason-Dixon line from western Pennsylvania to Delaware Bay.
Figure 5. Long profile of Little Falls with terrace surface in green and water surface in blue. The horizontal scale is the distance from the confluence with Gunpowder Falls. The location of this cross section is shown in Figure 2.
Figure 6. The $\delta^{18}O$ signal from the Camp Century ice core. As a 1st order approximation, the larger $\delta^{18}O$ values occur with warmer temperatures. The image is modified from that included in Zachary Sharp’s Principles of Stable Isotope Geochemistry.
Table 1: Collected samples for potential radiocarbon dating.

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<td>2.00</td>
<td>leaf</td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>2/8/2009</td>
<td>12:50 PM</td>
<td>approx. at water level (2.10)</td>
<td>wood; might be in gravel unit</td>
<td>26.3</td>
</tr>
</tbody>
</table>
Figure 8. The multiple gravel deposits site with all the stratigraphic units present. Numbers refer to stratigraphic units described in text: 1) Bedrock, 2) Rubble layer; 3) Quartzose gravel; 4) Organic-rich sediment; 5) Light grey sandy loam; and 6) Legacy sediment.
Figure 9. Interfingering oxidized iron and manganese layers with the saprolite-derived layer. Photo comes from slightly upstream of Site 1.
Figure 10. Stratigraphic column Site 3. Notice that radiocarbon dates and the magnetic susceptibility are included.
Figure 11. Stratigraphic column for the Site 1. Notice that radiocarbon dates and the magnetic susceptibility are included.
Figure 12. Grain size analysis for Site 1. Note that the first meter of sediments is legacy sediments. The next six centimeters are the paleosol, followed by the light grey sandy loam.
Figure 13. Buried road presumed to be colonial in age. Notice the axed ends of the wood logs.

Table 3. Radiocarbon dates for samples collected during the 2008-2009 academic year.

<table>
<thead>
<tr>
<th>Depth from Top of Terrace (m)</th>
<th>Description of Organic Matter</th>
<th>Conventional Radiocarbon Age (BP)</th>
<th>2 Sigma Calibrated Age Interval (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.02</td>
<td>tree</td>
<td>4290 ± 60</td>
<td>4710-4750 or 4810-4970</td>
</tr>
<tr>
<td>2.16</td>
<td>woody bits on quartz cobble clast</td>
<td>4360 ± 40</td>
<td>4859-5040</td>
</tr>
<tr>
<td>1.97</td>
<td>acorn</td>
<td>2890 ± 40</td>
<td>2920-3160 or 2890-2900</td>
</tr>
<tr>
<td>approx. on rubble deposit</td>
<td>tree root; in growth position</td>
<td>40 ± 50</td>
<td>260-220 or 140-20 or 0</td>
</tr>
<tr>
<td>1.97</td>
<td>wood; 10 cm upstream of magnetic susceptibility trench</td>
<td>9760 ± 60</td>
<td>11250-11100</td>
</tr>
<tr>
<td>approx. at water level (2.10)</td>
<td>wood; might be in gravel unit</td>
<td>9260 ± 60</td>
<td>10580-10250</td>
</tr>
</tbody>
</table>
### Table 2. Magnetic Susceptibility of Sites 1 and 3.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Depth from Top of Terrace (cm)</th>
<th>Date</th>
<th>Time</th>
<th>Reading (κ x 10^{-5})</th>
<th>Miscellaneous Field Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-10</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>96.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10-20</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>75.4</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20-30</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>47.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>30-40</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>52.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>40-50</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>53.2</td>
<td>Charcoal/Coal</td>
</tr>
<tr>
<td>1</td>
<td>50-60</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>41.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>60-70</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>64.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>70-80</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>24.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>80-90</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>14.4</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>90-110</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>100-110</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
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<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>120-130</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>130-140</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>7.2</td>
<td>Not bank slough</td>
</tr>
<tr>
<td>1</td>
<td>140-150</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>160-170</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>170-180</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>3.5</td>
<td>Increase in organics</td>
</tr>
<tr>
<td>1</td>
<td>180-190</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>1.8</td>
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</tr>
<tr>
<td>1</td>
<td>190-200</td>
<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>2.5</td>
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</tr>
<tr>
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<td>2/8/2009</td>
<td>11:31:24 AM</td>
<td>2.0</td>
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</tr>
<tr>
<td>3</td>
<td>bottom (170-180)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>middle (170-180)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>top (170-180)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>8.8</td>
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</tr>
<tr>
<td>3</td>
<td>bottom (160-170)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>middle (160-170)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>11.3</td>
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</tr>
<tr>
<td>3</td>
<td>top (160-170)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>bottom (150-160)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>middle (150-160)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
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</tr>
<tr>
<td>3</td>
<td>top (150-160)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>bottom (140-150)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>middle (140-150)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>79.8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>top (140-150)</td>
<td>9/30/2008</td>
<td>12:00:00 AM</td>
<td>50.7</td>
<td></td>
</tr>
</tbody>
</table>
Figure 14. Histogram of bank gravels volumes if axes measured are used to form a rectangular prism. Clasts from Site 3 are a random sample of fifty clasts, while those from Site 1 are the twenty-five largest. This histogram is intended to show general trends among the largest clasts.
Table 4. Imbrication Directions for Site 1 starting the furthest upstream.

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Date</th>
<th>Imbrication Direction Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>189</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>136</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>125</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>245</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>153</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>150</td>
</tr>
<tr>
<td>Site 1</td>
<td>10/21/2008</td>
<td>105</td>
</tr>
</tbody>
</table>

Figure 15. Plotted imbrication directions.
Figure 16. Representative cross section looking upstream showing most of the stratigraphic units. Note railroad embankment on mill pond sediment around 1600 ft.
Figure 17. Stream bank erosion at Little Falls between 1952 and 2005. Banks outlined in bright red, while the 2008-2009 sampling sites are yellow dots.

Figure 18. Marsh Creek, PA on March 19, 2009. This site somehow missed being covered by legacy sediment. Therefore this can act as a modern analog for the pre-settlement Holocene at Little Falls’s.
Figure 19. Wet meadow from New Jersey.

Figure 20. Big Spring Run in PA showing the lateral transition from the saprolite-derived layer to the wetland sediment (left to right). Note that legacy sediment covers both features.
Figure 21. Compiled stratigraphic column for the whole Little Falls field area. Note that the light grey sandy loam and the wetland sediment are contemporaneous with each other and topped by the paleosol.