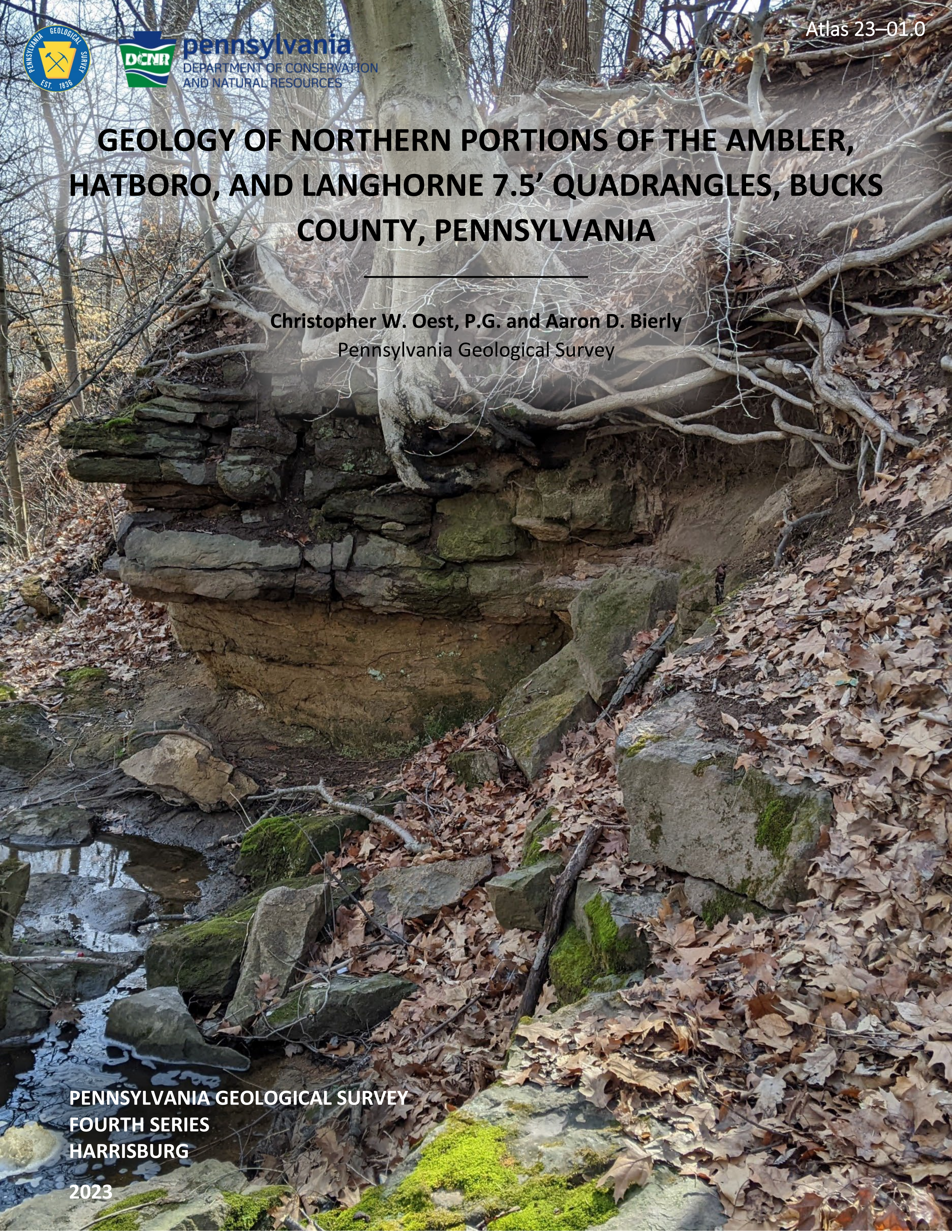

pennsylvania
DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

Atlas 23–01.0

GEOLOGY OF NORTHERN PORTIONS OF THE AMBLER, HATBORO, AND LANGHORNE 7.5' QUADRANGLES, BUCKS COUNTY, PENNSYLVANIA

Christopher W. Oest, P.G. and Aaron D. Bierly
Pennsylvania Geological Survey

PENNSYLVANIA GEOLOGICAL SURVEY
FOURTH SERIES
HARRISBURG

2023

Cover photograph: Outcrop of the middle member of the Stockton Formation in Newtown Creek south of Newtown, Pa. Photograph shows units 6 through 8 in the middle member reference section shown in Figure 8 of this report.

—Photograph by Chris Oest, 2022.

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This report and related map plates have been reviewed by the staff at the Pennsylvania Geological Survey. These documents have not undergone external peer review.

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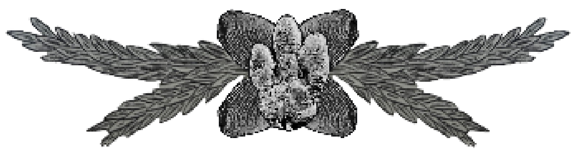

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GEOLOGY OF NORTHERN PORTIONS OF THE AMBLER, HATBORO, AND LANGHORNE 7.5' QUADRANGLES, BUCKS COUNTY, PENNSYLVANIA

by

Christopher W. Oest and Aaron D. Bierly

ABSTRACT

This report accompanies new mapping of bedrock (Bierly and Oest, 2023) and surficial (Bierly, 2023) materials in portions of the Ambler, Hatboro, and Langhorne 7.5-minute quadrangles in the Piedmont physiographic province in southeastern Pennsylvania. The primary objective of this investigation is to refine the current mapping of the Triassic Stockton Formation utilizing the three-member interpretation of Rima and others (1962) and to identify the density and orientation of fractures to support groundwater models being developed by the United States Geological Survey. The study area is principally underlain by sedimentary rocks with minimal structural deformation. A narrow belt of Proterozoic metamorphic rocks is included in the study area to provide stratigraphic context to the younger Newark Basin strata. Large-scale mapping confirms many previously mapped contacts and structures but also modifies contact placement and reveals local-scale structures based on new outcrop data. This investigation also documents the distribution of unconsolidated surficial materials, which range in age from Neogene to modern. Samples were collected and analyzed for mineralogy, bulk geochemistry, density, absorption, slaking, and compressive strength to provide a more thorough characterization of the strata.

INTRODUCTION

BACKGROUND

This report accompanies new bedrock (Bierly and Oest, 2023) and surficial (Bierly, 2023) geologic maps for portions of the Ambler, Hatboro, and Langhorne 7.5-minute quadrangles. The principal goal of this investigation was to conduct 1:24,000 scale mapping of the Stockton Formation and generate a robust dataset of fracture orientations in southern Bucks County to provide a framework for groundwater modeling. The need for this data is driven by detection of per- and polyfluoroalkyl substances (PFAS) in groundwater samples from wells near Naval Air Station Joint Reserve Base Willow Grove and former Naval Air Warfare Center Warminster in 2014 (Goode and Senior, 2020). The United States Geological Survey (USGS), at the request of the United States Navy, developed numerical groundwater flow models to aid in characterizing regional groundwater flow paths—a vital component in understanding the transport and fate of PFAS in the environment. The USGS requested that the Pennsylvania Geological Survey conduct

1:24,000 scale mapping within the study area since a more detailed stratigraphic framework would improve their initial models.

This investigation provides member-scale mapping of the Stockton Formation following the criteria of Rima and others (1962). This interpretation of the Stockton Formation distinguishes between shale and arkosic sandstone dominated lithofacies, highlighting the heterogeneity of hydraulic properties as a function of stratigraphic position. Large-scale mapping of these lithofacies provides model boundary conditions that are more representative of the physical stratigraphy compared to those derived from formation-scale observations. Additionally, Goode and Senior (2020) note that lateral groundwater flow principally occurs along bedding plane fractures with joints acting as secondary pathways and important connectors between bedding planes. Since current maps include very few bedding and fracture orientations, these features were measured wherever possible in order to understand the density and orientation of the fracture network as well as the spatial variability of these properties.

LOCATION

The study area is located in Bucks County in southeastern Pennsylvania (Figure 1). It is bound to the north by the northern edge of the Ambler, Hatboro, and Langhorne 7.5-minute quadrangles, to the east by the eastern edge of the Langhorne 7.5-minute quadrangle, to the south by an arbitrary line offset approximately half a mile from the current southern boundary of the Newark Basin, and to the west by the Bucks-Montgomery County line (Figure 1). The boroughs of Ivyland, Langhorne, and Newtown and the townships of Lower Makefield, Middletown, Newtown, Northampton, Lower Southampton, Upper Southampton, Warminster, Warrington, Warwick, and Wrightstown are within the study area.

The study area is bisected by the Neshaminy Creek and includes portions of the Neshaminy Creek, Pennypack Creek, Mill Creek, and Buck Creek watersheds. Within the study area, the Neshaminy Creek, Pennypack Creek, and Mill Creek watersheds drain to the south, while the Buck Creek watershed drains to the east (Figure 2). The area of each watershed within the study area is shown in Table 1.

Watershed	Total Area of Watershed (Square Miles)	Total Area of Watershed in Study Area (Square Miles)
Neshaminy Creek	165.25	67.18
Pennypack Creek	53.28	6.56
Mill Creek	18.92	0.77
Bucks Creek	6.94	1.15

Table 1. Areas in square miles for watersheds that influence the study area.

METHODS

BEDROCK GEOLOGIC MAPPING

Field mapping was conducted over a period of 12 months starting in October 2021. Due to low bedding dips, subtle topography, and development in the study area, bedrock exposure is scarce and access to available exposures posed a challenge. Bedrock is commonly well exposed in stream beds and cut banks. As such, this investigation utilized traverses of Southampton Creek, Mill Creek, Ironworks Creek, Newtown Creek, Core Creek, Little Neshaminy Creek, and Neshaminy Creek as corridors for data collection. Although these stream traverses provided sufficient data for contact drafting, supplemental data were collected from traverses of smaller tributaries, drainages, and culverts. These locations were identified as potential bedrock exposures by reviewing hillshade imagery derived from 1-meter resolution lidar digital elevation models (DEMs) for locally steep slopes, which served as evidence of downcutting or bank erosion. To maximize efficiency in the field, potential observation points were compiled in a web map using Esri ArcGIS Online and accessed in the field using a tablet equipped with Esri FieldMaps®. Traverses were planned with this map as a guide, and field validated areas were marked as "visited" to avoid inadvertently returning to the same location twice.

Rock characteristics, including grain size, sorting, rounding, and bed thickness were described at each location. In order to standardize observations, grain size cards and Munsell color charts (Munsell, 2009) were used to describe grain size and color, respectively. Field data—including planar feature (e.g. beds, joints, faults) orientations, outcrop descriptions, data confidence, and data quality—were recorded in field notebooks, transcribed to spreadsheets, and integrated into geodatabases. Where possible, stratigraphic sections were measured to document the stratigraphic variation in observed lithology. A Brunton® transit, with a magnetic declination set to 12 degrees west, was used to determine the strike and dip of planar features such as bedding planes, joints, faults, and cross stratification. Right hand rule was followed for all strike and dip measurements. Bedding and joints were plotted as planes, poles to planes, and contoured poles to planes using Stereonet 11 (Allmendinger and others, 2012). The stereonets produced were then used to evaluate the range in orientation and angular relationship between these structures. Contacts were interpolated between field observations and drawn on a lidar hillshade basemap. When available, water-well records from the Pennsylvania Groundwater Information System (PaGWIS) were used to constrain contact placement in the absence of outcrop control.

SURFICIAL GEOLOGIC MAPPING

Surficial mapping techniques used for this project included landform interpretation based on 1-meter resolution hillshade imagery and aerial photography. The presence of these mapped features was confirmed with field checks, which included recording complete lithologic descriptions following the same methods of bedrock description. Water-well records from PaGWIS were used to verify interpretations of lidar and aerial imagery and to verify the presence of surficial deposits in the absence of outcrop control. To refine the chronostratigraphic framework of alluvium and terrace deposits, samples were collected for radiocarbon and optical stimulated luminescence (OSL) analysis following the methods of the Penn State Radiocarbon

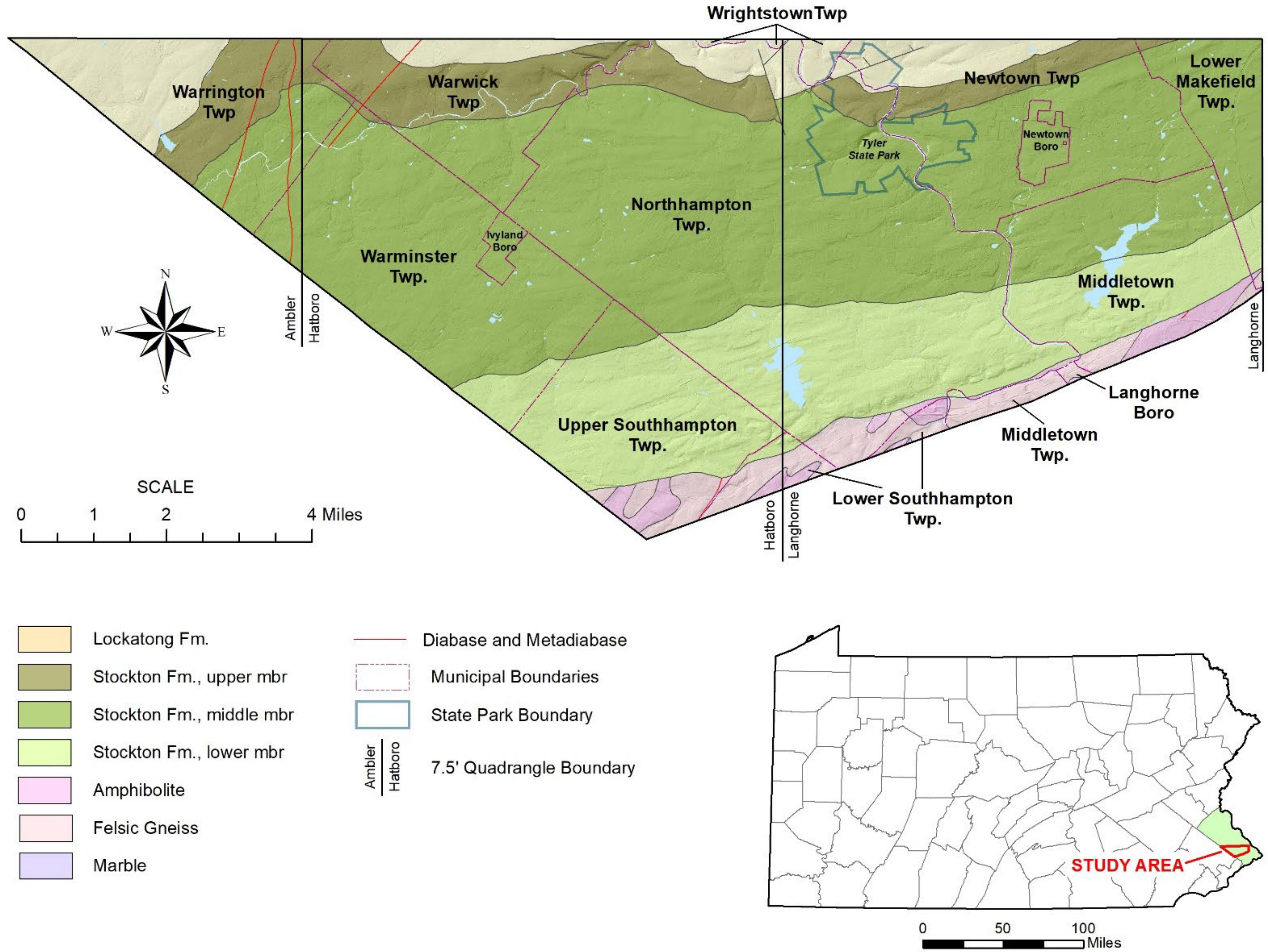


Figure 1. Map of the study area displaying the bedrock geology, townships, boroughs, and Tyler State Park. The location map in lower right corner of Pennsylvania highlights Bucks County (green) and the study area (red outline). Marble is present in Lower Southampton Township but cannot be seen at this scale—see Bierly and Oest (2023). Abbreviations: Twp—township; Boro—borough; Fm—Formation; mbr—member.

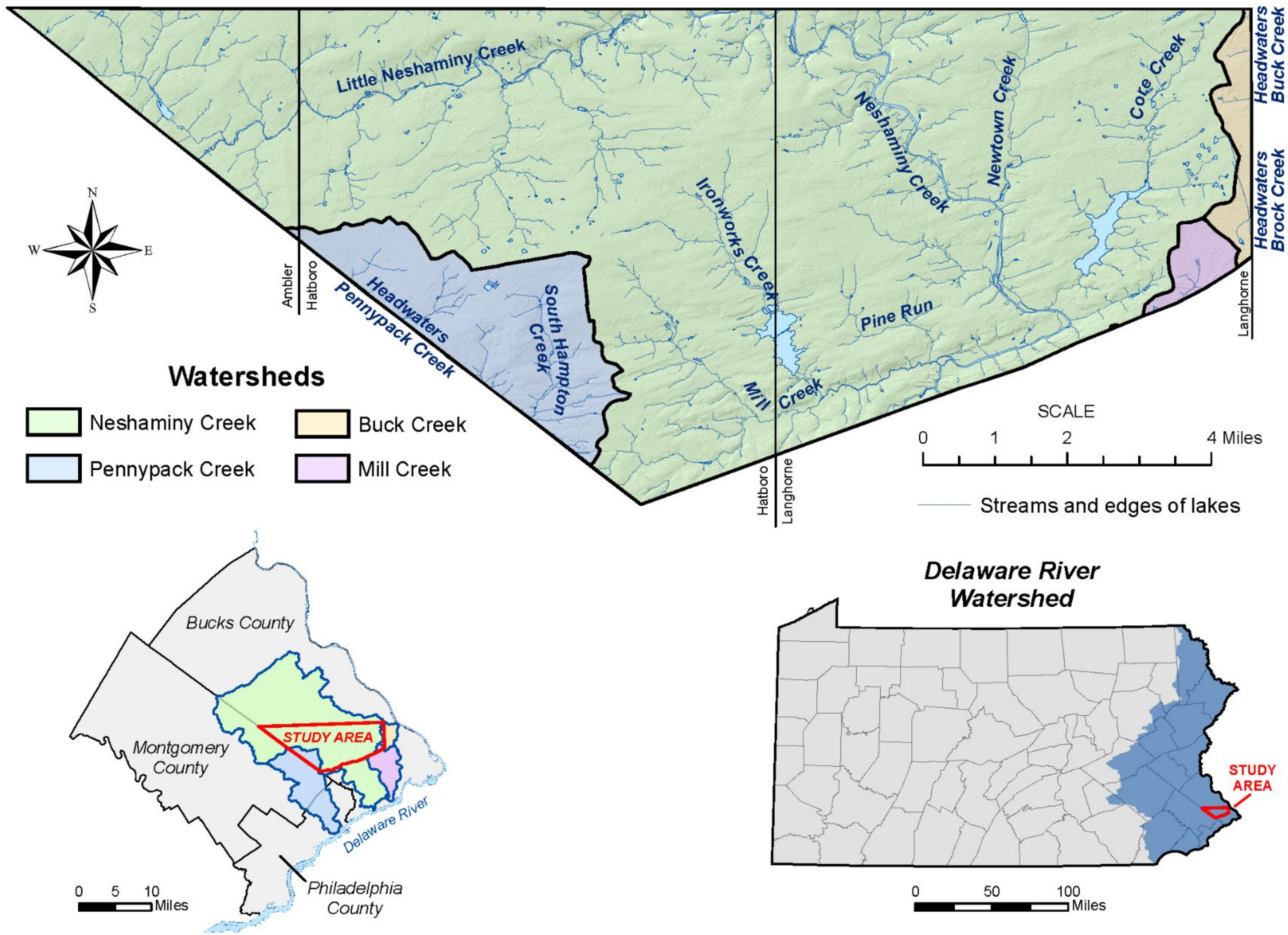


Figure 2. Map of the study area displaying extent of the four watersheds. The location map in lower right corner of Pennsylvania highlights the Delaware River Watershed (blue) and the study area (red outline).

Laboratory (Penn State Radiocarbon Laboratory, n.d.) and the Utah State University Luminescence Lab (Nelson and others, 2015). Radiocarbon and OSL data are included with this report in Appendix 1. Finally, an elevation-derived hydrography dataset was produced for the study area utilizing QL2 lidar data following methods developed for the Pennsylvania Hydrography Dataset (Fehrs, 2022).

SAMPLING AND ANALYSIS

Representative samples were collected from select field stations for petrographic, geochemical and geotechnical analysis. Bulk rock geochemical analyses were performed by ActLabs in Ancaster, Ontario, Canada and this data is included in Appendix 2. Bulk rock mineralogical analyses were performed in-house via powder x-ray diffraction[1]. Scanning electron microscopy[2] was also performed in-house for elemental analysis. Thin sections were prepared from oriented samples to qualitatively assess grain sorting and rounding. Point counting was performed on a petrographic microscope equipped with a mechanical stage to characterize the porosity and composition of sandstones following Folk (1974). An inventory of prepared thin sections and preliminary petrographic data utilized during this investigation are in Appendix 3. These data are described in detail in the subsequent sections of this report, as well as summarized within the map unit descriptions included on the complementary bedrock and surficial maps of Bierly and Oest (2023) and Bierly (2023), respectively.

BEDROCK GEOLOGY

STRATIGRAPHY

Bedrock units ranging in age from Middle Proterozoic to Late Triassic are mapped in the study area (Figure 3). These include marble, felsic gneiss, amphibolite, metadiabase, the Stockton Formation, the Lockatong Formation, and diabase (Figure 3). The Stockton Formation is herein subdivided into informal lower, middle, and upper members based on criteria established by Rima and others (1962) in Chester and Montgomery Counties in southeastern Pennsylvania. Details of this subdivision are described in the following section.

Middle Proterozoic

The Middle Proterozoic metamorphic rocks form an outcrop belt along the southern boundary of the study area (Bierly and Oest, 2023). These rocks are strongly deformed and vary widely in composition. The Middle Proterozoic metamorphic rocks form the basement of the Newark Basin within the study area, although in other parts of the basin the basement may be composed of Paleozoic sedimentary rock. While the focus of this study is principally the Stockton

[1] Malvern Panalytical Empyrean X-ray Diffractometer equipped with a copper anode generating K-alpha X-rays. Analysis performed at 40 kilovolts (kV).

[2] Hitachi scanning electron microscope equipped with an Oxford Instruments xPlore 30 energy dispersive spectrometer (EDS). EDS analysis was completed with a sample chamber vacuum of 30 pascals (Pa) and an incident beam voltage of 20 kV.

Formation, discussion of the Middle Proterozoic section is included to provide stratigraphic context to the overlying basin fill materials. As such, mapping within the Middle Proterozoic section was limited to confirming the location of the southern boundary of the Newark Basin, although reconnaissance-level mapping was completed in the metamorphic outcrop belt to confirm observations of previous authors and to supplement existing map unit descriptions. Contacts and map unit descriptions are modified from Willard and others (1959), Berg and others (1980), and Lyttle and Epstein (1987).

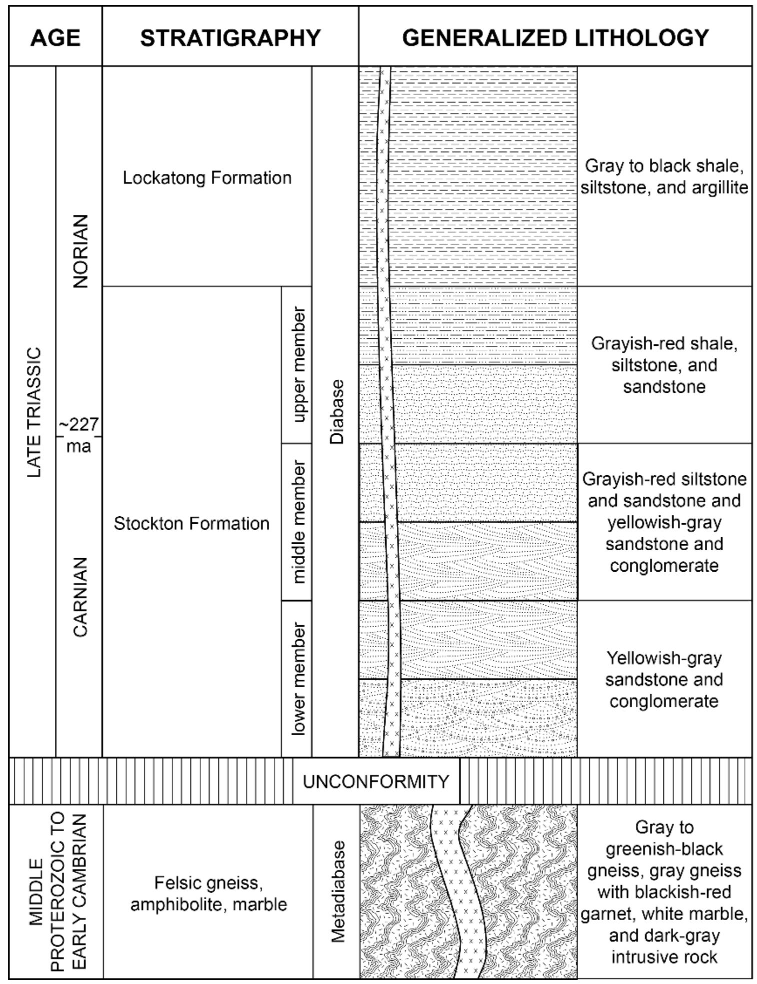


Figure 3. Generalized stratigraphic column for the study area. Patterns represent the generalized lithology for each unit. The stratigraphic position of the Carnian-Norian boundary is not definitive and approximated based on palynological analysis. See Bedrock Geology section on for details. Carnian-Norian age boundary from Cohen and others, 2013.

Marble

A small, isolated pod (approximately 2 acres in size) of marble is located south of Bridgetown Pike in Feasterville-Trevose within the study area (Bierly and Oest, 2023). The only known exposure of this unit is in the abandoned Vanartsdalen quarry, where it was historically extracted as a local source of lime (Sloto, 2022). This unit was previously correlated with the Franklin Marble of the New Jersey Highlands by Bascom (1909), an interpretation that was later shared by Willard and others (1959) and Berg and others (1980). However, similar lithologies occur in multiple stratigraphic positions within this interval, shedding doubt on equivalency with the Franklin Marble based on lithologic similarity alone (Lyttle and Epstein, 1987; Volkert, 1993). The marble is medium to coarse grained with massive, thick to very thick beds. It is locally dolomitic and includes disseminated coarse- to very coarse grained graphite flakes and medium- to coarsely crystalline phlogopite as accessory minerals. Although there are no observed relict sedimentary structures, a sedimentary protolith is interpreted based on its granular texture and the presence of amphibolite as lenses within the marble. The amphibolite lenses may be metamorphosed dolomitic or feldspar-rich interbeds in an otherwise limestone-dominated succession.

Felsic Gneiss

Felsic gneiss occurs throughout the outcrop belt of Middle Proterozoic rocks along the southern boundary of the study area (Bierly and Oest, 2023) and may be correlative to the granodioritic intervals of the Baltimore Gneiss (Willard and others, 1959). This unit is heterogenous and contains strata ranging from poorly- to well-foliated. It is primarily composed of biotite, feldspar, and quartz, with almandine present in some places. The unit is primarily light- to dark-gray with patches of moderate-orange-pink and blackish-red foliated rock. Where present, the almandine is coarse grained with crystal diameters in excess of 1.5 inches, as observed at one locality 190 ft northeast of the intersection of Holland Road and Buck Road in Northampton Township (Figure 4). Metasedimentary rocks were also observed within this unit. Metasandstone was observed only in float, and metaconglomerate was observed in outcrop at one location in an unnamed tributary to Mill Creek approximately 430 ft east of West Bristol Road.

Figure 4. Almandine-bearing gneiss outcrop 190 ft northeast of the intersection of Holland Road and Buck Road in Northampton Township. Sledgehammer is 10 inches long. Photo taken October 21, 2022. GPS: 40.17342°, -74.98682°

Amphibolite

Amphibolite occurs interlayered with felsic gneiss throughout the Middle Proterozoic outcrop belt (Bierly and Oest, 2023) and may be equivalent to gabbroic intervals of Baltimore Gneiss (Willard and others, 1959). Amphibolite is greenish black, medium to coarse grained, and moderately to well-foliated. Hornblende and plagioclase are the principal components of this unit. Interlayering of amphibolite with felsic gneiss implies a sedimentary protolith for these units.

Late Proterozoic to Cambrian (?)

Metadiabase

Metadiabase occurs as scattered dikes throughout the Middle Proterozoic outcrop belt in southeastern Pennsylvania. In the southeastern corner of the study area at Styer Orchard in Langhorne, metadiabase is observed as cobble- to boulder-sized float (Figure 5; Bierly and Oest, 2023). It was also identified in the southwestern corner of the study area by Lyttle and Epstein (1987). The age of metadiabase is uncertain; however, it likely intruded between Grenville and Taconic deformation. Lyttle and Epstein (1987) note that metadiabase may be coeval with the Catoctin Formation of Virginia, Maryland, and south-central Pennsylvania. Metadiabase samples collected from the field are finely crystalline and dark gray, with moderate yellowish-brown weathered surfaces observed in float material. A representative sample of metadiabase had a composition of hornblende (86 percent) and feldspar (14 percent).

Figure 5. Metadiabase boulder float in agricultural field in Langhorne. Note contrast between fresh color (dark gray, upper right of boulder in foreground)) and weathered color (moderate yellowish brown). Hammer is 12 inches long. Photo taken January 26, 2023. GPS 40.19511°, -74.89529

Late Triassic

Late Triassic siliciclastic rocks unconformably overlie Middle Proterozoic metamorphic rocks within the study area. These Late Triassic rocks represent the infilling of aulacogens by fluvial and lacustrine sedimentation associated with the rifting of Pangea. The Stockton Formation and the basal portion of the overlying Lockatong Formation outcrop within a roughly northeast-southwest striking belt within the study area (Figure 1). This belt is semi-parallel to the Paleozoic structural fabric observed north and south of the Newark Basin. Diabase intrusions are present as dikes in the northwestern portion of the study area.

Stockton Formation

The Stockton Formation is generally composed of interbedded red mudstones and pale-yellow to pale-orange sandstones and conglomerates arranged in fining-upward packages. These packages repeat within the section and become progressively finer overall up-section. McLaughlin (1945) defines a four-member subdivision of the Stockton Formation based on the topographic expression of ridge-forming sandstones. In ascending order, these members are the Solebury Member, Prallsville Member, Cuttalossa Member, and Raven Rock Member. Although this nomenclature has been used in subsurface investigations of the Newark Basin (e.g., Olsen, 1980; Olsen and others, 1996), contacts between these members are not readily observable in core or geophysical logs (Olsen and others, 1996). Additionally, the four-member interpretation has not been applied outside of the fault block containing the Stockton Formation type section in New Jersey (Smoot, 2010).

Rima and others (1962) defined a three-member system based on overall lithic character and apply this interpretation to mapping in Chester and Montgomery Counties in southeastern Pennsylvania. These members are, in ascending order, the lower arkose member, the middle arkose member, and the upper shale member. The contacts between these members are defined by the relative abundance of coarse-grained arkosic sandstone and conglomerate, fine- to medium-grained arkosic sandstone, and shale and siltstone, respectively.

This investigation utilizes a modified three-member interpretation of the Stockton Formation that emphasizes the spatial and stratigraphic heterogeneity of the hydraulic characteristics of the Stockton Formation. This interpretation facilitates member-scale mapping of the Stockton Formation in discontinuous outcrop exposure without the need for extensive stratigraphic control from core. The defining criteria for each member (i.e., abundance of lithologic type) as established by Rima and others (1962) are not changed by this investigation; however, this investigation modifies the nomenclature of Rima and others (1962) to exclude lithologic terms in order to avoid the potential misconception of lithic homogeneity. Members are referenced simply as the lower, middle, and upper members of the Stockton Formation.

Lower member

The lower member of the Stockton Formation is present across the study area (Bierly and Oest, 2023). It is heterogenous and contains strata of various colors including very light to light-gray, dusky-yellow, very pale orange, and pale-yellowish-orange. Medium- to coarse-grained sandstone, pebbly sandstone, and conglomerate are the principal lithologies within the lower member and are present as medium to thick cross-stratified beds (Figure 6).

A variety of primary sedimentary structures are observed within the sandstone beds of the lower member, principally tabular and trough cross stratification. Cross strata foresets are commonly 1 to 4 inches thick but are thicker in some locations. These structures are interpreted to represent in-channel deposition and bar form migration. A unique outcrop exposing dune structures with wavelengths of approximately 21 ft was observed within Neshaminy Creek 500 ft upstream from Bridgetown Pike. In order to produce these bedforms in sediment with a grain size of coarse sand to fine granule, water flow velocities ranging from approximately 1 to 3 ft per second are required (Southard, 1991). Scour and fill and lenticular sandstone morphologies are common (Figure 7). Locally, scouring cuts out underlying strata entirely, which has resulted in amalgamated bedding morphologies. Massive bedded sandstones are less common in the lower member but are present in some locations. Sandstones weather to large angular blocks where bedding is massive and to flaggy slabs where bedding is cross-stratified. Deeply weathered strata occur as friable sandstone masses with relict primary structure present in some locations. Friable beds are interbedded with more competent strata, suggesting bed-by-bed variability in cementation.

Conglomerates are common in the lower member and are massive to cross-stratified. These rocks are matrix supported. Matrix material generally ranges from medium- to coarse-grained sand, with fine- to very coarse grained sand in some locations. Clasts are subrounded to rounded and range from granules to very coarse pebbles. Some anomalously coarse clasts, with diameters greater than 3 in, were observed in float blocks along the western bank of Neshaminy Creek approximately 900 ft upstream of Bridgetown Pike. Quartz is the primary clast component. Subordinate quartzite and gneiss clasts are present near the contact between the lower member and the underlying felsic gneiss.

Mudstone is rare in the lower member and was only observed in outcrop in the bed of Pine Run just north of its confluence with Mill Creek. At this location, the mudstone is grayish red, although the only observed outcrop is highly weathered and color may vary in a fresh exposure or in core.

Sandstones within the lower member of the Stockton Formation are interpreted to have been deposited in a sand-dominated, braided fluvial setting. The coarse-grained texture of this interval, bedforms, and amalgamated bed morphologies are indicative of deposition on a high-gradient landscape with sediment supply in excess of accommodation space. Amalgamated bedforms and the paucity of floodplain fines in this interval suggest the lower member was deposited in a dynamic environment with poorly confined channels and frequent avulsions, which would entrain floodplain fines and bypass this material to distal portions of the basin.

Conglomerates within the lower member vary slightly in grain size and are interpreted to

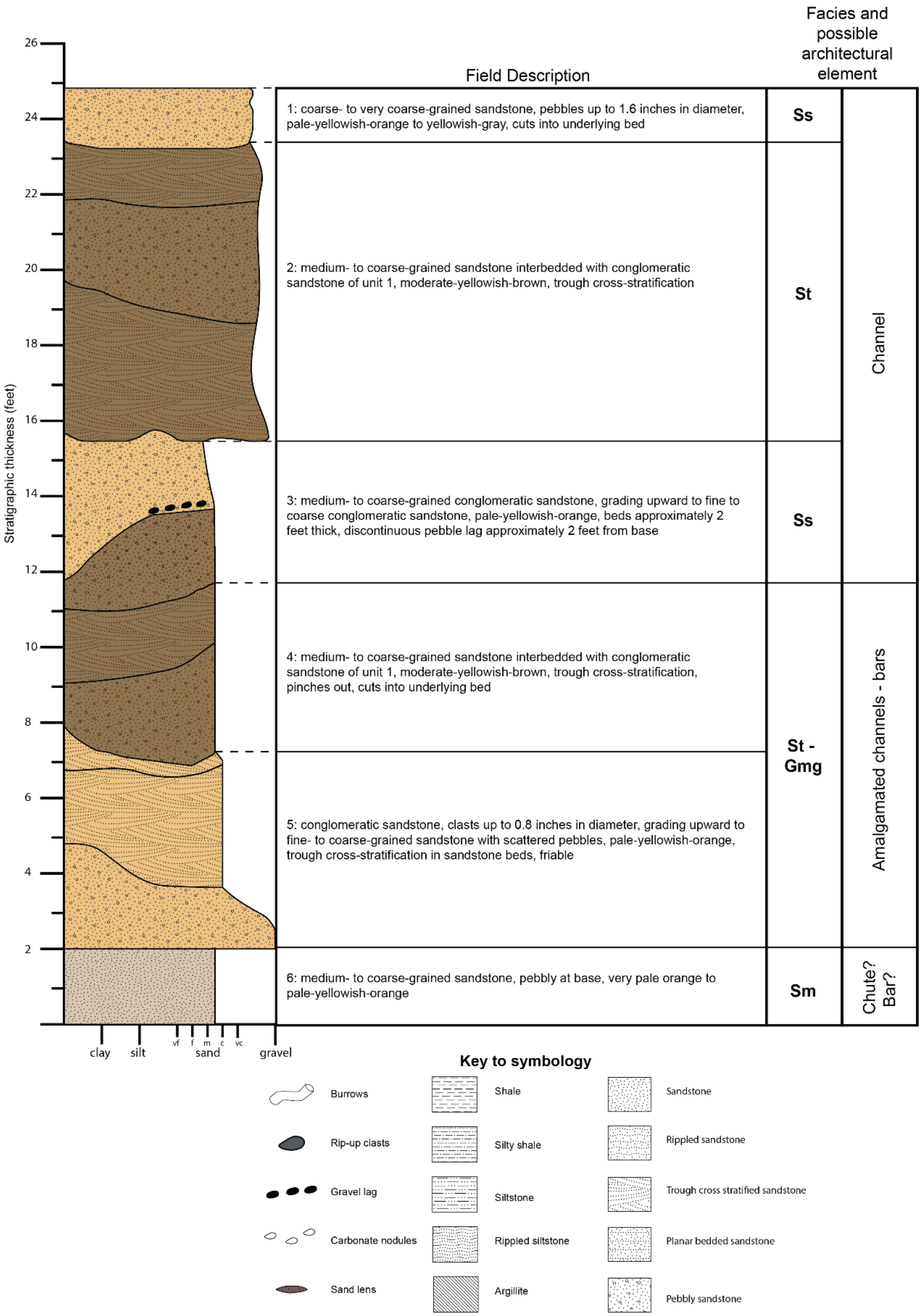


Figure 6. Reference section for the lower member of the Stockton Formation. Section is located on Chinquapin Road 570 ft north of the intersection with Holland Road in Northampton Township. Lithofacies are classified after Miall (1978) and potential fluvial architectural elements after Miall (1985). Lithofacies codes indicate the following: Ss – sand, fine to very coarse, may be pebbly with broad, shallow scours; St – sand, fine to very coarse, may be pebbly with trough cross beds; Gmg – matrix-supported gravel with inverse to normal grading; Sm – sand, fine to coarse, massive or faint laminations. Queried architectural elements indicate uncertainty in interpretation. GPS: 40.17439°, -74.98890°

Figure 7. A) Outcrop of the lower member of the Stockton Formation along Neshaminy Creek approximately 1500 ft north of the Bridgetown Pike bridge in Middletown Township. Note downcutting and substantial relief on bedding surfaces. B) Annotated photo showing examples of cross cutting surfaces (yellow dashed lines). The bed outlined in yellow is approximately 5 ft thick. Photo taken July 7, 2022. GPS: 40.18900°, -74.93119°

have been deposited in two depositional environments. The relatively coarse-grained conglomerates, with clasts ranging from granules to cobbles, are found along the southern boundary of the Newark Basin within the study area and represent deposition by alluvial fans. Clast size within these intervals suggest deposition in areas with locally greater relief than the surrounding paleo-landscape. Alluvial fan deposits, manifested as coarse-grained conglomerates along the southern boundary of the Newark Basin, are different from the “fanglomerates” present along the northern edge of the Newark Basin. The conglomerates of the lower member of the Stockton Formation are more laterally extensive and contain clasts that are texturally mature compared to the angular cobbles present in “fanglomerates.” The extent and textural maturity of these conglomerates suggests deposition in broader, relatively low-gradient fans compared to the areally restricted, high-gradient fan environments associated with “fanglomerates.” This is consistent with the half-graben model for the Newark Basin, wherein the gradient on the border fault side of the basin (northern edge, in this case) is expected to be greater than the gradient on the “hinge” side of the basin. The relatively fine-grained conglomerates, with clasts ranging from granules to pebbles, are observed throughout the lower member and represent gravel bar deposition in channels of the headwaters of braided fluvial systems.

The basal contact of the lower member of the Stockton Formation and the underlying Middle Proterozoic metamorphic rocks is not exposed in the study area and is inferred from outcrop observations, abundance of sedimentary or metamorphic float in stream beds, and water well drilling records. The calculated thickness of the lower member ranges from approximately 1,700 to 2,600 ft in Upper Southampton Township and thins eastward to approximately 850 to 1,300 ft in Woodbourne.

Middle member

The middle member of the Stockton Formation is present across the study area and is characterized by grayish-red sandstone, siltstone, and shale interbedded with yellowish-gray to dusky-yellow sandstone, conglomeratic sandstone, and conglomerate (Figure 8).

Light-gray, yellowish-gray, and dusky-yellow sandstones are medium to coarse grained and are commonly medium to thick bedded. These beds commonly bear trough cross stratification and, in some locations, upper flow regime planar bedding. Sandstones are interbedded with conglomeratic sandstone and conglomerate that are of similar color and texture. These lithologies are interpreted to represent channel fill and bar deposition. The color, lithology, and sedimentary structures within these beds echo the color, lithology, and sedimentary structures of the lower member; therefore, these beds are interpreted to be tongues of the lower member.

Grayish-red to pale-reddish-brown sandstones are fine- to medium-grained and are interbedded with grayish-red to pale-reddish-brown siltstones and shales. These lithologies host asymmetric ripples and laminations and occur in fining-upward packages, with intraformational conglomerate at their base in some locations (Figure 9). Intraformational conglomerates are typically 1 ft thick and contain clasts of calcareous nodules, possibly of pedogenic origin, and mudstone. Siltstones, mudstones, and shales are present at the top of fining-upward packages and are interpreted to have been deposited in floodplain environments based on lithology,

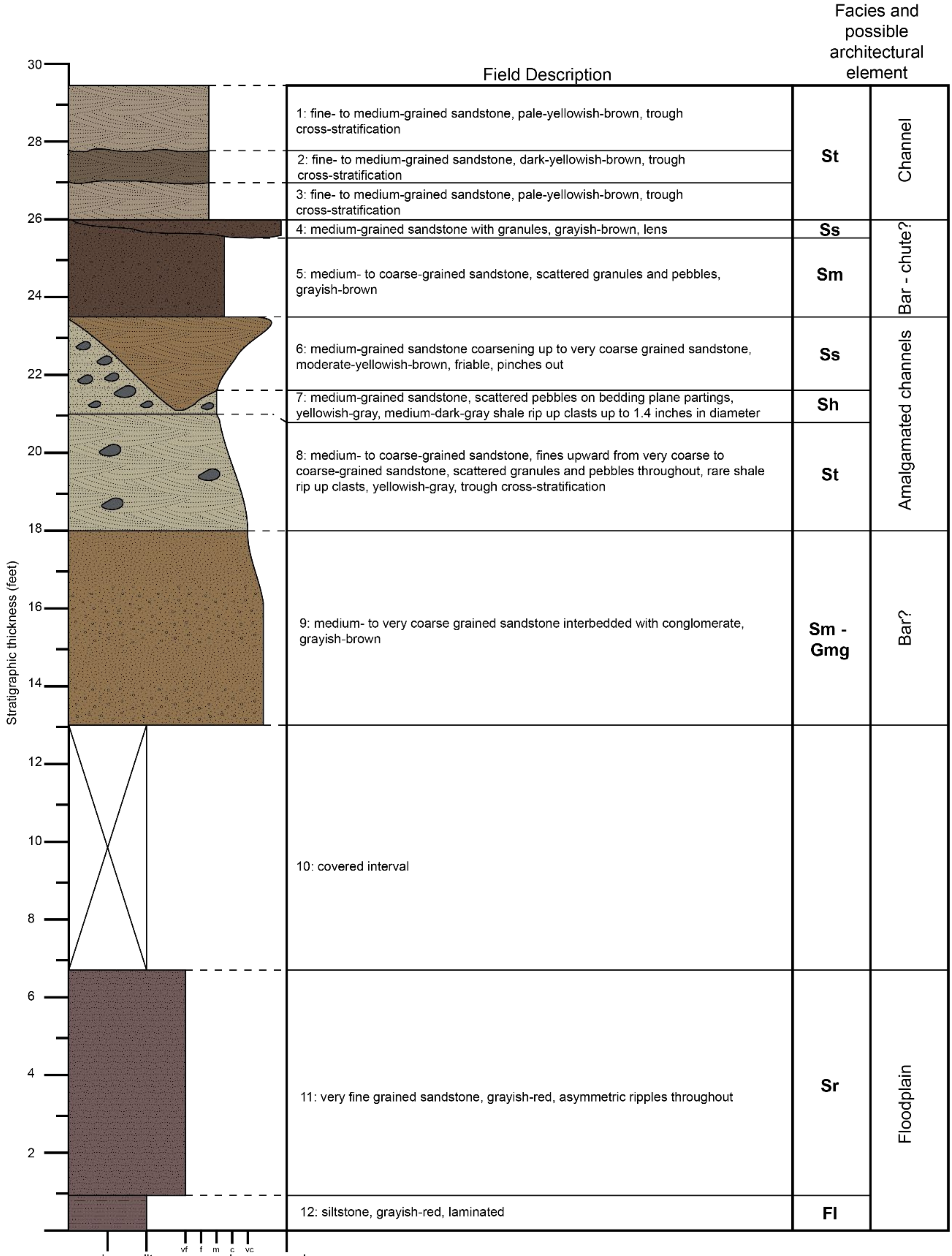


Figure 8. Reference section for the middle member of the Stockton Formation. Section is located along Newtown Creek approximately 400 ft south of Barclay Street in Newtown Township. See Figure 6 for key to symbology. Lithofacies are classified after Miall (1978) and potential fluvial architectural elements of Miall (1985). Lithofacies codes indicate the following: St – sand, fine to very coarse, may be pebbly with trough cross beds; Ss – sand, fine to very coarse, may be pebbly with broad, shallow scours; Sm – sand, fine to coarse, massive or faint laminations; Sh – sand, very fine to coarse, may be pebbly, hosting horizontal lamination or parting lineations; Sr – sand very fine to coarse, with ripple cross-lamination; Fl – sand, silt, mud with fine lamination or very small ripples. Queried architectural elements indicate uncertainty in interpretation. GPS: 40.22092°, -74.93884°

Figure 9. Small, abandoned quarry in the middle member of the Stockton Formation approximately 540 ft east of the intersection of the College Park Trail and Number 1 Lane Trail in Tyler State Park. Note fining upward package—sandstone in foreground below the individual is medium- to coarse-grained, and the rock ledge in the background is siltstone to very fine sandstone. See Figure 10 for measured section of this interval. Photo taken January 26, 2023. Individual is approximately 6 ft tall. GPS: 40.22615°, -74.98518°

sedimentary structures, and presence of invertebrate burrows. Evidence of subaerial exposure is commonly observed in mudstones at the top of these fining-upward packages and includes pedogenic features (such as ped structures), clay-infilled root traces, and desiccation cracks. *Scoyenia* ichnofacies burrows have been identified in paleosols cropping out in Tyler State Park in a streambank along a tributary to Neshaminy Creek approximately 500 ft north of Newtown-Richboro Road (Kopcznski and others, 2015). Weathering characteristics of sandstones within the middle member are similar to those of the lower member. Siltstones weather to form large blocks, and mudstones tend to form recessed intervals in outcrop. Fossil plants are only observed at one location in a small abandoned quarry approximately 540 ft east of the intersection of the College Park Trail and Number 1 Lane Trail in Tyler State Park (Figure 10).

Shale samples from the fossil-bearing interval were analyzed for spores. Palynomorphs from this interval indicate a depositional age of Middle to Late Carnian for the middle member (Zippi, 2022). This data revises the chronostratigraphic range for the Stockton and Lockatong Formations as shown on the Stratigraphic Correlation Chart of Pennsylvania (Berg and other, 1993), which currently shows the Carnian-Norian boundary occurring in the lower Passaic Formation. Kent and others (2017) establish a Norian age for the Raven Rock Member of the Stockton Formation, the upper-most member of the four-member subdivision of McLaughlin (1945). Based on this data and the palynological results for this study, the Carnian-Norian boundary can be inferred to occur between the middle member of the Stockton Formation and the basal Lockatong Formation.

The middle member represents a transition in depositional setting within the Stockton Formation. Finer-grained sediment, including floodplain fines, and sedimentary structures consistent with lower energy depositional environments, such as ripples and laminations, are

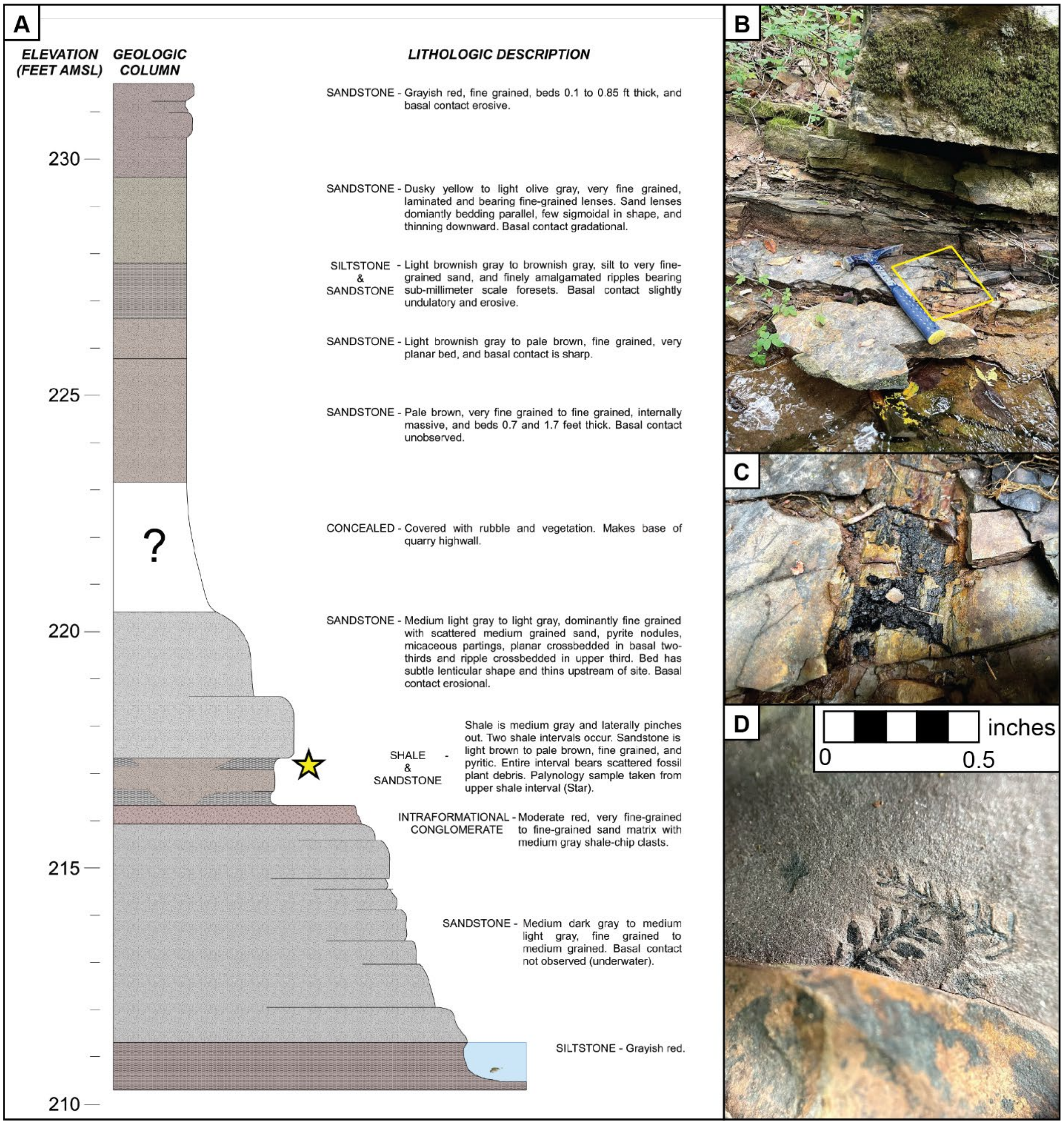


Figure 10. A) Measured section of the plant fossil-bearing outcrop. The star indicates the horizon where the fossil was located and where samples were collected for palynology. The profile of the section illustrates the topography of the outcrop face, not the grain size of each unit. Modified from Bierly and others (2023). (B) The fossil bearing interval displaying both shale layers. One-foot-long hammer rests on the lower shale. The plant fossil and sample yielding pollen and spores was collected from the upper shale interval. (C) Detailed view of yellow outlined area in (B). Directly underlying the lower shale to the right of the hammer in (B) is highly weathered coal. (D) Fossil plants recovered from this interval. This sample is now archived at the State Museum of Pennsylvania, Harrisburg, Pennsylvania (Specimen ID SMP-PB9682). GPS: 40.22615°, -74.98518°

present in the middle member. Paleosols and invertebrate burrows suggest an environment in which floodplains are stabilized and channel migration is restricted. This contrasts with the underlying lower member, which is replete with coarse sediments, amalgamated bedforms, and generally lacks fine-grained material: all features implying a high-energy, dynamic depositional environment in which channels frequently avulse and rework floodplain fines. Since tongues of lower member lithologies are present within the middle member, we interpret the middle member of the Stockton Formation as a transition from the sand-dominated, braided fluvial environment of the lower member to an anastomosing to meandering fluvial environment.

The basal contact with the underlying lower member is conformable, gradational, and is placed at the top of the highest conglomerate or coarse-grained sandstone of the lower member. The calculated thickness of the middle member is 2,190 to 3,315 ft. Like the lower member, the middle member thins eastward.

Upper member

The upper member of the Stockton Formation is present along the northern edge of the study area except where it is cut out by the Neshaminy Farms Fault in the central part of the study area (Bierly and Oest, 2023). The upper member is characterized by grayish-red, thin- to medium-bedded shale, siltstone, and medium- to thick-bedded, very fine grained sandstone (Figure 11).

Sandstones within the upper member are dominantly very fine to fine-grained and commonly have tabular and trough cross stratification and ripples. Climbing ripples were observed in one instance in outcrop along Grenoble Road approximately 250 ft north of Little Neshaminy Creek. Sandstones form sheets and lenticular bodies that may pinch out laterally at the outcrop scale and locally scour into underlying beds, particularly when mudstone is the underlying lithology. Sheet sandstones are interpreted to represent moderate energy flooding events, where sufficient flow was present to transport sand from channels to the floodplains but scouring and reworking of floodplain fines did not occur. Lenticular sand bodies likely represent splays or channel avulsions where energy was great enough to scour and transport floodplain materials. Lenticular sandstones do not occur as amalgamated beds as in the lower member, suggesting an environment with well-established floodplains and entrenched channels.

Mudstones commonly have ped structures, pedogenic slickensides, and clay-infilled root traces. Trace fossils are present in mudstones as bedding parallel (*Planolites*?) and vertical burrows. In some places, mudstones are observed to be weakly calcareous. Shales and siltstones have straight crested to sinuous ripples, planar laminations, and desiccation cracks. Rippled, laminated, and desiccated mudstones are interpreted as distal floodplain slack water deposits, where floodwater accumulated in depressions and fines were transported from channels to these depressions during flooding events.

Lithologies are commonly arranged in fining-upward packages, some of which are in excess of 10 ft thick (Figure 12). Desiccation cracks and calcareous paleosols imply at least periodic wetting and drying of floodplain environments and are consistent with the prevailing semiarid climate during the deposition of the Stockton Formation. Floodplain materials are abundant in

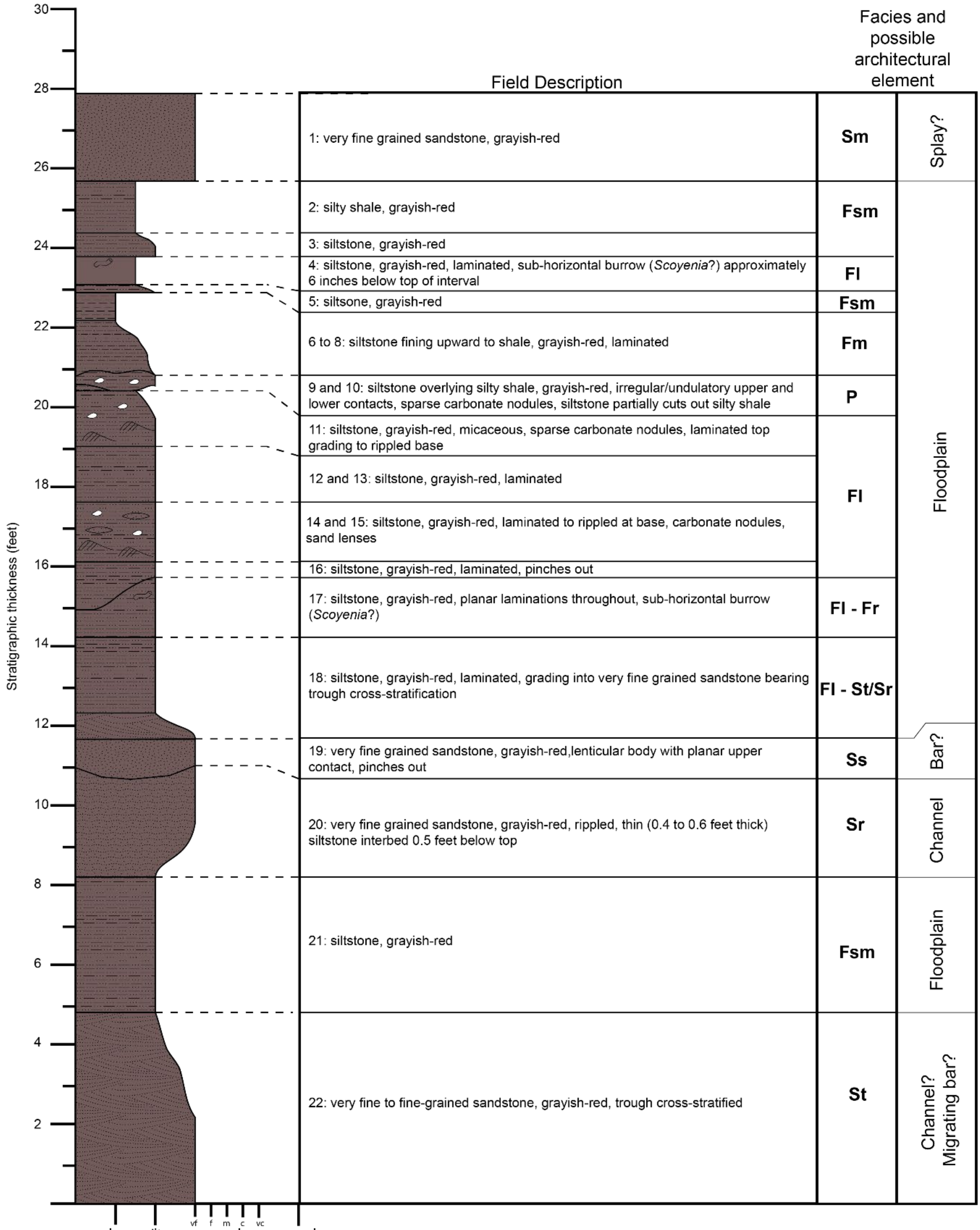


Figure 11. Reference section for the upper member of the Stockton Formation. Section is located along Grenoble Road approximately 250 ft north of Little Neshaminy Creek in Warwick Township. See Figure 6 for key to symbology. Lithofacies are classified after Miall (1978) and potential fluvial architectural elements of Miall (1985). Lithofacies codes indicate the following: Sm – sand, fine to coarse, massive or faint laminations; Fsm – silt and mud, massive bedding; Fl – sand, silt, mud with fine lamination or very small ripples; Fm – mud and silt, massive bedding with desiccation cracks; P – paleosol with calcareous nodules; Fr – mud and silt, massive to rooted and bioturbated; St – sand, fine to very coarse, may be pebbly with trough cross beds; Sr – sand very fine to coarse, with ripple cross-lamination; Ss – sand, fine to very coarse, may be pebbly with broad, shallow scours. Queried architectural elements indicate uncertainty. GPS: 40.24212°, -75.05561°

the upper member in contrast to the middle and lower members and is suggestive of deposition on a low-gradient alluvial plain where channel migration was limited to a meander belt.

The basal contact with the underlying middle member Stockton Formation is conformable and gradational and placed at the top of the highest medium- to coarse-grained sandstone of the middle member of the Stockton Formation. The calculated thickness of the upper member is between 435 and 515 ft.

Figure 12. Outcrop of the upper member of the Stockton Formation. Note blocky weathering and uniform grayish-red color. Individual is approximately 6 ft tall. Photo taken March 25, 2022. GPS: 40.24212°, -75.05561°

Lockatong Formation

Only the basal Lockatong Formation is present in the study area. It forms a discontinuous outcrop belt along the northern edge of the study area, the result of folding rotating these strata in and out of the study area (Bierly and Oest, 2023). The Lockatong Formation is a distinct lithologic break in the Late Triassic section and is characterized by light-olive-gray and medium-gray to dark-gray siltstone and argillite, dark-gray to black shale, and subordinate light-gray to medium-gray, very fine grained sandstones (Figure 13).

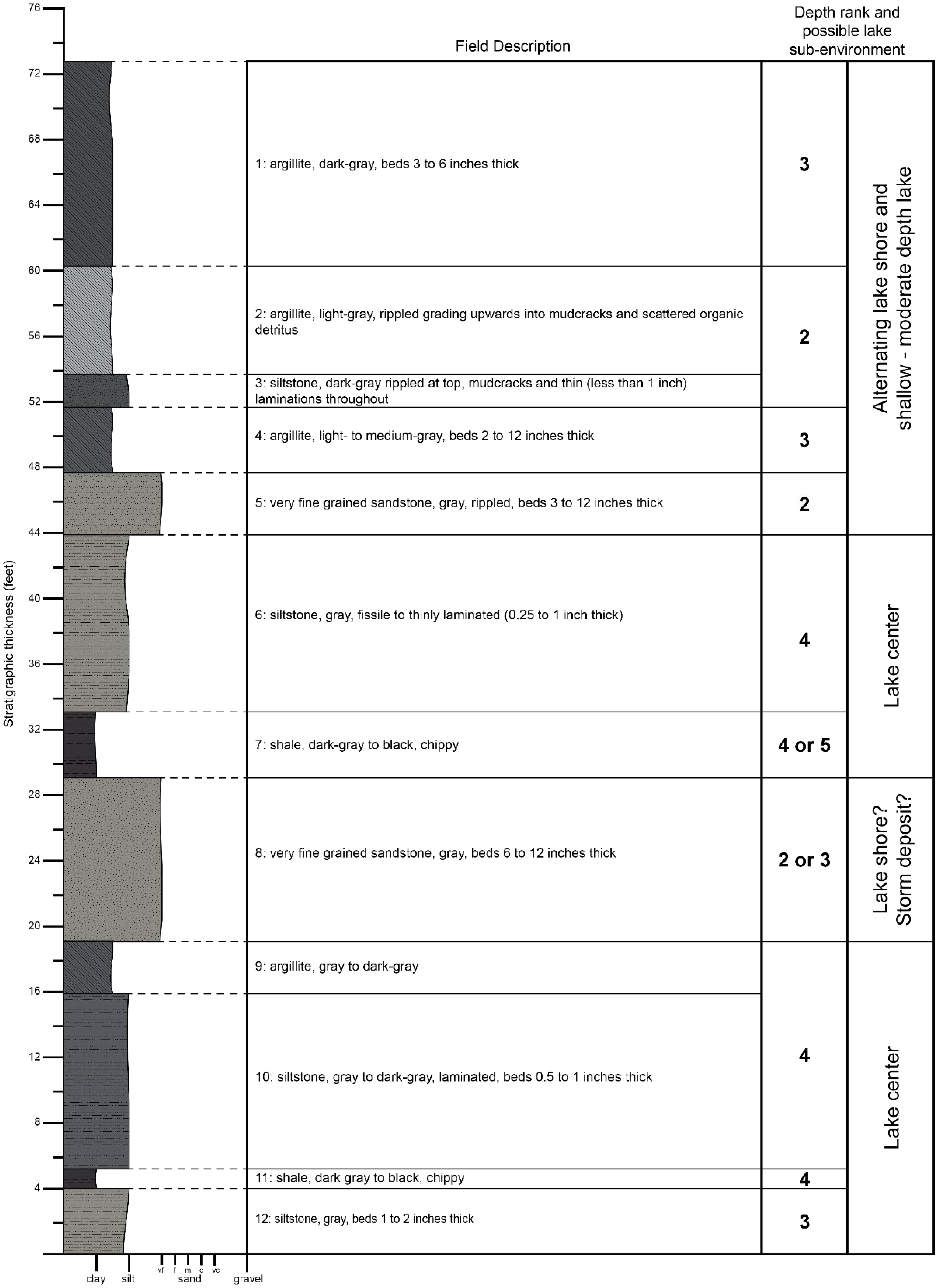


Figure 13. Reference section for the Lockatong Formation. Note distinct color and grain size change compared to the underlying Stockton Formation (Figure 6, 8, and 11). The section is located in a drainage 580 ft northwest of the Tyler State Park Covered Bridge parking lot. See Figure 6 for key to symbology. Lake depth ranks are of Olsen, 1986, 1989, and 2018; Olsen and Kent, 1996; and Olsen and others, 1996. The depth scale is inferred from lithology, where 0 is the shallowest lake condition (subaerially exposed and manifested by red, mudcracked mudstone) and 5 is the deepest lake condition (dark-gray to black, microlamintated mudstone). GPS: 40.24695°, -74.97926°

Within the study area, siltstone and argillite are the primary lithologies of the Lockatong Formation. These strata are medium- to thick-bedded, with argillite beds occurring in excess of 4 ft thick observed along Neshaminy Creek in Tyler State Park. Laminations, ripples, and mudcracks are present in siltstones. Soft sediment deformation is present within siltstone beds in some locations as convoluted bedding. Rippled and mudcracked siltstone beds are interpreted to have been deposited in marginal lacustrine environments in relatively shallow water. In contrast to the siltstones, argillite beds are commonly massive but locally have ripples. The finer-grained nature of argillite and the overall lack of sedimentary structures or bioturbation indicate deposition in deeper lacustrine environments (Figure 13). Argillite is exceptionally hard and weathers to form large blocks. Both the siltstone and argillite exposures are calcareous in some locations.

Subordinate lithologies observed within the study area include dark-gray to black shales and very fine grained sandstones. Shales are commonly fissile to chippy. Very fine grained sandstones are present as thin- to medium-bedded and massive beds and represent an influx of sediment during periods of high discharge from streams feeding the lake basin. Shales weather recessively (Figure 14), while sandstones form subtle benches that are readily observable in stream beds and form ledges in outcrop.

Figure 14. Outcrop of the Lockatong Formation approximately 1,765 ft east of the intersection of Second Street Pike and Twining Road in Northampton Township. Note the recessive weathering character of this shale-dominated section (directly behind individual) and ledge of slightly more resistant siltstone overlying the shale interval. Blocky boulders in foreground are mainly composed of argillite. Individual is approximately 6 ft tall. Photo taken October 19, 2022. GPS: 40.24276°, -75.00199°

Fossil fish are present in the Lockatong Formation, with particularly well-preserved specimens recovered from the Eureka quarry in the southeast portion of the Doylestown quadrangle (Olsen, 2018), 0.5 miles north of the study area. Fossil fish were not observed within the study area during this investigation.

Lake depth cyclicity is well-documented within the Lockatong Formation and is driven by orbital variations (McLaughlin, 1933; Van Houten, 1964, 1969; Olsen, 1986; Olsen and others, 1996). Shallowing-upward packages are identified by a succession starting with a basal structureless to laminated rock (either shale, siltstone, or argillite) grading into rippled to mudcracked rock (siltstone or argillite). Rock color covaries with the trend in lithology and sedimentary structures, with basal strata in these packages being dark-gray to black grading up-section to gray, light-gray, or light-olive-gray beds. Darker, fine-grained strata suggest deposition in low-energy, hypoxic to anoxic conditions and are interpreted to be the result of deep lake conditions while laminated to rippled, gray to light-gray strata indicate deposition in relatively shallow, more oxic conditions. Ultimately, light-gray to light-olive-gray, rippled and mudcracked beds suggest deposition in the shallowest lake conditions with at least periodic subaerial exposure occurring to produce the mudcracks. In some places, the shallowest portions of these cycles are marked by grayish-red mudstones, although this is only present at one outcrop within the study area. Lake depth ranks are assigned to the reference section for the Lockatong Formation in Figure 13, following the criteria of Olsen (1986, 1989, 2018), Olsen and Kent (1996), and Olsen and others (1996).

The basal contact with the upper member of the Stockton formation is gradational, with grayish-red siltstone occurring as interbeds with gray shale and gray siltstone. The contact is placed at the base of the lowest gray shale, siltstone, or argillite in this transitional zone. The lower 1,400 to 1,900 ft of the Lockatong Formation is present in the study area.

Diabase

Diabase is present as thin dikes in the northeastern portion of the Ambler quadrangle and the northwestern portion of the Hatboro quadrangle (Bierly and Oest, 2023). Outcrop of diabase was not observed during this investigation; therefore, mapping is based on float material and interpretation of lidar imagery. Diabase is a dark gray, finely crystalline, intrusive rock largely composed of plagioclase and pyroxene. One diabase sample was analyzed for bulk geochemistry (see Appendix 2) and is consistent with the York Haven type of Smith and others (1975).

All three dikes shown by Bierly and Oest (2023) were previously mapped by Lyttle and Epstein (1987). Only one dike, the center position dike (Figure 1), is expressed as a recognizable topographic high that can be traced using lidar-derived hillshade imagery (Figure 15). The orientation of this dike is modified from Lyttle and Epstein (1987) based on lidar imagery. Evidence of the other two mapped dikes is inferred from boulder float in and near Little Neshaminy Creek (Figure 16). Float observations confirm the existence of these dikes, however, without additional outcrop control or an observable lidar signature, the orientation of these dikes is not modified from what is shown by Lyttle and Epstein (1987). Dike inclination is inferred to be subvertical. Dikes may have intruded along existing joints or unrecognized faults. One small

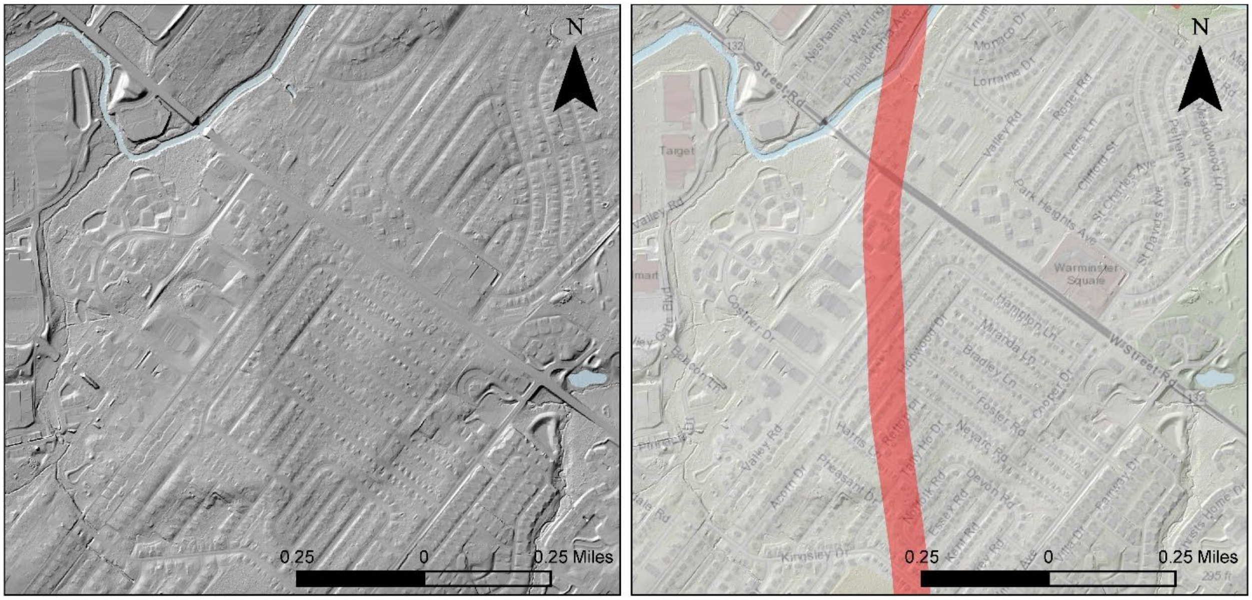


Figure 15. Left) Subtle topographic inflection identified in hillshade imagery corresponding to diabase boulder float observation in Little Neshaminy Creek. This is the center position dike on Map 23-01.0. Right) Diabase dike line placement relative to the topographic inflection (dike line width is not to scale).

Figure 16. A) Diabase boulder float along Little Neshaminy Creek approximately 890 ft northeast of the intersection of Street Road and Brinkworth Avenue. Stick is 4 ft long. B) Image shows detail of diabase. Note the contrast between weathered color (dark-yellowish-orange) on surface of the boulder shown in A and fresh color (dark-gray) of the hand sample in B. Photo taken May 5, 2022. GPS: 40.22611°, -75.12817°

diabase float cluster was observed upstream of the mapped dikes, which suggests the presence of an additional dike west of the mapped dikes; however, anthropogenic transport cannot be ruled out as a source of this float due to the developed and densely populated nature of the study area. For this reason, this feature is shown as an observation point on Bierly and Oest (2023) rather than as a line feature.

STRUCTURE

The Triassic strata within the study area are relatively undeformed. The dominant structural features are gently inclined bedding and steeply inclined jointing. This is in sharp contrast with the highly deformed Proterozoic metamorphic rocks adjacent to and underlying the siliciclastic basin fill material. Discussion in the subsequent sections focuses on the Newark Basin portion of the study area. All structural measurements are included in a geodatabase that accompanies Bierly and Oest (2023).

Bedding

In general, bedding is gently inclined (typically 7 to 15 degrees, as shown in Figure 17) to the north-northwest in the study area (Bierly and Oest, 2023). This is consistent with other bedding orientation observations within the Newark Basin, where structure is controlled by syndepositional slip on the border fault along the northern edge of the basin resulting in strata dipping towards the border fault. Anomalously steep bedding inclinations, ranging from 20 to 74 degrees, are locally present and are typically associated with faulting. For anomalous bedding inclinations on the lower end of this range, bedding orientation measurements may be skewed by primary sedimentary structures. Although efforts were made to select surfaces representative of bedding planes, influence from primary structures could not be ruled out due to limited outcrop exposure. This is particularly true in the intensely cross-stratified intervals of the lower and middle members of the Stockton Formation. South dipping beds were observed in some locations and occur along the axes of plunging folds.

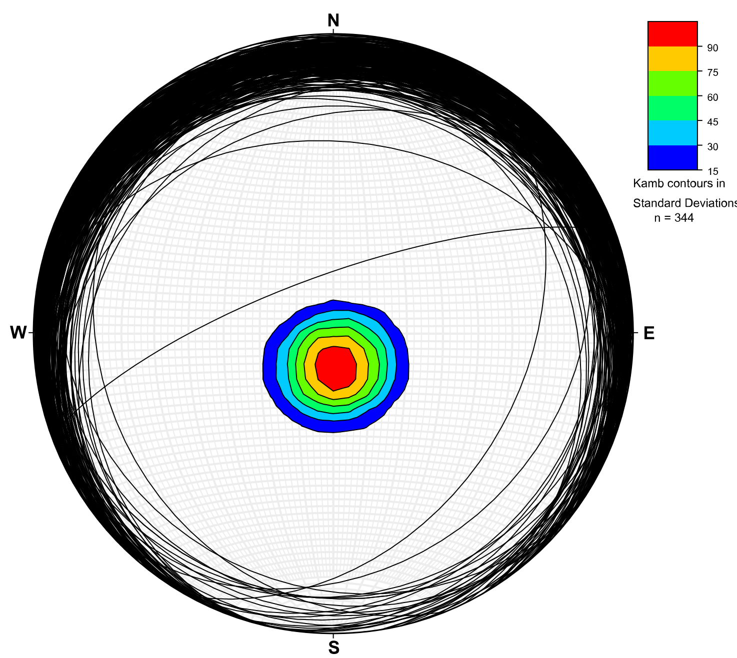


Figure 17. Lower hemisphere, equal area stereonet plot of bedding plane orientations (black lines) and Kamb contours of poles to bedding planes for all bedding measurements. Poles to bedding planes are not shown for clarity. Contour interval is 2 standard deviations.

Folds

Two regional folds are present within the study area: the Warrington Anticline and an unnamed syncline immediately east of the Warrington Anticline (Willard and others, 1959). This investigation confirmed the presence of these folds; however, the orientation of the axial trace of these folds is modified based on newly collected bedding orientations (Bierly and Oest, 2023). Field data suggests the fold axes trend nearly north-south, rather than northeast-southwest as shown by Faill (2011). This investigation also reveals an additional five anticlines and six synclines, all of which have limited areal extent and occur along the northern boundary of the study area. The fold axes trend subparallel to the regional dip direction and have broad wavelengths, with dimensions ranging from 4,700 to over 7,000 ft between axes. Folds are narrower southeast of the Neshaminy Farms Fault block, with wavelengths ranging from 1,200 to 3,600 ft. This pattern is thought to be related to stress accommodation in the vicinity of the Neshaminy Farms Fault.

Joints

Joints within the study area were observed to be non-mineralized, steeply dipping, and primarily in pairs oriented approximately north-south and east-west (Bierly and Oest, 2023). In the Lockatong Formation, the primary joint orientation is northwest-southeast with subordinate joint sets oriented east-west and north-south (Figure 18A). Joints are steeply to very steeply inclined (72 to 86 degrees). The jointing pattern in the Stockton Formation varies slightly as a function of stratigraphic position. Joints in the upper member are primarily oriented north-south with subordinate joints oriented east-west and northwest-southeast (Figure 18B). Joints in the middle member have consistent orientations with a primary north-south set and an east-west set with most strikes from each set falling in a 60-degree range (Figure 18C). Joints in the lower member are the most varied in terms of their range in orientation but are approximately evenly distributed between northeast-southwest and north-south striking pairs (Figure 18D). Similar to the joints observed within the Lockatong Formation, joints within the Stockton Formation are steeply inclined with dip magnitudes ranging from 72 degrees to vertical.

Joint variability as a function of stratigraphic position can in part be attributed to primary sedimentary structure and lithology. The strike of joints in intensely cross-stratified intervals rotate at the outcrop scale. Efforts were made to determine strike on representative planes (i.e. the most consistent orientation observed within a particular outcrop); however, this proved to be difficult in instances where outcrop was limited. Similarly, joint surfaces were much more irregular in coarser-grained rocks, such as granular to pebbly sandstones and conglomerates, compared to those within siltstones and very fine grained sandstones.

Faults

This investigation confirms the location and relative motion on the Neshaminy Farms Fault (see Willard and others, 1959; Berg and others, 1980; Lyttle and Epstein, 1987). However, field

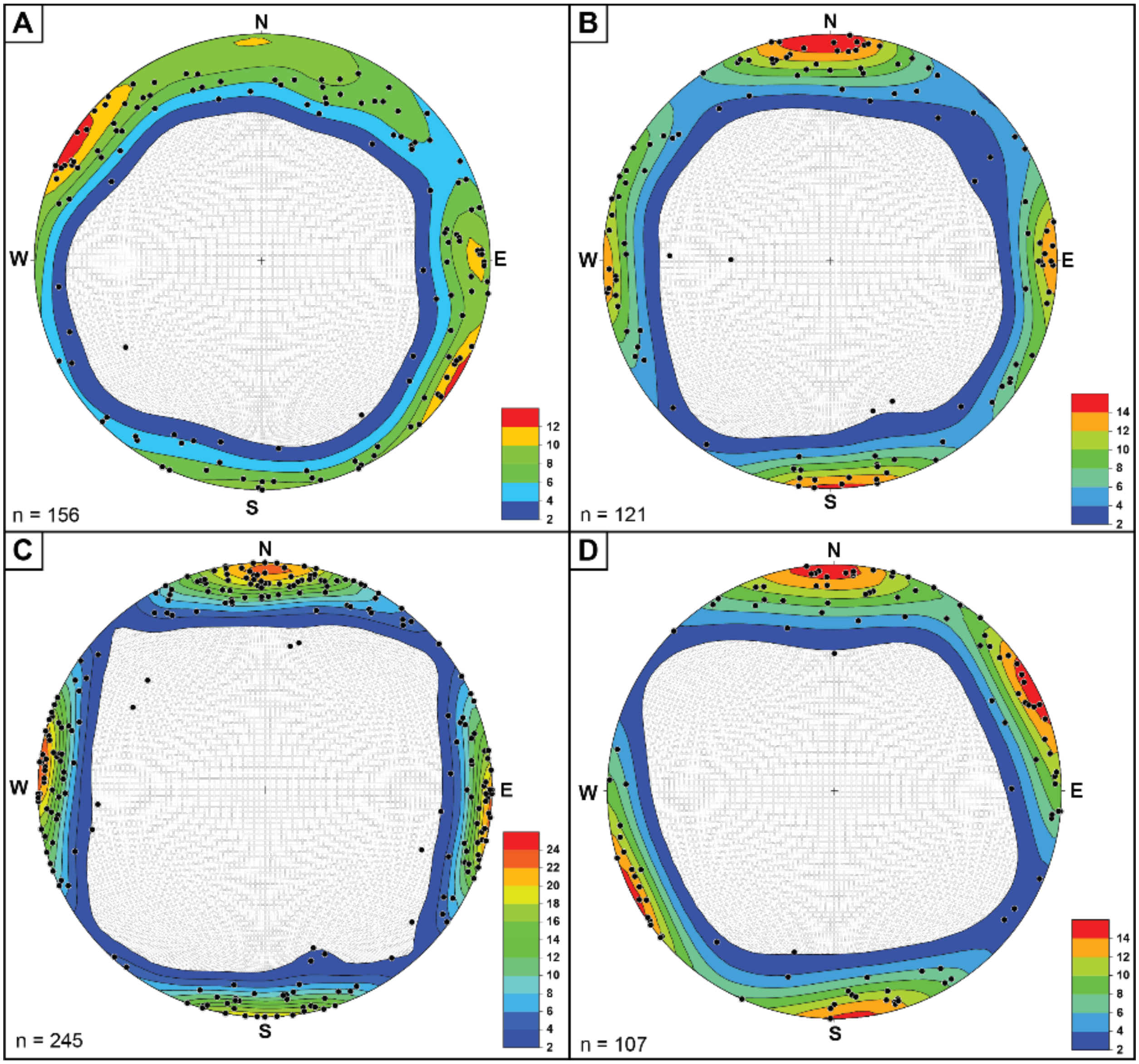


Figure 18. Lower hemisphere, equal area stereonet plots of contours of poles (black circles) to joint planes for the A) Lockatong Formation, B) upper member Stockton Formation, C) middle member Stockton Formation, and D) lower member Stockton Formation. Color scale is Kamb contours in standard deviations. Contour interval is 2 standard deviations for each plot.

data collected during this investigation indicate the Neshaminy Farms Fault dips southeast, which is opposite to the dip direction reported by Willard and others (1959). New outcrop data collected along Swamp Road in Newtown Township suggest that this structure is at least 11,500 ft long along strike, approximately double the originally mapped surface trace. The Neshaminy Farms Fault strikes east-northeast and is steeply inclined, with one exposure dipping 73 degrees (Bierly and Oest, 2023). Kinematic indicators are sparse: slickenlines and disturbed bedding were only observed along Neshaminy Creek, approximately 0.5 miles south from the intersection of Worthington Mill Road and Swamp Road. Relative motion along the fault is inferred as reverse because of the observed juxtaposition of the Lockatong Formation against the middle member of the Stockton Formation. The collocation of these units was observed in an unnamed tributary to Neshaminy Creek approximately 1,300 ft west of Worthington Mill Road in Richboro. Fault throw is estimated to be at least 525 ft because this is the average thickness of the upper member of the Stockton Formation immediately adjacent to the area where it is entirely cut out by faulting.

A previously unmapped fault was identified approximately 3,500 ft north-northwest of the Neshaminy Farms Fault. This fault strikes north-northeast subparallel to the Neshaminy Farms Fault and dips 70 degrees. Offset is apparent at this outcrop and is minimal (observed to be approximately 2 ft).

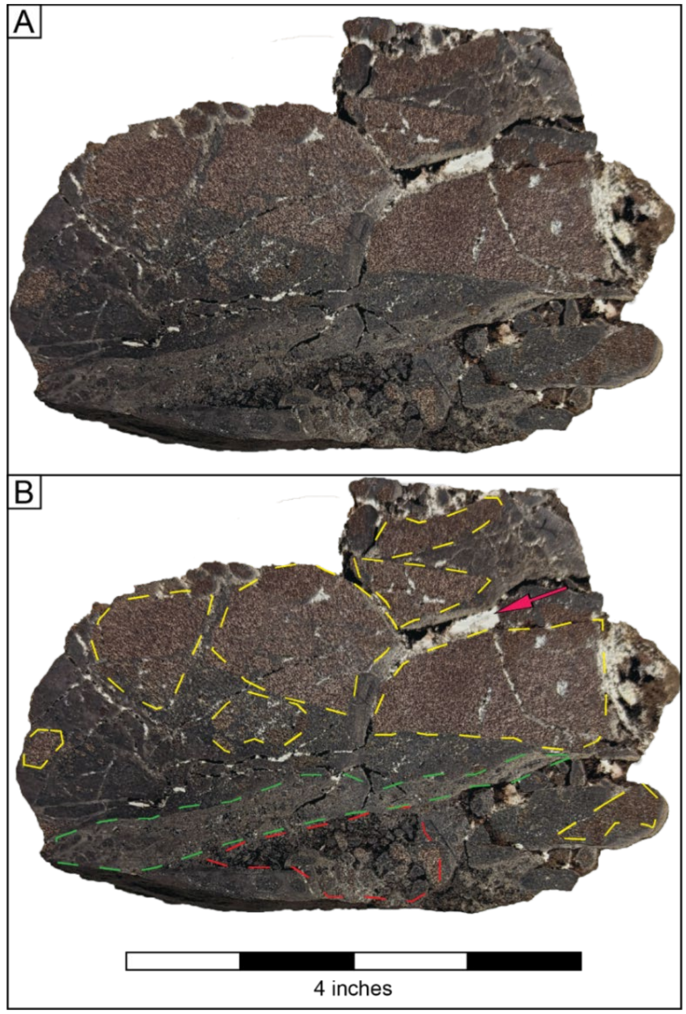


Figure 19. A) Slabbed hand sample of brecciated fault material collected from a small northwest-southeast striking fault observed in a drainage on the south bank of Neshaminy Creek 2,600 ft east of the intersection of the Neshaminy Farms Fault and Worthington Mill Road. The red arrow indicates a soft, white mineral identified as dickite. Dickite is partially infilling intragranular pore space. B) Yellow outlines show angular fine- to medium-grained sandstone clasts. Green outline shows smeared mudstone. Red outline shows subrounded to subangular granules of sandstone and mudstone. Scale in B applies to both images. GPS: 40.24221°, -74.98766°

A second previously unmapped fault occurs approximately orthogonal to both aforementioned structures (Bierly and Oest, 2023). The dip direction and magnitude are uncertain for this structure. The fault surface is not exposed and features indicative of faulting—such as slickensides, brecciated material, or disturbed bedding—were not observed in outcrop. The presence of this structure is inferred from the juxtaposition of lithologies consistent with the middle member of the Stockton Formation against the Lockatong Formation where the upper member of the Stockton Formation was absent. The Neshaminy Farms Fault and the unnamed fault to the north both terminate against this structure. This abutting relationship implies three possible scenarios for the timing of faulting. First, because the Neshaminy Farms Fault and the unnamed north-northeast fault apparently terminate against the north-northwest striking fault, it is possible that the north-northwest fault is older than the Neshaminy Farms Fault and the north-northeast fault. Alternatively, the north-northwest fault could be younger than the

Neshaminy Farms Fault and the north-northeast fault if evidence of faulting to the west of the north-northwest striking fault has been lost to erosion. Finally, since the faults abut against, but do not cut, the north-northwest striking fault, there is ambiguity in the age relationships of these structures, and it is equally possible that all three of these faults formed coevally as a rotating block. Since a normal sense of motion is observed on the north-northeast fault and reverse sense of motion is observed on the Neshaminy Farms Fault, the most likely scenario to explain this faulting is localized rotation in response to regional tension due to rifting and these structures likely formed concurrently.

Nine other faults, with a lateral extent of 1,000 ft or less along strike, are identified by this investigation (Bierly and Oest, 2023). Eight of these faults occur in the northern portion of the study area and are oriented either subparallel or suborthogonal to the strike of the Neshaminy Farms Fault and are interpreted to be related to this structure. Kinematic indicators are sparse or not present on many of these small-scale faults and their presence is inferred by disturbed bedding or brecciated material. In some locations, dickite mineralization has occurred within the pore spaces of this brecciated material (Figure 19). Offset along these faults is interpreted as minimal and highly localized.

SURFICIAL GEOLOGY

Mapping of surficial units was performed by interpreting geomorphological elements from lidar-derived hillshade imagery and aerial photography. Based on the lidar, landforms could be delineated, and elevation profiles could be constructed and used to identify most of the surficial deposits. Field observations confirmed feature identification and provided descriptions of each material that was observable within the study area. Eleven surficial units were identified within the study area and include bedrock, residuum, and colluvium, undifferentiated; Pensauken Formation; upper terrace; middle terrace; lower terrace; alluvial fan; alluvium; alluvial fan and delta, undifferentiated; quarry; fill; and water.

PROTEROZOIC THROUGH QUATERNARY

Bedrock, Residuum, and Colluvium, Undifferentiated

Saprolite, residuum, and weathered bedrock are predominantly located on hilltops and hillsides across the entire study area (Bierly, 2023). These deposits occur where bedrock has been exposed to physical and chemical weathering processes at the surface and shallow subsurface. Examples of these processes include freeze-thaw, groundwater fluctuation, bioturbation, and rainwater percolation. Together, these processes cause interstitial cement present in bedrock to dissolve and mineral grains of the rock to alter to forms more stable at surface pressure and temperature conditions (e.g., feldspar weathering to clay). *In situ* weathered bedrock that has lost all cementation but has retained its primary structures is saprolite. *In situ* weathered bedrock lacking any identifiable primary structure is residuum. Within the Newark Basin, bedrock is dominantly sandstone and mudstone. Outside of the basin, marble, gneiss, and amphibolite are present. Sandstone, gneiss, and amphibolite weather to sandy saprolite and residuum (Figure 20), while mudstone weathers to clay and diamict.

Colluvium is observed in topographic lows between hilltops, at the base of steep slopes, and in upland draws (Bierly, 2023). These deposits form when bedrock, soil, or other surficial deposits flow down slope under gravity and are deposited at the base of the slope. Rainwater percolation and freeze-thaw cycles are important in the development of colluvium, as these physical processes encourage erosion of rock fragments from *in situ* strata and generate material that can migrate down slope. Colluvium is composed of poorly sorted, angular to subangular, granule- to boulder-sized clasts of locally sourced bedrock in a clay to silty or sandy clay matrix. Colluvium, bedrock, saprolite, and residuum were mapped as one unit, because the individual units are not resolvable at the 1:24,000 scale. Additionally, widespread suburban development within the study area obscures colluvial geomorphological features, making identification and delineation difficult to impossible.

Water wells indicate saprolite, residuum, and colluvium are commonly 5 to 15 ft thick and, in some places, up to 36 ft thick. Residuum is broadly Quaternary in age but may be as old as the Paleogene (Sevon, 2000). Colluvium is largely dated to the Quaternary, with most development likely occurring during the Pleistocene.

Figure 20. In an unnamed tributary to Ironworks Creek downstream of Springfield Lake, an exposure of residuum of highly weathered sandstone is overlain by 2 ft of headwater alluvium (dominantly overbank silt/loam) deposit. Above the residuum-alluvium contact (yellow dashed line), angular sandstone pebbles eroded from the underlying bedrock (Stockton Formation, lower member) are present. Rock hammer is 1 foot long. Photo taken October 27, 2021. GPS: 40.179131°, -74.989219°

PLIOCENE TO PLEISTOCENE

Terraces

Terrace deposits are abandoned floodplains that form when streams cut down through previously deposited floodplain sediments and into the underlying bedrock, thus creating a newer floodplain at a lower elevation. This downcutting occurs when the stream gradient increases due to isostatic rebound or lowering of sea level. This process can occur several times, creating a series of terraces. In the study area, terrace formation is attributed to a complex relationship between eustatic and isostatic sea level fluctuations responding to climate variability during the Pleistocene. The exception to this is the Pennsauken Formation, which may include older strata.

Meandering channels often erode large portions of the original floodplain over time, to the point where only scattered fragments of the terrace remain. Thus, terraces are commonly identified as discontinuous topographic benches with similar lithologies at similar elevations. Four terrace deposits have been identified in this study area; of these, the oldest (with the highest elevation) is the Pensauken Formation and is a terrace of the Delaware River. The other three terraces (upper terrace, middle terrace, and lower terrace) are younger terraces reflecting downcutting of Neshaminy Creek and its tributaries. Age-dating was attempted for terrace deposits, but organic carbon or sediment suitable for OSL analysis was not present.

Pensauken Formation

The Pensauken Formation is present at Styer Orchard near Langhorne (Bierly, 2023). Rounded pebbles and cobbles of sandstone, milky quartz, quartzite, gneiss, and schist provide the only evidence of its presence (Figure 21). The Pensauken Formation is a thin veneer, which coincides geographically with the cobbles observed at Styer Orchard. It is probable that the mapped areal extent is overestimated due to periglacial and agricultural activity. Thus, additional data and field visits are required to refine the extent of this unit.

Figure 21. Rounded clasts of Stockton Formation sandstone interpreted to be of the Pensauken Formation. Scale is in centimeters. GPS: 40.19736°, -74.89953°

PLEISTOCENE

Upper Terrace

The upper terrace is a topographic bench is estimated to be between 0 to 5 ft thick at an elevation of approximately 50 to 57 ft above the present stream channel. Mapping is based solely on lidar and elevation profile interpretation (Bierly, 2023). Additional field work is required to confirm the existence of this terrace since it has not been observed in outcrop.

Middle Terrace

The middle terrace is a topographic bench estimated to be between 5 and 23 ft thick located approximately 23 to 40 ft above the present stream channel (Bierly, 2023). Delineation of this unit was completed using lidar and correlation of elevation profiles. Additional field work is required to confirm the existence of this terrace since it has not been observed in outcrop. As a result, this unit likely includes alluvial fan deposits of similar age. Correlation of elevation profiles suggest this unit may represent two discrete terraces located 23 to 35 ft and 35 to 40 ft above the present stream channel.

Lower Terrace

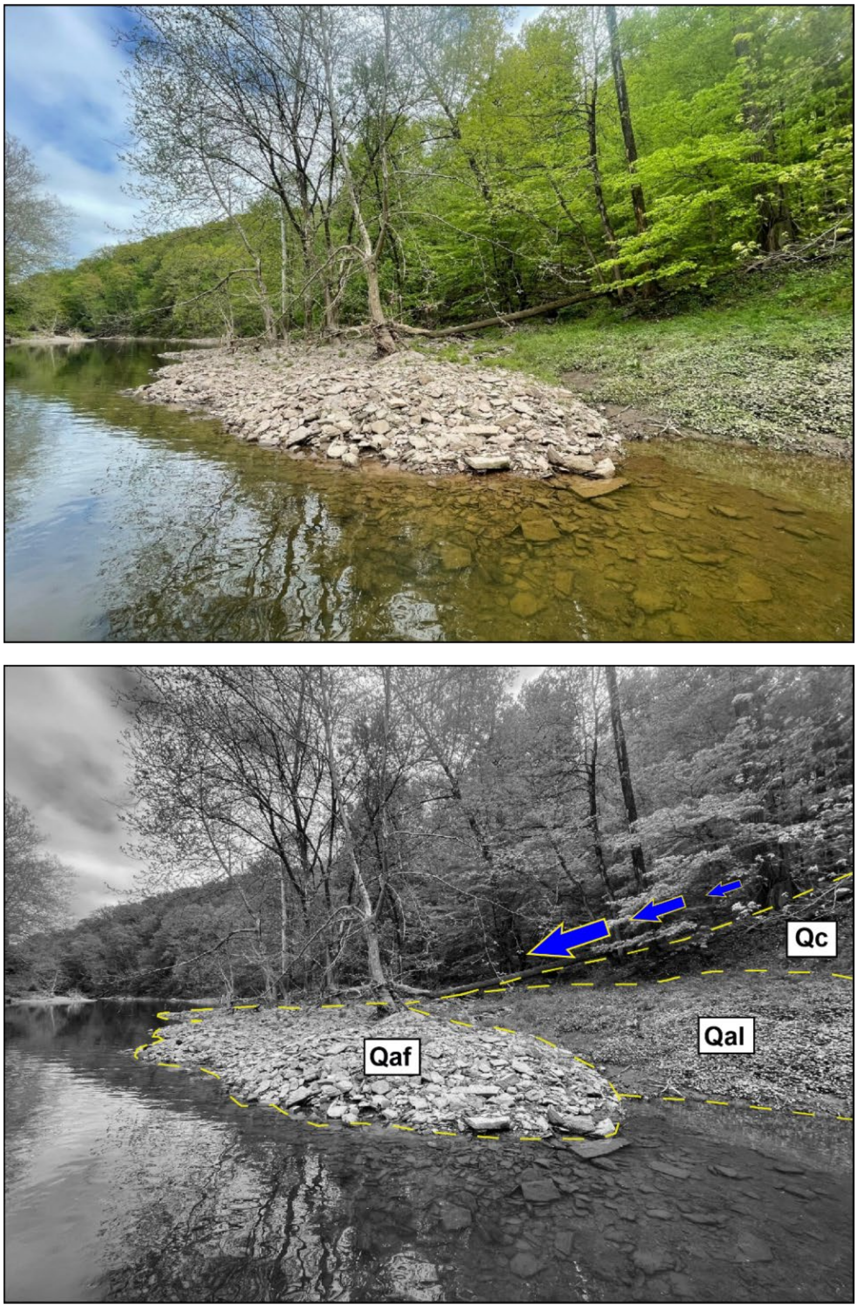
The lower terrace is a topographic bench between 5 and 10 ft thick located atop bedrock ledges approximately 10.5 to 23 ft above the present stream channel (Bierly, 2023). The base of the deposit is a gravel or dark-reddish-brown diamict up to 4.1 ft in thick. The gravel deposits are composed of subrounded cobbles to small boulders in a sandy silt matrix. Imbrication of gravel size clasts is observed in some locations. Overlying the gravel is a moderate-yellowish-brown to brownish-gray, medium-stiff, silt and loam that was observed to be up to 10 ft thick in places. As with the middle terrace, the lower terrace may include alluvial fan deposits of similar age. Lower terrace deposits overlie bedrock ledges and have a total estimated thickness of 5 to 10 ft.

Terrace, Undefined (Qt)

Unidentified terraces between 5 and 10 ft thick were observed where topographic benches occur less than 10.5 ft above the present stream channel along Core Creek, Mill Creek, Newtown Creek, and Little Neshaminy Creek and its tributaries (Bierly, 2023). The lithology of this unit is similar to alluvium and may be correlative to lower terrace.

PLEISTOCENE (?) TO HOLOCENE

Alluvial Fan



Alluvial fans occur at the mouth of headwater streams when they intersect the floodplain of a larger stream within the study area (Figure 22). They are commonly between 5 and 10 ft thick within the study area, however, larger fans are estimated to be as thick as 30 ft. Alluvial fans were identified in lidar imagery by their characteristic lobe shape found at the mouths of tributaries (Bierly, 2023). In the study area, deposits include grayish-brown to medium-gray, moderately to poorly sorted gravel and diamict. Clasts are commonly angular to subangular and range in size from granules to small boulders. Imbrication and normal grading were observed in some locations. These sediments are overlain by moderate-yellowish-brown to grayish-brown silt and very fine to very coarse grained, moderately to poorly sorted sand that commonly fines upward. The distal edges of fans are interfingered with alluvium. (Figure 22). This observation, combined with clast size,

Figure 22. An alluvial fan splays out into Neshaminy Creek across from the Eureka Stone Quarry at Rushland. The fan is composed primarily of angular to subangular cobble to boulder gravel. In the background, behind the trees, the feeder stream (shown with blue arrows) is flowing over a bedrock dip slope. Sediment is deposited on the fan during heavy precipitation events when eroded bedrock and colluvium (Qc) is carried in the stream, across the bedrock dip slope, and deposited at the tributary's mouth across Neshaminy Creek's floodplain and stream channel. Photo taken May 11, 2022. GPS: 40.24845°, -75.021225°

suggests sediment transport and deposition within these alluvial fan deposits was punctuated and occurred primarily during heavy precipitation events.

HOLOCENE

Alluvium

Alluvium includes sediment deposited by flowing water on modern-day floodplains of active stream channels. In this study, alluvium is mapped based on interpretation of lidar imagery and elevation profiles. Deposits are composed of stratified layers of clay, silt, sand, and gravel (Figure 23).

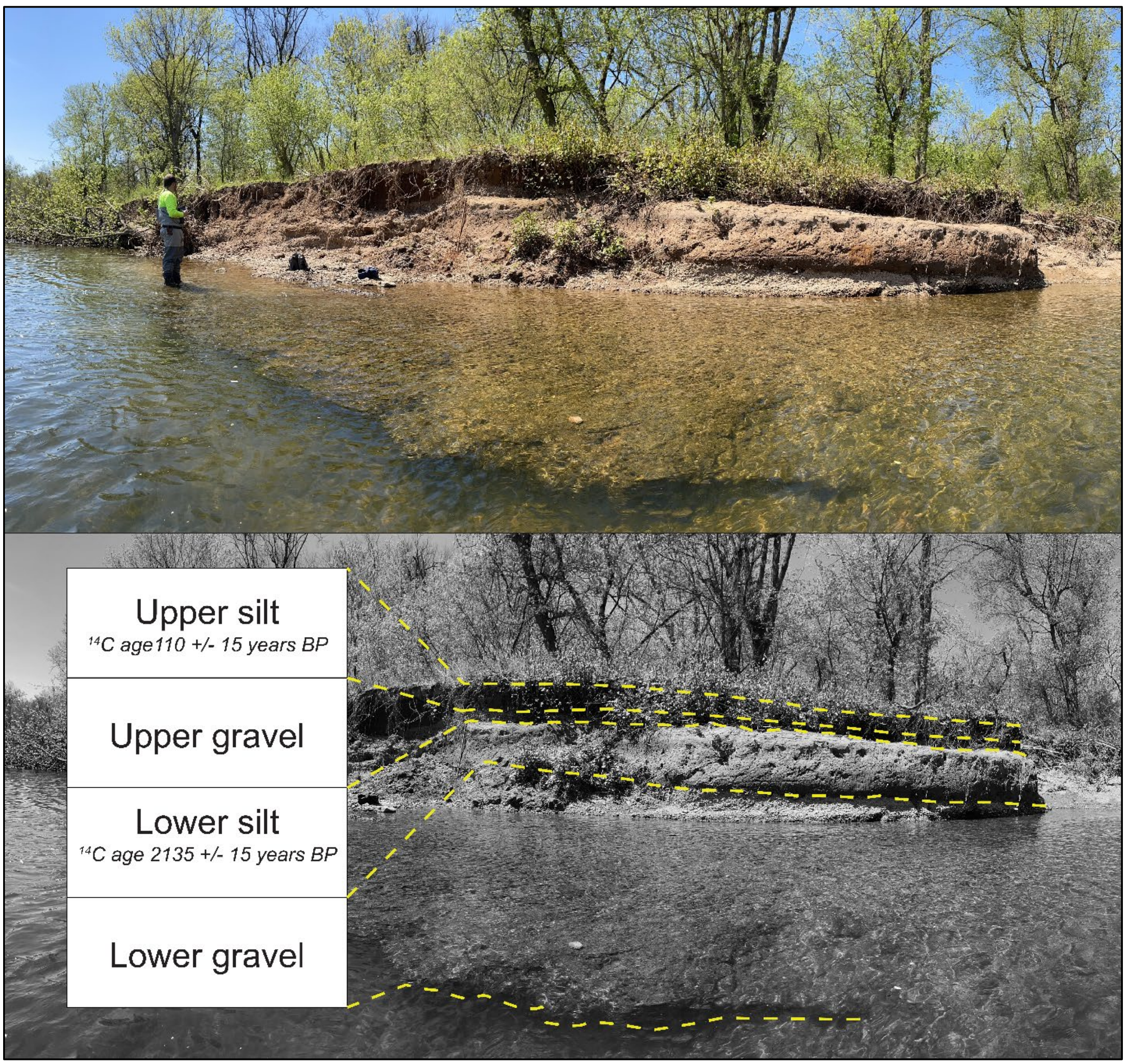


Figure 23. (previous page) Alluvium exposure along Neshaminy Creek across from Playwicki Park in Middletown Township. Exposure bears two sets of stream channel gravel overlain by overbank silt. Both silt horizons contained charcoal fragments. The upper silt produced a radiocarbon age of 110±15 years BP (calibrated age between 1693 AD to 1919 AD). The lower silt produced an age of 2,135±15 years BP (calibrated age between 343 BC and 58 BC). Note the thick ledge of gravel under water. Individual is approximately 6 ft tall. Photo taken April 29, 2022. GPS: 40.17884°, -74.95561°

A common depositional sequence of gravel, sand, loam/silt was observed throughout the study area. The gravel is medium-gray in color, stiff to very stiff, and with varying degrees of imbrication. Clasts are composed of locally sourced bedrock subangular to rounded shape that range in size from granule to small boulders. The matrix between clasts varies from clay to sand. Gravels are commonly 0.5 to 2 ft thick, except in Neshaminy Creek where gravel beds were observed in excess of 6 ft thick. These gravels are locally overlain by a poorly sorted, very fine to fine-grained sand, which contains pockets of charcoal fragments and plant detritus consisting of bamboo, American black walnuts (*Juglans nigra*), acorns (*Quercus* sp.), and hickory nuts (*Carya* sp.), as well as unidentifiable leaves, sticks, and bark. The uppermost loam/silt deposit is composed of two distinct horizons – a lower mottled pale-brown to grayish-brown and grayish-orange silt and sandy silt and an upper moderate-yellowish-brown to grayish-brown, soft to stiff, clay, silt, and loam. The upper silt marks the modern floodplain deposit as evidenced by the presence of refuse (e.g., broken glass, leather, etc.). Both silt horizons can contain scattered charcoal fragments and moderate to poorly sorted sand lenses and may have a basal lag of plant detritus. These horizons have a combined thickness that ranges from 0.5 to 4 ft, with the exception of near the mouths of Mill Creek and Neshaminy Creek where these units are up to 9 ft in thickness (Figure 23).

Throughout the field area, headwater alluvium is typically less than 4 ft (Figure 24); however, headwater alluvium deposits in larger tributary streams, such as Core Creek, Newtown Creek, Mill Creek, and Little Neshaminy Creek, are commonly 4 to 10 ft thick. Neshaminy Creek deposits are commonly 5 to 10 ft thick, except in the southern edge of the study area near mouth of Mill Creek and Playwicki Park, where water-well data suggest thicknesses between 10 and 35 ft

Figure 24. A cutbank exposure of headwater alluvium displaying two fining upward packages. The dashed yellow line is the contact between each package. The lower package includes a stream channel gravel (below water level) fining upward to a silty diamict. The upper package starts at the base of the rock hammer as either a stream channel or flood deposit of imbricated gravel and fines upward to an overbank silt deposit. Hammer is approximately 12 inches long. Photo taken January 3, 2022.
GPS: 40.24322°, -74.97099°

(Bierly, 2023). The oldest radiocarbon date obtained during this study indicates an age of 4,540 ± 25 BP, implying the oldest alluvium is at least Northgrippian (middle Holocene; Walker and others, 2018).

Quarry

Quarries were mapped based on excavated bedrock and associated with spoil piles using lidar imagery. Abandoned quarries in the Stockton Formation contain reddish-brown sandstones and likely produced dimension stone (brownstone) for buildings. Quarries in the Lockatong Formation produce aggregate and rip rap. In Playwicki Farm Park, marble was extracted from the Vanartsdalen quarry as a local source of lime (Figure 25). Quarries date from present day to mid-eighteenth century.

Figure 25. View of the abandoned Vanartsdalen's quarry in Playwicki Farm Park, Lower Southampton Township. Quarry is located primarily in marble with some thin beds of amphibolite observed in the walls. A small spring emerges in the quarry creating a pool. The water exits at the entrance of the quarry and eventually drains to Turkey Run Creek. Photo taken November 3, 2022. GPS: 40.169558°, -74.966544

Alluvial Fan and Delta, Undifferentiated

Undifferentiated alluvial fan and delta deposits estimated to be between 5 to 15 ft in thickness were identified and mapped using aerial imagery and lidar. Because of their similar lithologic character, geomorphology, and confinement impoundments built between the 20th and 21st century these sediments were mapped as a singular unit. In general, the lithology of the undifferentiated alluvial fan and delta sediments are the alluvial fan unit, however, the distinguishing characteristic of this unit are thicker silt and sand deposits and thinner gravels. These deposits are observed as lobes and fans of sediment prograding into impounded waterbodies (Bierly, 2023). The age of the undifferentiated alluvial fan and delta deposits is present day to twentieth century.

Water

Water is mapped in impoundments and drainage basins with standing water and water-filled stream channels greater than 30 ft in width (Bierly, 2023). The impoundments range from present day to twentieth century.

Larger impoundments are a source for water withdrawal and are used for recreational activities. Some recreational activities may be impacted by surface water and sediment contamination. One such contaminant, PFAS, is subject to current surface and groundwater investigations and has been detected in the Neshaminy Creek watershed (MacGillivray and Conkle, 2023; Breitmeyer and others, 2023). As such, the Pennsylvania Fish and Boat Commission and Pennsylvania Department of Environmental Protection have issued a no eat advisory for fish in this watershed due to the detection of the PFAS compound perfluorooctane sulfonate.

SUMMARY

This investigation mapped the Stockton Formation at the member scale through southern Bucks County in southeastern Pennsylvania. The lower member of the Stockton Formation is characterized by cross bedded medium- to coarse-grained sandstone, pebbly sandstone, and conglomerate—all of which vary in color from very light gray to light-gray, dusky-yellow, very pale orange, and pale-yellowish-orange. The middle member of the Stockton Formation is a transitional unit and contains lithologies similar to the lower member interbedded with grayish-red sandstone, siltstone, and shale. Palynological analysis of a sample collected from a plant fossil-bearing interval in this member yields a depositional age of Middle to Late Carnian for the Stockton Formation within the study area; this implies that the Carnian-Norian boundary is present between the sampled interval and the basal Lockatong Formation. The upper member is similar to the grayish-red intervals within the middle member. The main difference between these units is that the dominant lithologies of the upper member are shale, siltstone, and mudstone, whereas the middle member hosts a prevalence of grayish-red sandstones. The three-member interpretation of the Stockton Formation of Rima and others (1962) may now be continuously traced through the outcrop belt in Chester, Montgomery, and Bucks Counties and will aid in refining regional groundwater models. Previously mapped diabase dikes were confirmed during this investigation. Float along Little Neshaminy Creek suggests the presence of additional dikes, although evidence of these dikes is limited to the observed float cluster upstream from the mapped dikes. Reconnaissance mapping along the southern boundary of the Newark Basin confirmed the contact between the Mesozoic siliciclastic strata and the underlying Proterozoic metamorphic rocks.

The identification of a previously unmapped fault was facilitated by member-scale mapping of the Stockton Formation, as evidence for this structure was limited to the observation of contact between the middle member of the Stockton Formation and the Lockatong Formation. A second previously unmapped fault with a normal sense of motion was identified through new field observations to the north of the Neshaminy Farms Fault. Similarly, the location and relative motion of the Neshaminy Farms Fault are confirmed by this investigation, although new field observations suggest this structure is approximately twice as laterally extensive as previously thought and dips opposite the direction reported by Willard and others (1959).

Joints within the study area are steeply dipping and typically occur in north-south and east-west oriented pairs. Joint strike varies slightly with respect to stratigraphic position; however, this general trend is true for the entirety of the Stockton Formation. Two regional-scale folds, the Warrington Anticline and an unnamed syncline immediately to the east of this structure, are present within the study area. Bedding orientations collected during this investigation refine the orientation of these fold axes to trend north-south rather than northeast-southwest as previously reported.

Surficial mapping was completed for the first time in this region and identified a previously unmapped outlier of Pensauken Formation, three terrace deposits in the Neshaminy Creek drainage basin, alluvial fans, and extensive alluvium throughout the study area. Lidar and aerial imagery were used extensively for mapping these deposits and only alluvium, alluvial fans, and the lower terrace were observed in the field. Alluvium consists of stratified clay, silt, sand, and gravel occurring in a predictable, albeit variable, sequence throughout the study area. Alluvial fans are composed of normally graded beds of gravel and diamict and are present where headwater streams abruptly lose gradient, and therefore energy, and deposit sediment. Terraces are composed of diamict and locally imbricated gravel, with clasts ranging from cobbles to boulders. Although absolute ages could not be determined for terraces, dating was successful in alluvium and, coupled with the mapping of surficial deposits, establishes a framework for understanding the Cenozoic stratigraphy within the Neshaminy Creek, Pennypack Creek, Mill Creek, and Buck Creek watersheds.

SUGGESTED FUTURE RESEARCH

This investigation did not establish a correlation between the three-member system of Rima and others (1962) and the four-member system of McLaughlin (1945). Detailed mapping and correlation are required to evaluate equivalency between these units. Similarly, mapping using the three-member subdivision of the Stockton Formation should be completed in other fault blocks within the Newark Basin to assess the regional viability of this stratigraphic interpretation.

The Stockton Formation was deposited in fluvial environments and, as such, is lithologically heterogeneous laterally and stratigraphically. Considerable thickness variability along strike within the Stockton Formation members is attributed to this heterogeneity. Additional borehole data are necessary for new mapping to cartographically represent the tonguing between the Stockton Formation members in a more accurate manner than currently shown by Bierly and Oest (2023).

The members of the Lockatong Formation, as defined by Olsen and others (1996), are likely recognizable and mappable within the study area; however, this level of detail was below the resolution of this investigation. Such an effort would require a robust borehole dataset supplemented by substantially complete and thick measured sections in order to reliably identify these members. Paleomagnetism studies would also be useful in identifying and correlating these members within the study area.

Diabase boulder float was found both upstream and substantially downstream from mapped dikes, implying that unmapped dikes are present in the study area. Accurately mapping these dikes is important, as the dikes may alter regional groundwater flow paths predicted by groundwater models. This has implications for groundwater remediation projects or projects requiring properly sited high-yield wells. Future work could include refining the distribution of diabase dikes and could be accomplished through geophysical surveys, targeted drilling, excavations, or reporting by third parties actively working in the area as these dikes are encountered.

While this investigation focused on the Stockton Formation, reconnaissance-level mapping of Middle Proterozoic metamorphic rocks was completed to place the Stockton and Lockatong Formations within a regional geologic context. Reconnaissance-level mapping revealed some inconsistencies from previous mapping, particularly the geometry of marble in Vanartsdalen quarry in Feasterville-Trevose. It is recommended that future mapping focus on this interval to accurately depict the distribution of these units at a large scale and to possibly establish correlations with metamorphic belts in the New Jersey Highlands and the Piedmont in southeastern Pennsylvania.

Radiocarbon ages range from 85 ± 15 BP to 4,540 ± 25 BP, implying that the modern floodplain began developing no earlier than the Northgrippian (middle Holocene; Walker and others, 2018). However, sampling was conducted only along pre-existing stream cut exposures. Due to the meandering nature of fluvial channels and lateral progradation of point bar deposition, older sediment may be preserved in the floodplain away from current stream cut exposures. Future work in the study area should focus on extracting datable material via test pits or sediment cores from the edges of the floodplain to determine if older deposits are present. Additional dating will refine our understanding of sedimentation and erosion in the tributaries of the Delaware River following the last glacial maximum. Archeologists will also benefit from additional age-dating of these materials, which may help identify potential sites for archeological investigation. No datable material from any of the terrace deposits was found during the mapping of this study area. Datable material for terraces, particularly the lowest terrace, are likely to be recovered from test pits or sediment cores. Any dates from the terraces will allow correlation across drainage basins, which will in turn provide insight as to how these fluvial systems responded to sea level change during the Pleistocene.

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