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Understanding Lower Neshaminy Creek Direction Change and Barbed Tributary Evidence, Bucks County, Pennsylvania, USA

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Abstract

Neshaminy Creek is located in southeast Pennsylvania (USA) and flows in a southeast direction through a series of incised meanders roughly parallel to the nearby southeast-oriented Delaware River before turning to flow in southwest, south, northeast, and south directions before reaching the Delaware River, which has also abruptly turned to become a southwest-oriented river. Throughout their parallel southeast-oriented courses northeast-oriented barbed tributaries join both the Delaware River and Neshaminy Creek and shallow northeast- to southwest-oriented through valleys cross the Delaware River-Neshaminy Creek drainage divide. These drainage features formed when massive southwest-oriented floods of possible glacial melt water origin flowed across southeast Pennsylvania. The deep southwest-oriented Delaware River channel segment first eroded headward along what was probably a major southwest-oriented flood flow channel and the southeast-oriented Neshaminy Creek valley then eroded headward from it to capture southwest-oriented flood flow with the southeast-oriented Delaware River valley segment next eroding headward across the same southwest-oriented flood flow. Northeast-oriented (and barbed) Neshaminy Creek and Delaware River tributaries and the northeast-oriented Neshaminy Creek channel segment were developed by reversals of flow on northeast ends of beheaded southwest-oriented flood flow channels.

Keywords: barbed tributary, Delaware River, elbow of capture, incised meander, through valley

1. Introduction

Neshaminy Creek is located in the southeastern Pennsylvania where it begins at the confluence of its southwest-oriented North Branch and southeast- and northeast-oriented West Branch and then flows in a southeast direction through a series of incised meanders before making abrupt direction changes to flow in southwest, south, and then northeast directions. Finally Neshaminy Creek turns in a southeast and south direction to join the southwest-oriented Delaware River. The Neshaminy Creek drainage basin is 236.5 square miles (612.5 square kilometers) in size of which 86% is located in Bucks County with remaining 14% located in Montgomery County (McCarren, 1972) and is entirely located in the southeast Pennsylvania Piedmont Province (see Potter, 1999). Figure 1 shows theNeshaminy Creek drainage route and the adjacent southeast- and southwest-oriented Delaware River. Note how the Delaware River and Neshaminy Creek flow in roughly parallel directions before the Delaware River turns abruptly to flow in a southwest direction and to be joined by Neshaminy Creek and other south-oriented streams. Also note how in its lower reaches Neshaminy Creek makes a jog to the southwest and then after flowing in a south direction jogs again this time in a northeast direction. Not easily seen in figure 1 are northeast-oriented barbed tributaries joining both Neshaminy Creek and the Delaware River and the asymmetric Delaware River-Neshaminy Creek divide. The abrupt Neshaminy Creek direction changes, multiple barbed tributaries, the asymmetric Delaware River-Neshaminy Creek divide,and the abrupt Delaware River direction change raise questions for geomorphologists trying to understand the regional drainage history. For example why does the Delaware River change direction after flowing in a southeast direction parallel to nearby Neshaminy Creek? And why does southeast-oriented Neshaminy Creek make abrupt direction changes to flow in southwest and northeast directions before turning to reach the southwest-oriented Delaware River?

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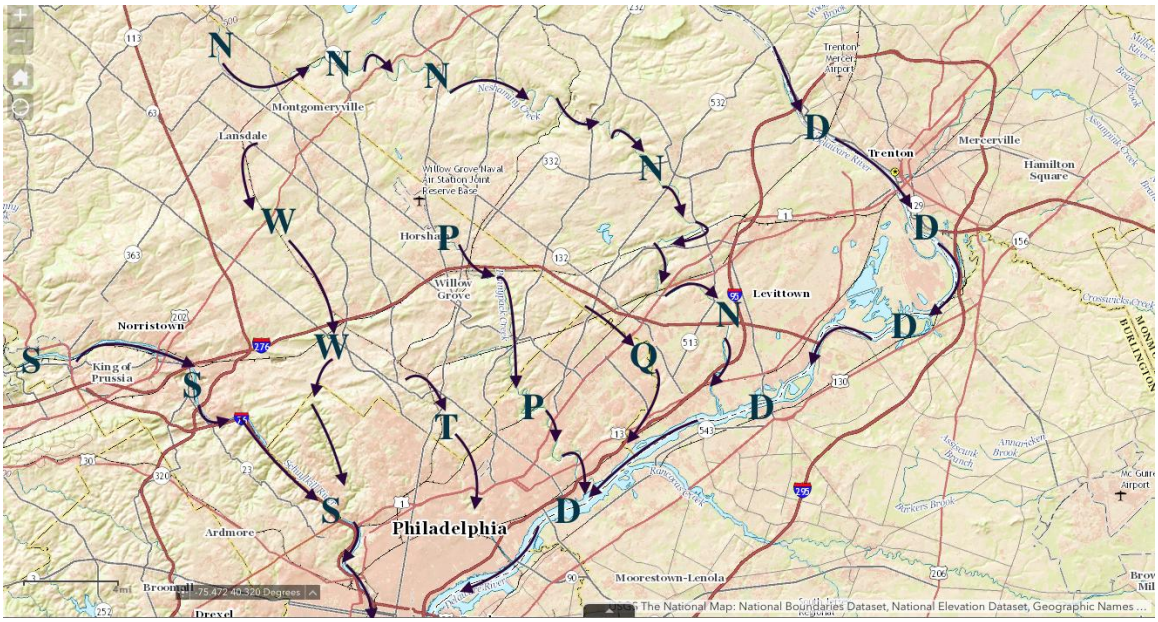

Figure 1: Location map modified from a United States Geological Survey (USGS) National Map website map by adding letters and arrows to identify drainage routes and flow directions. "D" identifies the Delaware River, "N" Neshaminy Creek, "Q" Poquessing Creek, "P" Pennypack Creek, "T" Tookany (Tacony) Creek, "W" Wissahickon Creek, and "S" the Schuylkill River. Latitude and longitude given on the black bar are 75.472 and 40.320 degrees. The scale line in the southwest corner represents 4 miles (6.44 km).

2. Literature Review

To answer their questions geomorphologists must first determine what type of drainage system existed previous to Neshaminy Creek drainage basin erosion. However, because early workers did not have detailed topographic maps or even complete coverage by the less detailed maps of their time, they focused their attention on major rivers and neglected smaller, but still locally important streams such as Neshaminy Creek. For example theclassic1889 Davis paper titled, "The rivers and valleys of Pennsylvania" made use of sediment evidence indicating Appalachian region late Permian drainage had been to the northwest. Davis then attempted to explain how northwest drainage was reversed to produce southeast-oriented rivers. Problems with the Davis theory led Johnson in 1931 to suggest a Cretaceous sea transgression obliterated the original drainage and deposited a marine cover over the entire region. He proposed southeast-oriented rivers are superposed descendants of consequent streams that had developed on a Cretaceous cover mass after the Cretaceous sea had withdrawn. Five years later problems with Johnson's theory led Meyerhoff and Olmstead (1936) to argue the southeast-oriented rivers originated in Permian time on slopes and surfaces developed during Appalachian folding. Strahler (1945) found major problems that led him to reject all known theories, except Johnson's superposition theory, for which he could find no supporting evidence.

These early studies focused entirely on large southeast-oriented rivers originating in or flowing through the Appalachians and then across the Piedmont Province to reach the Atlantic Ocean and made little or no effort to address origins and the development of smaller yet locally important streams such as Neshaminy Creek or to address sediment evidence that suggested a large late Cenozoic southwest oriented river had once flowed near the Coastal Plain-Piedmont Province boundary. More recent workers, while still neglecting somewhat smaller streams such as Neshaminy Creek, tried to address the southwest-oriented river omission and Braun et al (2003) state, "When the entire assemblage of wind and water gaps in the region are examined and tied to the Coastal Plain sedimentary record the [southeast-oriented] Delaware River appears to be a relative latecomer, occupying the gap in Miocene to even early Pleistocene time…. More significantly, the upper Cenozoic stratigraphy and sedimentology of the lower Delaware valley and Coastal Plain indicates that the Hudson River drained through that region and the Delaware was a very minor tributary of that system until the Plio-Pleistocene."

Evidence for the major late Cenozoic southwesterly flowing river located approximately along the Coastal Plain-Piedmont Province boundary includes the Bridgeton and Pensauken Formations of late Cenozoic age (Owens and Minard, 1979, Stanford, 1997, and Stanford, 2010). Pensauken sediments cover some Neshaminy Creek drainage basin areas downstream from the abrupt Neshaminy Creek direction changes (McCarren, 1972)and provide evidence that a large late Cenozoic southwesterly flowing river once crossed what is today the southern Neshaminy Creek drainage basin. Mapped Cenozoic sediments of any type covering higher elevation Triassic and early Paleozoic and Precambrian southeast Pennsylvania Piedmont Province bedrock, including all upstream Neshaminy Creek drainage basin areas, are sparse (e.g. Bascom et al, 1909) and include isolated sand and gravel deposits known as the Bryn Mawr Formation. Owens (1999) reports, "The Bryn Mawr is a fluvial deposit…[but] not enough is known about the Bryn Mawr to speculate about the nature of the river, or rivers, that deposited the gravel." While mapped Pensauken sediments provide evidence a large southwest-oriented river once flowed across what are now the southernmost Neshaminy Creek drainage basin areas and Bryn Mawr sediments provide evidence that some type of drainage once crossed much, if not all, of the present day upstream Neshaminy Creek drainage basin additional evidence for pre-Neshaminy Creek drainage history must be obtained from regional erosional landforms. Detailed topographic maps provide an excellent resource from which erosional landform evidence can be interpreted. Clausen (2016a, 2016b, 2016c, and 2017) used topographic map interpretation methods to determine that large southwest-oriented floods eroded the south-oriented Pennypack, Tookany(Tacony), and Wissahickon Creek drainage basins and three north-oriented water gaps, which are all located west of the Neshaminy Creek drainage basin. Those southwest-oriented floods should have also crossed the Neshaminy Creek drainage basin. The study reported here tests that prediction by using detailed topographic maps to analyze Neshaminy Creek erosional landforms.

3. Analysis of Specific Landform Features

3.1 Asymmetric divide between the Delaware River and Neshaminy Creek

Figure 2 illustrates the southern end of the asymmetric Delaware River-Neshaminy Creek drainage divide. The figure is modified from the 1890 United States Geological Survey 1:62,500 scale Burlington Pennsylvania-New Jersey topographic map by adding letters, arrows, and numbers so as to better identify major drainage routes, flow directions, and points discussed in the text.[The 1890 map was chosen to illustrate southwest-oriented Rock Run-Common Creek, which is labeled "R" in figure 2, and which has more recently been buried under urban development.] Rock Run-Common Creek headwaters are located almost on the edge of the 80-foot (24-meter) deep southeast oriented Delaware River valley rim(just north of number "1")and immediately west of Trenton, New Jersey. Rock Run-Common Creek flows in a southwesterly direction to join the southwest-oriented Delaware River near Tullytown, Pennsylvania. The asymmetric Delaware River-Rock Run-Common Creek drainage divide seen at number "1" and the southwest-oriented Rock Run-Common Creek drainage route suggest the southeast-oriented Delaware River valley at Trenton, New Jersey eroded headward across southwest-oriented water moving to the downstream southwest-oriented Delaware River valley. Number "2" is located on a northeast-to-southwest oriented erosional ridge located between the southwest-oriented Rock Run-Common Creek drainage basin and a northeast-to southwest-oriented through valley used by the railroad at location "4".

The number "3" is on the divide between the southeast oriented Delaware River and a southwest oriented tributary to southwest-oriented Core Creek, which joins Neshaminy Creek near number "5". Note how the Core Creek drainage basin originates near the Delaware River valley edge suggesting the southeast-oriented Delaware River valley eroded headward across southwest-oriented flow also moving water to the Neshaminy Creek valley. The railroad at number "4" is located near the southeast margin of a shallow northeast-to-southwest oriented through valley linking northeast and north oriented Brock Creek with southwest- and south-oriented Mill Creek (east), which joins the southwest-oriented Delaware River at Bristol. The floor of this northeast-to-southwest oriented through valley extends north of the railroad to the southwest-oriented Core Creek valley suggesting that an extensive sheet of southwest-oriented water crossed what is now the Delaware River-Neshaminy Creek drainage divide with some of the water being captured by headward erosion of the south-oriented Mill Creek (east) valley from the southwest-oriented Delaware River valley while the remainder of the water was captured by headward erosion of the deep Neshaminy Creek valley to the number "5" location.

If so the south-oriented Mill Creek (east) valley eroded headward from the southwest oriented Delaware River valley at Bristol to the Woodbourne area and the Neshaminy Creek valley eroded headward to at least number "5" prior to headward erosion of the southeast oriented Delaware River valley across the southwest-oriented flow (the Core Creek drainage basin is further analyzed in the following section).

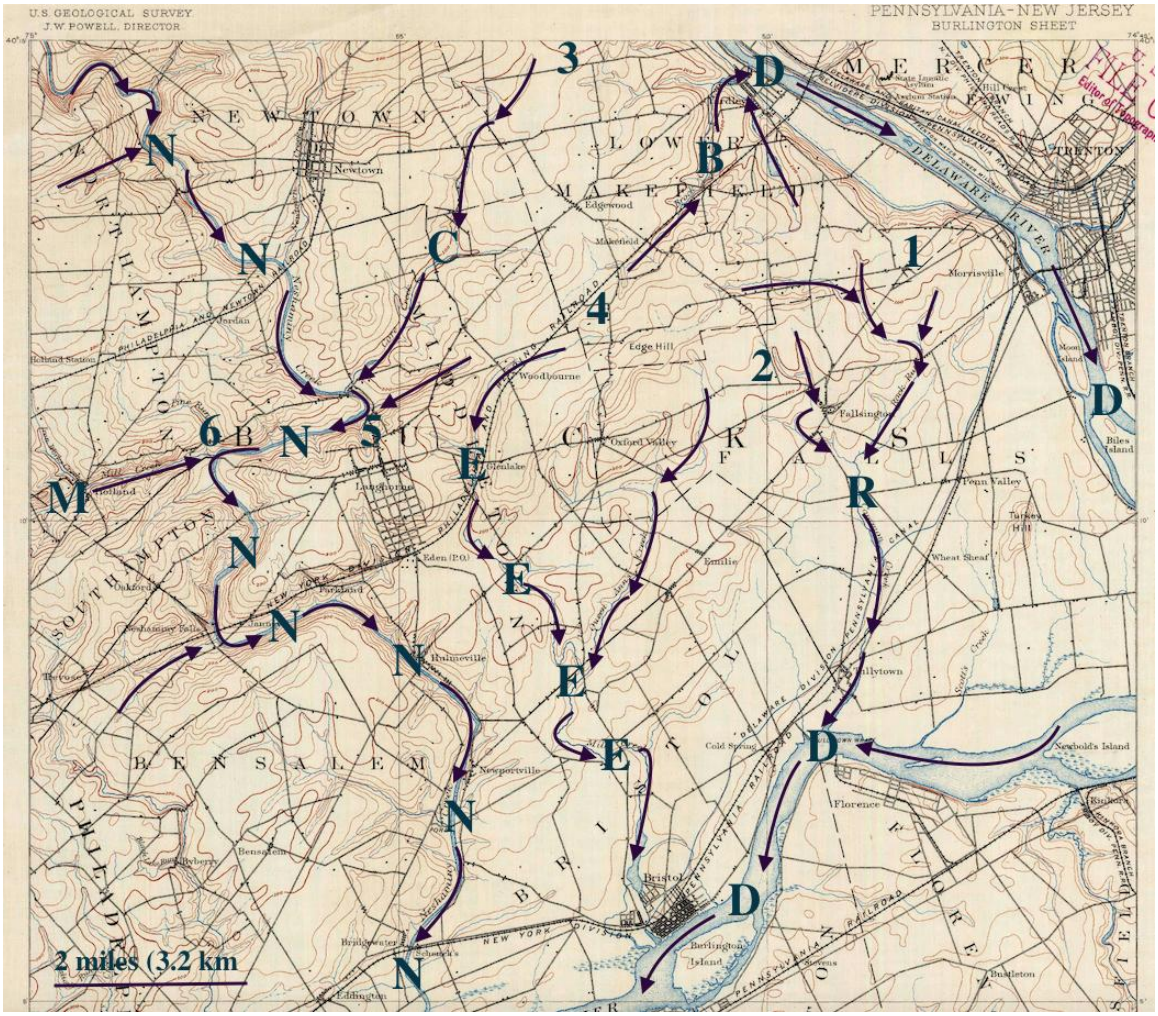

Figure 2: Drainage divide area between Delaware River and Neshaminy Creek as seen on a modified section of theUSGS 1890 Burlington (NJ-PA) 1:62,500 scale topographic map. Large letters and arrows have been added to identify drainage routes and flow directions and numbers identify locations discussed in the text. "D" identifies the Delaware River, "N" Neshaminy Creek, "M" Mill Creek, "C" Core Creek, and "B" Brock Creek. The contour interval is 20 feet (6.1 meters).

3.2 Barbed tributaries flowing to the Delaware River and Neshaminy Creek

Figure 3 is modified from a map taken from the USGS National Map website to illustrate barbed tributaries flowing to the Delaware River and to Neshaminy Creek (upstream from the major Neshaminy Creek direction changes). Arrows and letters have been added to better identify major drainage routes and flow directions. Note how the southeast-oriented Neshaminy Creek segment seen in figure 3 flows in a series of bedrock-walled incised meanders and is joined by a northeast-oriented barbed tributary from the southwest and by southwest- and south-oriented tributaries from the northeast. The Delaware River segment seen in figure 3 is flowing in a southeast direction and is also joined by short northeast-oriented barbed tributaries from the southwest and by southwest-oriented tributaries from the northeast. Note how the Neshaminy Creek incised meanders include short northeast-and southwest-oriented channel segments along with more frequent southeast and south oriented channel segments.

The deep southeast-oriented Neshaminy Creek valley eroded headward across multiple shallow southwest-oriented flood flow channels and sometimes eroded headward for short distances along one of those southwest-oriented flow channels before continuing to erode headward across the southwest-oriented flood flow again. Sometimes, headward erosion of the deep Neshaminy Creek valley beheaded and reversed flow on the northeast end of a southwest-oriented flow channel. When the reversed flow was able to capture enough water from yet to be beheaded southwest-oriented flood flow channels further to the northwest the actively eroding Neshaminy Creek valley head eroded for a short distance in a southwest direction before continuing to erode headward across the southwest-oriented flow again.

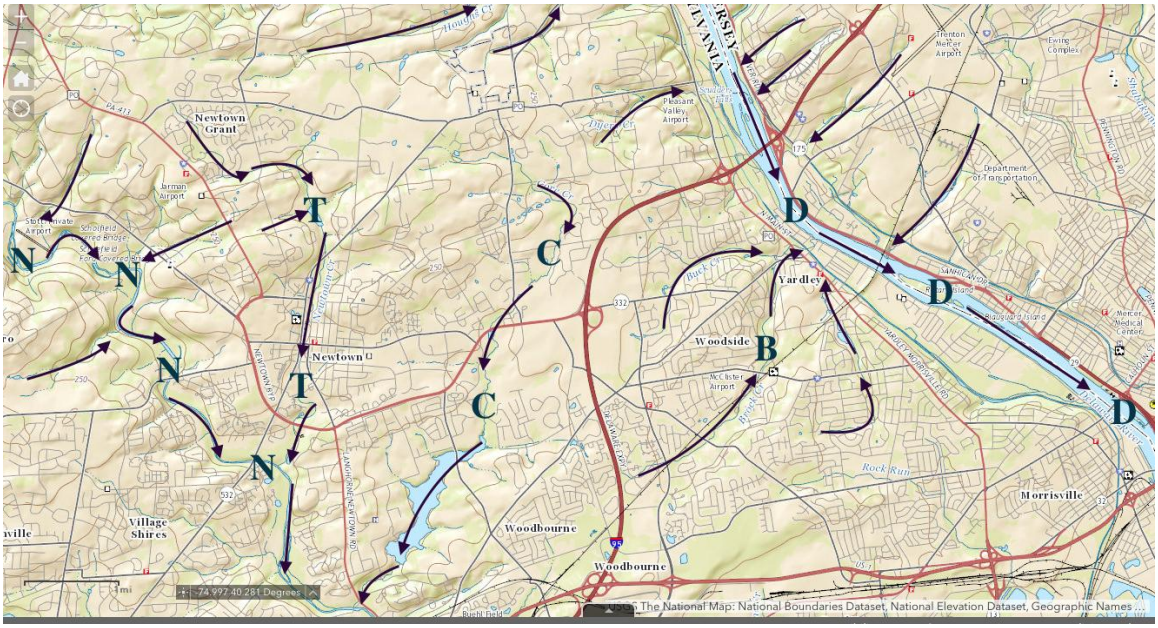

Figure 3: Map from the United States Geological Survey National Map website modified by adding letters and arrows to identify drainage routes of interest and flow directions. "D" represents the Delaware River, "N" Neshaminy Creek, "B" Brock Creek, "C" Core Creek, and "T" Newtown Creek. Scale line in southwest corner represents 1 mile (1.6 km). Contour interval is 50 feet (15.24 meters)

A more detailed explanation of drainage routes seen in figure 3 begins with large volumes of southwest-oriented water moving across the region on a low gradient surface at least as high as the highest elevations today (before any of the present day drainage routes existed). The southwest-oriented water carved shallow northeast- to southwest-oriented flow channels along zones of easy to erode bedrock, but these channels were not deep because base level was everywhere the same. The base level situation changed as the deep southwest-oriented Delaware River valley (seen in figures 1 and 2) eroded headward into the region (probably along a major southwest-oriented flow channel), which permitted the deep southeast-oriented Neshaminy Creek valley to erode headward across the southwest-oriented flow. Headward erosion of the southeast-oriented Neshaminy Creek valley enabled flow on northeast ends of some beheaded southwest-oriented flow channels to reverse flow direction and to move toward the newly eroded and much deeper Neshaminy Creek valley head. Because flow channels were beheaded in sequence from the southeast to the northwest reversed flow in newly beheaded channels captured southwest-oriented water from yet to be beheaded channels further to the northwest. Such captures enabled some reversed flow channels to erode valleys of what are today the northeast-oriented barbed Neshaminy Creek tributaries and northeast-oriented Neshaminy Creek channel segments while southwest-oriented water moving into the newly eroded and deep Neshaminy Creek valley eroded the southwest-oriented tributary valleys and southwest-oriented Neshaminy Creek channel segments. This zigzag erosion process continued as headward erosion of the deep Neshaminy Creek valley progressed in a northwest direction across multiple much shallower southwest-oriented flow channels. The south-oriented Newtown Creek valley eroded headward from the newly eroded southeast-oriented Neshaminy Creek valley and beheaded and reversed flow channels leading to what was at that time the newly eroded Neshaminy Creek valley.

Note in figure 3 how a through valley north of Newtown is drained in a northeast direction to Newtown Creek and in a southwest direction to Neshaminy Creek. Just north of that through valley Newtown Creek jogs for a short distance in a northeast direction along what was a beheaded and reversed flow channel that had once moved water to the newly eroded Neshaminy Creek valley. Southwest-oriented flow to the newly eroded Neshaminy Creek and Newtown Creek valleys ended when headward erosion of the deep southwest-oriented Delaware River valley captured the southwest-oriented flow. Valleys of the short northeast-oriented barbed tributaries to the southeast-oriented Delaware River segment seen in figure 3 were eroded by reversals of flow on the northeast ends of the beheaded southwest-oriented flow channels while southwest-oriented Delaware River tributary valleys eroded headward along captured southwest-oriented flow channels.

3.3 Southwest-oriented Neshaminy Creek channel segment

After meandering in a southeast direction Neshaminy Creek turns abruptly to flow approximately 2 km (1.2 miles) in a southwest direction on the floor of a northeast-to-southwest oriented through valley. East of the Neshaminy Creek abrupt direction change the through valley extends to the Delaware River and a short southwest-oriented tributary drains the through valley to the southwest-oriented Neshaminy Creek segment while northeast-oriented Brock Creek ("B" in figure 2) drains the through valley to the southeast-oriented Delaware River. The through valley is at location 4 in figure 2and was eroded by southwest-oriented water moving from New Jersey to what at that time was the newly eroded and much deeper Neshaminy Creek valley. Headward erosion of the deep southeast-oriented Delaware River valley captured the southwest-oriented flood flow and caused a reversal of flow that eroded the Brock Creek valley. West of the southwest-oriented Neshaminy Creek segment the through valley is drained by Mill Creek (west), which as seen in figures 2 and 4 flows in a northeast direction to join southwest-oriented Neshaminy Creek as a barbed tributary at the point where Neshaminy Creek abruptly turns to leave the through valley and to flow in a south and southeast direction. Clausen (2017, 2016c) describes how west of the northeast-oriented Mill Creek (west)channel segment the through valley continues in a southwest direction across the Neshaminy-Pennypack drainage divide to reach the south-oriented Pennypack Creek valley, and next across the Pennypack-Wissahickon drainage divide to reach the south-oriented Wissahickon Creek valley, and finally across the Wissahickon-Schuylkill drainage divide to reach the southeast-oriented Schuylkill River valley.

This majornortheast- to southwest-oriented through valley follows the contact between Precambrian felsic gneiss to the southeast and Triassic age Stockton Formation arkosic sandstone to the northwest(Lyttle and Epstein, 1987) and was first developed as a shallow low gradient flow channel on a topographic surface at least as high as the present day Neshaminy-Pennypack and Pennypack-Wissahickon drainage divides. Deep erosion of this shallow low gradient flood flow channel occurred in stages as deep south-oriented valleys eroded headward across it. Headward erosion of the deep south-oriented Wissahickon Creek valley captured water moving in the southwest-oriented flood flow channel to the southeast-oriented Schuylkill River valley and diverted that water in a south direction to flow through what is today the Wissahickon Creek gorge. The deep Wissahickon Creek valley provided a much lower base level, which enabled the southwest-oriented flow to erode a deeper through valley floor headward in a northeast direction. Next headward erosion of the deep Pennypack Creek valley captured water moving in the southwest-oriented flood flow channel and diverted the water in a south direction to the southwest-oriented Delaware River valley. The lower elevation Pennypack Creek valley base level again enabled southwest-oriented water to further erode a deeperflood flow channel floor headward in a northeast direction. Headward erosion of the Neshaminy Creek valley then captured southwest-oriented water moving in the flood flow channel and the actively eroding Neshaminy Creek valley head then began to erode headward in a northeast direction along the flood flow channel floor.

Northeast-oriented Mill Creek (west) joins Neshaminy Creek at an elbow of capture where headward erosion of the deep southeast-oriented Neshaminy Creek valley captured flood flow in what at that time was a shallow and low gradient and southwest-oriented flood flow channel. Capture of the southwest-oriented flow beheaded and reversed flow at the northeast end of that southwest-oriented flood flow channel so as to create what is today the northeast-oriented Mill Creek (west) drainage route, which today joins Neshaminy Creek at its elbow of capture (where it turns from flowing in southwest direction to flow in a southeast direction).

Mill Creek (west) has south-oriented headwaters and a major south-oriented tributary (Ironworks Creek) that captured southwest-oriented flood flow moving north of the then actively eroding southwest-oriented Neshaminy Creek channel segment (at that time the southeast-oriented upstream Neshaminy Creek valley did not exist). Capture of that northern flood flow enabled reversed flow on the Mill Creek (west) alignment to erode the deep northeast-oriented Mill Creek (west) valley, which today joins Neshaminy Creek as a barbed tributary.

Headward erosion of the deep southeast-oriented Delaware River valley next captured southwest-oriented flood flow moving to the actively eroding southwest-oriented Neshaminy Creek valley segment, however southwest-oriented flow moving north of the actively eroding Delaware River valley head and north of the newly eroded southwest-oriented Neshaminy Creek valley segment enabled headward erosion of the deep southeast-oriented upstream Neshaminy Creek valley from the southwest-oriented Neshaminy Creek valley segment to proceed faster than the Delaware River valley was able to behead southwest-oriented flow channels to that actively eroding Neshaminy Creek valley head. These observations and interpretations strongly suggest headward erosion of the Neshaminy Creek and southeast-oriented Delaware River valleys must have occurred during the same massive southwest-oriented flood flow events.

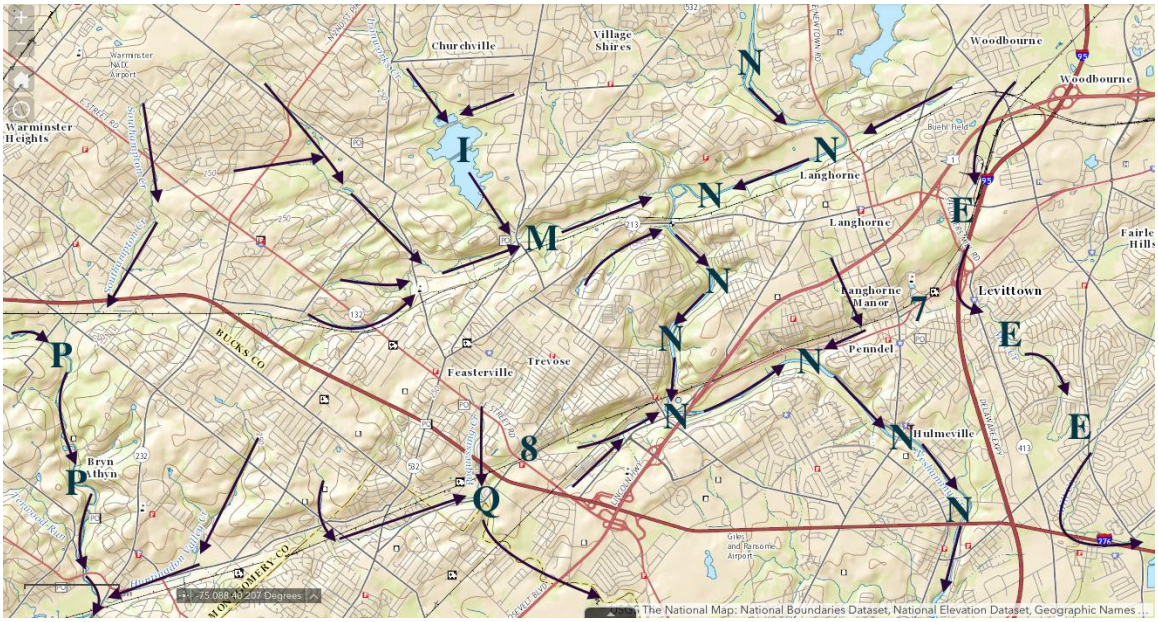

Figure 3: Map showing Neshaminy Creek direction changes downstream from figure 3modified from a United States Geological Survey National Map website map by adding letters and arrows to identify drainage routes of interest and flow directions. "N" represents Neshaminy Creek, "M" Mill Creek (west), "E" Mill Creek (east), "I" Ironworks Creek, "Q" Poquessing Creek, and "P" Pennypack Creek. Scale line in southwest corner represents 1 mile (1.6 km) and the contour interval is 50 feet (15.24 meters)

3.4 Neshaminy Creek valley between its southwest- and northeast-oriented segments

Between the southwest-oriented Neshaminy Creek channel segment and its northeast-oriented channel segment the Neshaminy Creek valley has been eroded across a northeast-to-southwest oriented belt of gneiss and quartzite bedrock. As already described Neshaminy Creek after leaving its southwest-oriented channel segment first is oriented in a southeast direction as its valley is cut across the regional geologic structures. However the Neshaminy Creek valley subsequently turns in a southwest and then south direction to reach its northeast-oriented channel segment. The southwest-oriented channel segment in this region of gneiss bedrock was also eroded headward along a shallow southwest-oriented flood flow channel. Note in figure 4 a short southwest-oriented tributary joining Neshaminy Creek at the point where Neshaminy Creek turns from flowing in a southeast direction to flow in a southwest direction.

A south- and east-oriented tributary can be seen joining Neshaminy Creek at the southwest end of this short southwest-oriented valley segment suggesting a reversal of flow on the northeast end of the beheaded southwest-oriented flood flow channel and capture of yet to be beheaded southwest-oriented flood flow moving across regions to the north and west. The Neshaminy Creek turn from being southwest-oriented to being south-oriented represents another elbow of capture where headward erosion of the deep south-oriented Neshaminy Creek valley captured what was at that time a shallow southwest-oriented flood flow channel.

3.5 Northeast oriented Neshaminy Creek channel segment

The one-mile (1.6 km) long northeast-oriented Neshaminy Creek channel segment is located in another northeast-to-southwest oriented through valley. East of the Neshaminy Creek drainage basin this secondmajor through valley extends across the Neshaminy-Mill Creek (east) drainage divide at location "7" (in figure 4) and to the west the through valley extends across the Neshaminy-Poquessing Creek drainage divide at location "8" and then across the Poquessing-Pennypack Creek drainage divide. Continuing further west the through valley extends across the Pennypack Creek drainage basin beyond figure 4 to the south oriented Wissahickon Creek valley and then still further west to the Schuylkill River valley. The through valley is located along a northeast-oriented fault line where Wissahickon Formation metamorphic rocks (e.g. schist, phyllite, and gneiss)were moved over Cambrian age quartzite (Lyttle and Epstein, 1987). The fault line provides a zone of easier to erode bedrock material and prior to headward erosion of the deep Neshaminy Creek valley was the location of another shallow and low gradient southwest-oriented flood flow channel.

When headward erosion of the deep Neshaminy Creek valley reached this southwest-oriented flood flow channel it captured the southwest-oriented flood flow and also reversed flow on the beheaded channel's northeast end. Headward erosion of the south-oriented Mill Creek (east) valley then captured the southwest-oriented flow ending headward erosion of a deep southwest-oriented valley. Note how a short southwest-oriented tributary joins the northeast-oriented Neshaminy Creek channel at the point where Neshaminy Creek turns to flow in a southeast direction. Reversed flow on the northeast end of the beheaded southwest-oriented flood flow channel was more successful in capturing southwest-oriented flood flow moving north of the actively eroding Mill Creek (east) valley head. The deep Neshaminy Creek valley head eroded headward in a southwest direction along the reversed flow channel and then to the north across the quartzite and gneiss bedrock zone as it captured southwest-oriented flood flow still moving north of the actively eroding Mill Creek (east) valley head. The short northeast-oriented Neshaminy Creek tributaries near location 8 (in figure "4") were also eroded by reversed flow on the northeast end of the beheaded southwest-oriented flood flow channel.

This second major through valley along which the northeast-oriented Neshaminy Creek channel segment is located can be used to determine the sequence in which south-oriented valleys eroded headward across it and also provide valuable information about the amount of erosion that took place as southwest-oriented flood flow crossed the region. As previously mentioned the through valley was initiated as a shallow and low gradient southwest-oriented flood flow channel moving water across a topographic surface much higher than the present day surface. Headward erosion of the southeast-oriented Schuylkill River valley from the deep southwest-oriented Delaware River valley significantly lowered base level enabling the flood flow channel to erode a deeper channel headward in a northeast direction. Next headward erosion of the deep south-oriented Wissahickon Creek valley as described by Clausen (2016c) from the Schuylkill River valley captured the southwest-oriented flood flow and again provided a lower base level enabling the southwest-oriented flood flow channel to erode a deeper valley headward in a northeast direction. Clausen (2016b and 2017) describes how the process was repeated as the south-oriented Tookany (Tacony) Creek valley captured the southwest-oriented flow, but was unable to erode headward across the quartzite ridge and headward erosion of the south-oriented Pennypack Creek valley then captured the southwest-oriented flow and was able to erode headward across the quartzite ridge before Neshaminy Creek valley headward erosion captured the southwest-oriented flood flow. Following the Pennypack Creek valley capture of the flood flow Poquessing Creek valley headward erosion captured flow in the southwest-oriented flood flow channel, but was unable to erode much further north because Neshaminy Creek valley erosion beheaded all flood flow routes to its actively eroding valley head.

This sequence suggest the south-oriented valleys were eroded headward from the head of the actively eroding and deep southwest-oriented Delaware River valley and also explains the progression of lower drainage divide elevations as the through valley is followed from the southwest to the northeast. The northern through valley (where Neshaminy Creek flows in a southwest direction) is also crossed by several of the same south-oriented valleys with drainage divide elevations also suggesting the same erosion sequence.

3.6 Downstream from the northeast oriented channel segment

Downstream from its northeast-oriented valley segment Neshaminy Creek turns to flow in a southeast, south, southwest, and south direction before reaching the southwest-oriented Delaware River. This southernmost Neshaminy Creek valley segment is located in a region capped by Bridgeton and Pensauken Formation sedimentary deposits (e.g. McCarren 1972 and the geologic map on the Pennsylvania Department of Natural Resources website). Stanford (1997 and 2010) interprets Bridgeton and Pensauken Formation alluvium to have been deposited by late Cenozoic southwest-oriented rivers that flowed from the Hudson River valley across New Jersey to the present day southwest-oriented Delaware River valley. The Neshaminy Creek valley is eroded into bedrock below these alluvial sediments and the presence of these sediments suggests, quite independently of erosional landform evidence that this Neshaminy Creek valley segment eroded headward across southwest-oriented flow. Mapped alluvial sediments do not extend north and west of the northeast-oriented Neshaminy Creek channel segment, although the southwest-oriented flow probably crossed the entire Neshaminy Creek drainage basin and the entire Neshaminy Creek valleywas eroded headward continuously from the deep Delaware River valley.

4. Discussion

Headward erosion of deep valleys along and across massive southwest-oriented flood flow explains lower Neshaminy Creek direction changes and barbed tributaries and further explains how most if not all present day southeast Pennsylvania drainage routes and drainage divides formed. Except in Neshaminy Creek drainage basin areas closest to the modern day southwest-oriented Delaware River flood deposited sediments are rare and at least to date have yielded little useful information. As a result upstream Neshaminy Creek drainage basin erosional landform features represent the only good evidence for the immense southwest-oriented floods that must have crossed the region. These floods were of sufficient magnitude and duration to deeply erode theNeshaminy Creek drainage basin and surrounding areas. Flood waters came from an unknown northeast source and as described were captured in sequence by headward erosion of the Schuylkill River, Wissahickon Creek, Tookany (Tacony) Creek, Pennypack Creek, Poquessing Creek, Neshaminy Creek, and (southeast-oriented) Delaware River valleys. This sequence of valley erosion suggests the southeast and south oriented valleys eroded headward from an actively eroding and deep Delaware River valley head, which must have been eroding headward along a major southwest-oriented flood flow channel.

Bridgeton and Pensauken sediments covering lower Neshaminy Creek drainage basin areas are sometimes considered to be Tertiary in age (Owens, 1999) and do not contain typical glacial outwash materials. Stanford (1997 and 2010) used pollen and other evidence to suggest a later age and the possibility of deposition during an early interglacial period. However, the only geologic event known to this author capable of generating immense and prolonged floods of the type described in this paper is the melting of a 2 to 3 kilometer (1.2-1.8 mile) thick or thicker continental ice sheet. The southeast Pennsylvania Piedmont region where the Neshaminy Creek drainage basin is located is not known to have been glaciated, although mapped ice sheet margins are located nearby (Crowl and Sevon, 1999). As those nearby continental ice sheets melted massive southwest-oriented melt water floods almost certainly flowed across the southeast Pennsylvania Piedmont Province. Warm climates would be required to initiate and continue continental ice sheet melting with mild climate flora and fauna probably flourishing in ice marginal regions. Further, most melt water from a 2 to 3 kilometer (1.2 or 1.8 mile) thick or thicker ice sheet would contain little or no sediment as it flowed from the ice sheet location. Floods of such melt water would deeply erode regions over which it flowed and leave little or no sediment evidence to indicate the floodwater source. Logically massive floods of such melt water should have crossed the Neshaminy Creek drainage basin and represent the most likely erosion agent responsible for eroding the Neshaminy Creek drainage basin and probably for eroding most if not all other southeast Pennsylvania drainage basins.

5. References

Bascom, F., Clark, W.B., Daron, N.H., Knapp, G.N., Kuemmel, H.B., Miller, B.L., and Salisbury, R.D., 1909, Philadelphia folio, Norristown, Germantown, Chester, and Philadelphia, Pennsylvania-New Jersey-Delaware: Folios of the Geologic Atlas 162.

Braun, D.D., Pazzaglia, F.J., and Potter, N., 2003, Margin of Laurentide Ice to the Atlantic Coastal Plain: Miocene-Pleistocene landscape evolution in the Central Appalachians: *in* Easterbrook, D. editor, Quaternary Geology of the United States: INQUA 2003 Field Guide Volume: Desert Research Institute, Reno, NV, 220.

Clausen, E., 2016a, Origin of three north oriented Montgomery County water gaps: Pennsylvania Geographer, 54 (2) 42-61.

Clausen, E., 2016b, Using topographic map interpretation methods to determine Tookany (Tacony) Creek erosion history upstream from Philadelphia, Pennsylvania, USA: Journal of Geography and Geology, 8 (4) 30-45.

Clausen, E., 2016c, Wissahickon Creek drainage basin origin as determined by topographic map interpretation: Middle States Geographer, 49 (in press).

Clausen, E., 2017, Pennypack Creek drainage basin erosion history: Bucks, Montgomery, and Philadelphia Counties, PA, USA: Journal of Geography and Geology, 9 (1) 37-52.

Crowl, G.H. and Sevon, W.D., 1999, Quaternary: *in*The Geology of Pennsylvania: Schultz, C. H., editor, Pennsylvania Geological Survey and Pittsburgh Geological Society. p. 224-231.

Davis, W.M., 1889, The rivers and valleys of Pennsylvania: National Geographic Magazine*,* 1, 183-253. *Alsoin* Davis, W.M., 1909, Geographical Essays: Ginn and Company, Boston. 413-484.

Johnson, D., 1931, Stream sculpture on the Atlantic slope: a study in the evolution of Appalachian rivers: Columbia University Press, New York, 142p.

Lyttle, P.T. and Epstein, J.B., 1987, Geologic map of the Newark 1 degree x 2 degrees quadrangle, New Jersey, Pennsylvania, and New York: United States Geological Survey Miscellaneous Investigations Map I-1715.

McCarren, E.F., 1972, Water Quality of streams in the Neshaminy Creek basin, Pennsylvania: United States Geological Survey Water-Supply Paper 1999-O. 33p.

Meyerhoff, H.A., and Olmstead, E.W., 1936, The origins of Appalachian drainage: American Journal of Science: 236, 21-42.

Owens, J.P., 1999, Cretaceous and Tertiary: *in* Schultz, C.H. ed., The Geology of Pennsylvania: Pennsylvania Geological Survey, Harrisburg and Pittsburgh Geological Society, Pittsburgh. 218-223.

Owens, J.P., and Minard, J.P., 1979, Upper Cenozoic sediments of the lower Delaware Valley and northern Delmarva Peninsula, New Jersey, Pennsylvania, Delaware, and Maryland: U.S. Geological Survey Professional Paper 1067D, 47p.

Pennsylvania Department of Conservation and Natural Resources, DCNR Interactive Map Resources, http://www.dcnr.state.pa.us/learn/interactivemapresources/index.htm(accessed June 9, 2017)

Potter, N, 1999, Part V: Physiography: in *The Geology of Pennsylvania*: Schultz, C. H., editor, Pennsylvania Geological Survey and Pittsburgh Geological Society. 342-344.

Stanford, S.D, 1997, Pliocene-Quaternary Geology of Northern New Jersey: an Overview: *in* Pliocene-Quaternary Geology of Northern New Jersey: Guidebook for the 60th Annual Reunion of the Northeastern Friends of the Pleistocene: 1.1-1-26.

Stanford, S.D., 2010, Pliocene and Quaternary Geology of the Trenton area: *in* Lacombe, Pierre, editor, Geology of the Greater Trenton area and its impact on the Capital City: Twenty Seventh Annual Meeting of the Geological Association of New Jersey Field Guide and Proceedings: 120-131.

Strahler, A.N., 1945, Hypotheses of stream development in the folded Appalachians of Pennsylvania: Geological Society of America Bulletin, 56(45-88).

United States Geological Survey Historical Map Collection website: https://ngmdb.usgs.gov/topoview/(accessed June 9, 2017

United States Geological Survey National Map website: https://viewer.nationalmap.gov/advanced-viewer/(accessed June 9, 2017)