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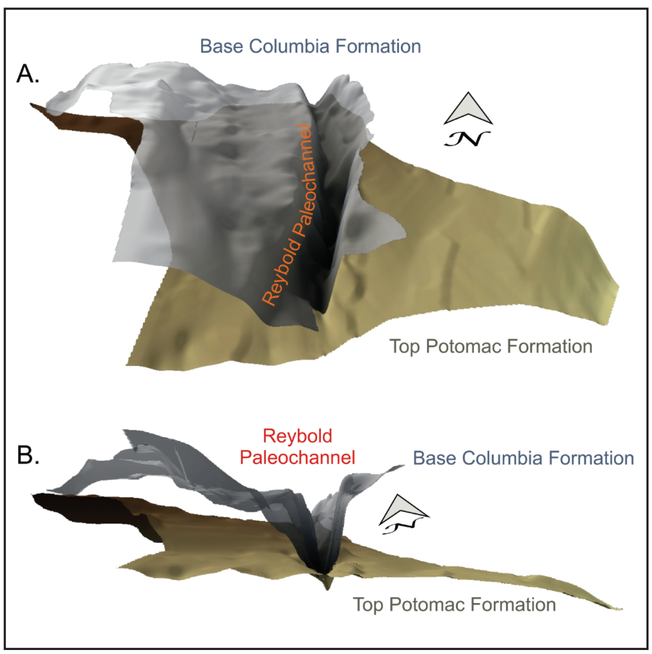
SUBSURFACE GEOLOGY OF THE AREA BETWEEN WRANGLE HILL AND DELAWARE CITY, DELAWARE

By

John W. Jengo[1], Peter P. McLaughlin, Jr.[2], and Kelvin W. Ramsey[2]



University of Delaware
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[1] MWH Americas, Inc.
[2] Delaware Geological Survey

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ABSTRACT

The geology and hydrology of the area between Wrangle Hill and Delaware City, Delaware, have been the focus of numerous studies since the 1950s because of the importance of the local groundwater supply and the potential environmental impact of industrial activity. In this report, 490 boreholes from six decades of drilling provide dense coverage, allowing detailed characterization of the subsurface geologic framework that controls groundwater occurrence and flow.

The region contains a lower section of tabular Cretaceous strata (Potomac, Merchantville, Englishtown, Marshalltown, and Mount Laurel Formations in ascending order) and a more stratigraphically complex upper section of Pleistocene-to-modern units (Columbia, Lynch Heights, and Scotts Corners Formations, latest Pleistocene and Holocene surficial sediments and estuarine deposits). The lowermost Potomac Formation is a mosaic of alluvial facies and includes fluvial channel sands that function as confined aquifer beds; however, the distribution of aquifer-quality sand within the formation is extremely heterogeneous. The Merchantville Formation serves as the most significant confining layer. The Columbia Formation is predominantly sand and functions as an unconfined aquifer over much of the study area.

To delineate the distribution and character of the subsurface formations, densely spaced structural-stratigraphic cross sections were constructed and structural contour maps were created for the top of the Potomac Formation and base of the Columbia Formation. The Cretaceous formations form a series of relatively parallel strata that dip gently (0.4 degrees) to the southeast. These formations are progressively truncated to the north by more flatly dipping Quaternary sediments, except in a narrow north-south oriented belt on the east side of the study area where the deeply incised Reybold paleochannel eroded into the Potomac Formation.

The Reybold paleochannel is one of the most significant geological features in the study area. It is a relatively narrow sand-filled trough defined by deep incision at the base of the Columbia Formation. It reaches depths of more than 110 ft below sea level with a width as narrow as 1,500 ft. It is interpreted to be the result of scour by the sudden release of powerful floodwaters from the north associated with one or more Pleistocene deglaciations. Where the Reybold paleochannel cuts through the Merchantville confining layer, a potential pathway exists for hydrological communication between Columbia and Potomac aquifer sands.

East of the paleochannel, multiple cut-and-fill units within the Pleistocene to Holocene section create a complex geologic framework. The Lynch Heights and Scotts Corners Formations were deposited along the paleo-Delaware River in the late Pleistocene and are commonly eroded into the older Pleistocene Columbia Formation. They are associated with scarps and terraces that represent several generations of sea-level-driven Pleistocene cut-and-fill. They, in turn, have been locally eroded and covered by Holocene marsh and swamp deposits. The Lynch Heights and Scotts Corners Formations include sands that are unconfined aquifers but complicated geometries and short-distance facies changes make their configuration more complex than that of the Columbia Formation.

INTRODUCTION

Purpose and Scope

The purpose of this report is to document the subsurface geological framework controlling groundwater in the area between Wrangle Hill and Delaware City, Delaware (Fig. 1). The geology and hydrology of this area have been the focus of decades of study because of the heavy utilization of groundwater by industry, the development of aquifer storage and recovery wells, and the need to assess the potential impacts on groundwater quality from intensive industrial activity.

The study area lies within the Atlantic Coastal Plain physiographic province in east-central New Castle County, just west of Delaware City and east of the cross-roads of Wrangle Hill in the vicinity of Delaware Route 1, U.S. Route 13, Delaware Route 7, and Delaware Route 72 (Wrangle Hill Road) (Fig. 1). The study area is bounded by Red Lion Creek to the north, the Delaware River along the east, and Dragon Run to the south, just north of the Chesapeake and Delaware Canal. Land surface elevations range from sea level along the tidal waterways to nearly 80 ft in the upland areas between Red Lion Creek and Dragon Run.

The subsurface geology is characterized by a southeastward-dipping wedge of Cretaceous sediments that unconformably overlie lower Paleozoic-age crystalline rocks and associated saprolite; these Cretaceous sediments are unconformably overlain by a thin veneer of Pleistocene and Holocene sediments. The lower part of the Cretaceous section is a thick interval of non-marine sediments, referred to as the Potomac Formation; the upper part of the Cretaceous succession is characterized by a succession of thinner marine formations (Fig. 2). Groundwater is principally obtained from the deeper, confined aquifer sands of the Potomac Formation, and from shallow, unconfined aquifer sands in the Pleistocene-age Columbia Formation.

The stratigraphy, distribution, and correlation of the geological units examined in this study are presented through a series of cross sections and derivative maps. The study is focused on the shallow (less than 150 ft below land surface) subsurface geology because there are more data available, but interpretations of the deeper subsurface geology also are presented on the basis of more limited data. The foundation for this report is work by the senior author (Jengo) on the subsurface geology of the Delaware City refinery property, including adjacent refinery-owned undeveloped land. Previous studies and

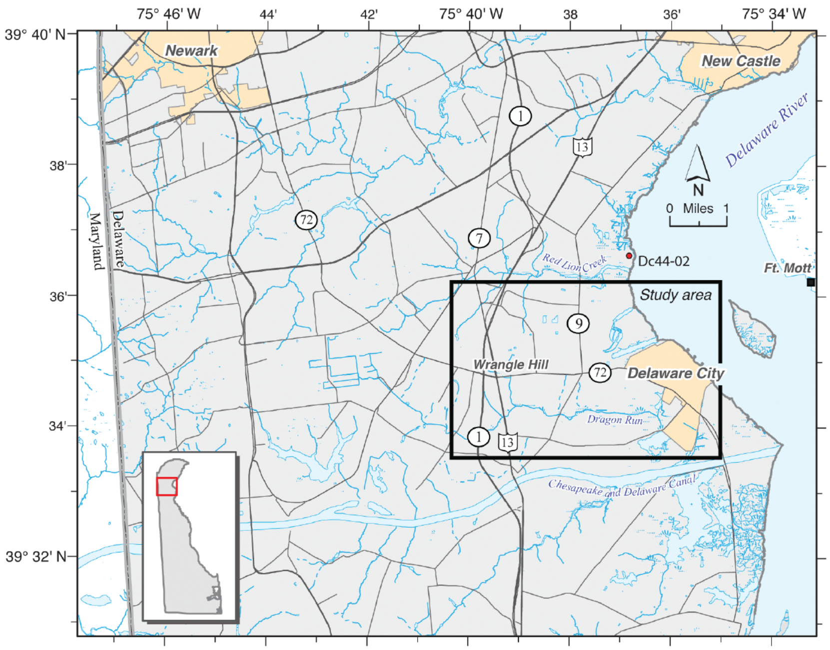

Figure 1. Location map, central New Castle County, Delaware. Study area is bounded by black box.

additional interpretive work by the Delaware Geological Survey (DGS) provided a broader context for this site-specific information.

Knowledge of the geological framework in the study area has significant implications for ascertaining the distribution, transmission, and quality of the groundwater resources that are utilized by local industrial, public, and agricultural users. Use of this enhanced framework will enable investigators to select optimal locations for future groundwater monitoring wells, select appropriate screen depths for target hydrogeological intervals, and improve the understanding of groundwater occurrence and flow in and near the study area, which will result in more accurate site characterizations, environmental investigations, and water supply studies.

Previous Work

The industrial area near Delaware City has been the focus of numerous environmental and hydrogeological assessments by state and local government agencies as well as consultants under contract to government and industry. A number of the older publications in and around the study area examined the surficial geology, including exposures of Cretaceous formations that exist, or once existed, along the Chesapeake and Delaware Canal (Carter, 1937; Owens et al., 1970; Houlik et al., 1983). Pickett (1970a) authored a 1:24,000 map of the subcrop geology of the Chesapeake and Delaware Canal area. Ramsey (2005) updated this framework in a 1:100,000 map of the surficial geology of New Castle County and showed the subsurface stratigraphy on geologic cross sections. Dugan et al. (2008) provided a concise summary of the formations within the study area as well as maps showing the extent of aquifers in southern New Castle County, just south of the study area.

For subsurface geology, Spoljaric (1967b) examined the lithofacies of the Potomac Formation, including maps of the distribution of sand bodies within the stratigraphically complex Potomac interval. Spoljaric (1973) presented a basement map for the area and hypothesized the existence of a network of normal faults in the basement rocks. Doyle and Robbins (1977) did a detailed study of fossil angiosperm pollen in two wells in the refinery area, Dc53-07 and Ec14-01, and supported the reproducibility of the zonation they established by showing its consistency with the geophysical log correlations for the wells. More recently, the DGS performed several related studies of the Potomac Formation in New Castle County, resulting in a significantly improved understanding of stratigraphic correlations and facies (McKenna et al., 2004; Benson, 2006; McLaughlin, 2006).

A number of previous studies have examined hydrology and aquifers in the study area (Rasmussen et al., 1957; Jordan, 1962, 1964; Sundstrom et al., 1967; Sundstrom and Pickett, 1971; Woodruff, 1986, 1988; Donnelly and Hinaman, 1996a, b). The existence of Pleistocene-age channels in the Chesapeake and Delaware Canal area was noted in Groot et al. (1954), Rasmussen et al. (1957), and Spoljaric (1967a); Woodruff (1986) depicted a paleochannel on a cross section using one well from the study area (Ec13-06, same location as Ec13-21 in this study).

For decades, consulting geologists have conducted basic descriptive geologic and hydrologic work in the Delaware City area; however, there have been few published works since the early 1970s that present the geology of this area in detail. Most of the hydrogeological data generated by environmental consultants (primarily soil boring logs, water well production data, and monitoring well descriptive and geophysical logs) were included as appendices to environmental reports or as well record submissions to various regulatory agencies, but no attempt has been made to integrate these data into a comprehensive hydrogeological framework. In addition to dozens of water production wells, more than a thousand soil borings and hundreds of groundwater monitoring wells were installed during the industrial development and subsequent investigations of the Delaware City area. In this study, we utilize large volumes of these types of data; however, it was a challenge to reconcile the wide variation of detail and interpretation by past geologists. In addition, the interpretations in many of the past works were out of date; for example, logs recorded in the 1950s referenced formation names not currently used in Delaware or reported deposits that have subsequently been interpreted to be absent in the study area (e.g., Red Bank, Navesink, Wenonah, Raritan, Patuxent). As described below under the Data and Methods section, a significant effort was expended to standardize the interpretations of these logs and assign them valid and consistent geographic coordinates so that they could be utilized in this study.

Acknowledgments

The senior author recognizes the efforts of numerous field geologists over the last 15 years, including Vince Piazza, Stephen Zahniser, Suzanne Eckel, Bryn Welker, Scott Knoflicek, Gus Remenicky, and Chad Smith. Thanks also to the former environmental management team at the refinery for their support of this stratigraphic analyses project of the facility and its environs.

We wish to acknowledge valuable reviews by Dana Desonie, Michael J. Brayton (USGS), Scott Stanford (NJGS), and A. Scott Andres (DGS), which significantly improved the manuscript. Final illustrations were created by Lillian T. Wang. Discussions of hydrology and regional geology with Thomas E. McKenna were helpful and are gratefully acknowledged. We also thank student interns Lauren Cook and Curt Romanchok for significant efforts in data collection, quality control, reproduction, and cataloguing.

DATA AND METHODS

This study utilized borehole lithologic and geophysical logs from 490 sites in the area between Wrangle Hill and Delaware City, Delaware (Appendix 1; Plate 1). The data include well logs obtained from test holes drilled in the mid-1950s as part of the siting process for the original Tidewater Associated Oil Company refinery as well as from a large number of water production wells and geo-technical borings associated with the facility’s construction. Extensive datasets of soil borings, temporary groundwater sampling points, and permanent monitoring wells that were part of various hydrogeological investigations and groundwater characterization studies over the last 30 years were also utilized. Much of the older data have been on file at the Delaware Geological Survey since the 1950s and 1960s; the more recent soil boring and well log data were filed with Delaware state government agencies as part of reporting requirements for well permitting and environmental compliance. The primary identification scheme used to represent these data on the maps and cross sections was by DGS ID numbers. All locations in this report are given as meter coordinates in a Universal Transverse Mercator (UTM), Zone 18, North American Datum of 1983 (NAD 83) projection; all elevations cited are relative to the North American Vertical Datum of 1988 (NAVD 88).

This large and diverse dataset required intensive review. Drilling permit records, historic project maps and reports, and multiple generations of aerial photographs were utilized to establish accurate locations and elevations of borehole sites. Historical research was needed to ascertain revised elevations for borings that were drilled before the site was leveled because the original elevations were no longer valid. Georectified topographic maps and aerial photographs were interpreted and used to define the extent of the post-Columbia stratigraphic units. Published and unpublished pre-construction topographic maps and modern topography based on recent (2007) LiDAR acquired for the State of Delaware were used to identify geomorphic terraces; a comparison of lithology from boring logs and samples allowed us to recognize mappable stratigraphic units related to these terraces. Pre-construction aerial photographs from 1936 and 1954 were critical in mapping the extent of the Holocene marsh and swamp deposits and the Quaternary units, which are now covered by dredge spoil. The pre-spoil land surface elevations and the known locations of pre-construction tidal channels and other features provided a baseline for picking the contact of the base of the dredge spoil.

Borehole record quality and formation assignments also required close scrutiny. Because the lithologic logs were described over decades by a variety of geologists and drillers who emphasized different aspects of the stratigraphy, inconsistencies were evident even between closely spaced borings. Therefore, for this study, every boring log was thoroughly reviewed and reinterpreted, as needed. Some of the previous geological interpretations that had to be rectified included the lack of recognition of the Englishtown Formation or confusion of this unit with the upper Merchantville Formation; the erroneous assignment of gray, micaceous, Holocene-age marsh sediments to the Merchantville Formation; a lack of distinction between *in situ* Holocene-age deposits and the extensive dredge spoil hydraulic fill on the eastern portion of the site; and the need to identify where the Columbia Formation was disturbed to level the site. An additional challenge was converting the horizontal survey data of the older boring logs from the NAD27 datum to NAD83 and determining a valid elevation.

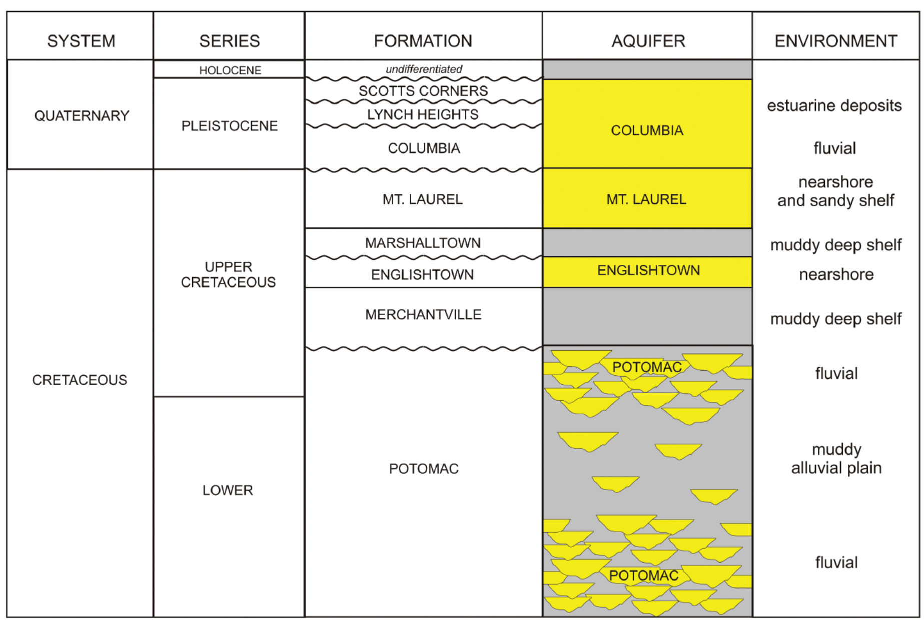

Figure 2. Generalized stratigraphic column for the area between Wrangle Hill and Delaware City and nearby parts of New Castle County. Chronostratigraphy is provided in the System and Series columns. Wavy lines in the Formation column indicate unconformable contacts. Yellow intervals in the Aquifer column indicate aquifer sands; the presence of discontinuous sands is indicated by multiple small yellow lenses. Gray intervals indicate less permeable non-aquifer and confining beds. Generalized environments of deposition are identified in the Environments column.

Table 1. Radiocarbon dates collected for this study; samples were analyzed using the radiometric technique. Abbreviations: yrs BP = years before present where present = 1950 AD; ft bls = depth in feet below land surface; ft NAVD = elevation in feet relative to the North American Vertical Datum of 1988.

DGS RC No.	DGS ID	Laboratory Sample ID	Sample Depth (ft bls)	Northing	Easting	Sample Elev. (ft NAVD 88)	Measured ^{14}C Age (yrs BP)	$^{13}C/^{12}C$ Ratio	Conventional ^{14}C Age (yrs BP)	2 Sigma Calibrated Result (95% Probability)
306	Dc53-188	Beta-233549	36.2	4382912	447055	-14.6	1620 ± 40	-29.8	1540 ± 40	Cal AD 420 to 610 (Cal BP 1530 to 1340)
307	Dc53-127	Beta-233550	31.2	4382151	446979	-24.3	4290 ± 60	-28.3	4240 ± 60	Cal BC 2920 to 2840 (Cal BP 4880 to 4790) & Cal BC 2820 to 2670 (Cal BP 4770 to 4620)
308	Dc54-18	Beta-233551	42.0	4381835	447302	-10.1	2460 ± 60	-27.2	2420 ± 60	Cal BC 770 to 390 (Cal BP 2720 to 2340)
310	Dc54-19	Beta-233553	21.0	4382544	447148	-9.5	1490 ± 50	-24.7	1490 ± 50	Cal AD 430 to 650 (Cal BP 1520 to 1300)
311	Dc54-20	Beta-233554	37.0	4382502	447228	-15.8	1280 ± 40	-28.0	1230 ± 40	Cal AD 680 to 890 (Cal BP 1270 to 1060)

A total of 188 high-quality boring logs were selected for inclusion on ten structural stratigraphic cross sections (Plate 2). These borings represent the highest level of stratigraphic detail, well defined formational or erosional contacts, and a fairly evenly-spaced geographic distribution. The cross sections were specifically developed to illustrate the geometry and slope of a significant north-south trending Pleistocene-age paleochannel, and its erosion through the Merchantville Formation and incision into the top of the Potomac Formation, and the offlapping relationship between the Holocene deposits and the Cretaceous and Pleistocene formations along the eastern portion of the study area. The vertical extent of each borehole appears on the cross sections as a line extending from the elevation of the top of the hole at the time of drilling to the elevation of the bottom of the hole. When a location was excavated or filled since the borehole was drilled, the top of the borehole appears above or below present-day ground level, respectively. Selected borings have associated geophysical logs (natural gamma, spontaneous potential, or resistivity) that are depicted adjacent to the vertical line depicting the borehole; in some instances, geophysical log shifts may appear slightly offset from the formation contacts they represent because those contacts were drawn through the vertical borehole lines.

Structural contour maps were constructed for two surfaces that are crucial to understanding the hydrogeology of the study area: the top of the Potomac Formation (Plate 3) and base of the Columbia Formation (Plate 4). The top of the Potomac Formation map was developed by mapping 138 borings that encountered the top of the formation. The lateral extent of the Columbia Formation was determined by mapping 339 borings that penetrated the entire formation, 17 borings that partially penetrated the formation, and 134 borings where the formation was determined not to be present. Elevations for each surface, compiled from the cross sections and from boring sites in between the sections, were then contoured. Elevation grids were constructed from each contour map using ArcMap software and both were surfaces rendered in three dimensions in the same scene using ArcScene software.

Peat samples from borings advanced through probable Holocene-age sediments along the eastern boundary of the study area were submitted for Carbon-14 (^{14}C) analyses in an effort to distinguish between Pleistocene-age and Holocene-age sediments. The radiocarbon dating was carried out by Beta Analytic Inc. (USA); all analyses were performed using an accelerator mass spectrometer (AMS) with extended counting times. Conventional ^{14}C age results were calculated by applying a ^{13}C /^{12}C correction to measured ^{14}C ages. Calibration to calendar years before present (cal years BP) used Intcal 98 (Stuiver et al., 1998). Corrections, calibrations, and other adjustments to the measured ^{14}C dates are listed with the data on Table 1.

STRATIGRAPHY

The stratigraphy overlying bedrock in the study area can be divided into two parts, a lower section of Cretaceous sediments and an upper section of Quaternary sediments (Fig. 2). The Cretaceous section includes five formations: the Potomac, Merchantville, Englishtown, Marshalltown, and Mount Laurel. The Magothy Formation appears to pinch out just south of study area. The Quaternary sediments include the Columbia Formation, the Delaware Bay Group (Lynch Heights and Scotts Corners Formations), Holocene-age swamp, marsh, and estuarine deposits, and anthropogenic fill.

In the section below, we review the definition, age, and lithologic characteristics of each formation present in the study area, including composition, texture, and depositional environment in addition to geophysical log characteristics. The thickness, distribution, and stratigraphic relationships of the formations are presented on the accompanying maps (Plates 1, 3, and 4) and cross sections (Plate 2). Data used to construct the cross sections are included in Appendix 2.

One of the most notable geological features identified in this study is a thick, north-south trending band of Columbia Formation sediments in the eastern part of the study area. Along this trend, the base of the Pleistocene-age sediments of the Columbia Formation incises deeply into the underlying Cretaceous section. Although this feature will be described in more detail later in this section, its presence frames the geology of most of the stratigraphic units present in the study, so is introduced here at the start of the stratigraphy section. This feature is referred to as the Reybold paleochannel herein. The term paleochannel is used because it is a narrow trend of thick fluvial deposits with an erosive base that represents an abandoned and buried watercourse. For the purposes of this report, the term paleochannel does not imply that the channel was part of a connected drainage network or that the channel fill deposits are contemporaneous with the formation of the paleochannel.

Potomac Formation

Definition and Age

The Potomac Formation, a thick succession of nonmarine silts, clays, and sands, is the lowest known Cretaceous sedimentary unit in the Coastal Plain of Delaware. The formation was first described by McGee (1886a, b) to characterize the sands and iron-ore clays overlying the crystalline basement in Maryland, Virginia, and the District of Columbia. In Maryland, the Potomac deposits are considered a group that is subdivided into three formations (Patuxent, Arundel, Patapsco), but in Delaware, this subdivision cannot be recognized and the Potomac deposits have formation status (Jordan, 1962, 1983; Benson, 2006).

In Delaware, the Potomac Formation is predominantly silt, silty clay, sandy silt, and sand (Jordan, 1962, 1983; Benson, 2006). The sand intervals compose approximately 20 to 30 percent of the thickness of the formation (Benson, 2006). Sands are mostly quartzose and typically fine-grained, but coarse- and medium-grained sand is common, particularly in the lower part of the formation (Groot, 1955; Jordan, 1962, 1983). Thicker sands in the Potomac Formation have good aquifer characteristics and provide significant quantities of groundwater in central and southern New Castle County (Sundstrom et al., 1967; Dugan et al., 2008). The finer-grained lithologies are whitish gray, red-to-orange, and tan-to-yellow muds with variable proportions of silt and clay, and are commonly mottled or variegated (Jordan, 1962; McKenna et al., 2004). Clays are predominantly kaolinite with lesser illite (Groot and Glass, 1960). Plant-derived materials, including lignitic beds and charcoal, are common.

In New Castle County, the Potomac Formation is mostly a subsurface unit, although it crops out in a few areas near the Fall Line (Marine and Rasmussen, 1955; Ramsey, 2005). The base of the formation lies unconformably above a basement of Paleozoic and older metamorphic rocks and associated saprolite. The top of the formation is an unconformity overlain by Upper Cretaceous sediments of the Magothy or Merchantville Formations, or by Quaternary sediments. The thickness of the Potomac Formation ranges from zero at the northern margin of the Coastal Plain Province through more than 1,600 ft in southernmost New Castle County to more than 4,600 ft at Ocean City, Maryland (Benson, 2006; Hansen, 1982).

Fossil spores and pollen recovered in samples indicate deposition during the Early (Aptian, Albian) and Late (Cenomanian) Cretaceous Period, about 125 to 96 million years (Ma) ago (Doyle and Robbins, 1977; Hochuli et al., 2006; McLaughlin, 2006).

Composition, Textures, and Depositional Environment

In the study area, the Potomac Formation is composed of sand, silt, and clay. The sand lithologies include moderately- to well-sorted, silty, very fine- to fine-grained sand. The silt lithologies include clayey silt, silt, and fine-grained sandy silt. The sands and silts are variable in color, with a number of tones of white, pink, brown, yellow, red, and gray. Clay beds are common, can occur in relatively thick intervals, and are typically silty, highly plastic, mottled, and they exhibit a range of colors with different tones of white, pink, yellow, red, brown, and gray. Lignite and highly oxidized ironstone/siderite nodules have been noted throughout the formation and can be present in distinct layers.

Regional core and geophysical log data suggest that the Potomac Formation sediments of Delaware were deposited in an aggrading alluvial plain, probably associated with predominantly anastomosing river systems, with coarser channel sands enclosed by finer overbank, flood-plain, and interfluvial (region of higher land between two rivers in the same drainage system) paleosol deposits (McKenna et al., 2004).

In the study area, the Potomac Formation lithologies reflect depositional environments consistent with the regional understanding of this unit. On study area geophysical logs, the thicker sands occur in blocky packages (Plate 2, Dc52-05 on C-C', Ec12-02 on E-E', and Ec22-16 on G-G') and in packages that fine upward (Plate 2, Dc52-08 and Dc53-07 on A-A') suggesting deposition in channels in anastomosing river systems. The range of muddy (silt and clay) facies indicates that the Potomac-age environments include the wet floodplain (overbank, lake, swamp) and interfluvial areas subject to paleosol-forming conditions. The connectivity of the fluvial sands of the Potomac Formation is too complex to be addressed in this study but is discussed in other DGS publications (Benson, 2006; McKenna et al., 2004).

Thickness, Distribution, and Bounding Relations

The Potomac Formation occurs across the entire study area. Four borings used in the study penetrated the entire Potomac Formation and reached saprolite or crystalline bedrock. The thickness of the Potomac Formation at these sites ranges from 625 ft (Ec14-01) to 684 ft (Dc53-07). The elevation of the base of the formation has a narrow range between −716.1 ft (Dc53-07) and −748.9 ft (Ec12-03), indicating a general dip from north to south across the study area. This is consistent with various published structural contour maps of the top of crystalline basement in this area (e.g., Fig. 5 in Sundstrom and Pickett, 1971).

The unconformity at the top of the Potomac Formation ranges in elevation from −1.0 ft to below −120 ft in the study area (Appendix 3). The Merchantville Formation unconformably overlies the Potomac Formation in most areas west of the paleochannel where the contact deepens from around −10 ft in the northwest to more than −80 ft in the south. The Merchantville Formation also lies immediately above the Potomac Formation in the southeastern part of the site, with the contact as deep as −128 ft in Delaware City. The structural contour map of the top of the Potomac Formation suggests that the Merchantville – Potomac contact is a gently undulating surface with a dip of approximately 0.4 degrees to the southeast and a strike of approximately N50°E (Plate 3).

The contact between the Potomac Formation and the dark silts of the overlying Merchantville Formation is readily recognizable on geophysical and lithologic logs when the uppermost Potomac lithologies are sand (e.g., Plate 2, Dc53-50, Dc53-51, Dc53-07, and Dc53-77 on A-A', Ec13-24 on F-F', and Dc53-78 on H-H'). Where the Merchantville Formation directly overlies the fine-grained facies of the upper Potomac Formation (e.g., Plate 2, Ec13-28 and Ec22-16 on G-G', and Dc53-74 on H-H'), the contact is difficult to identify from geophysical logs and from lithologic logs if the quality of geologic description is poor. The Potomac–Merchantville unconformity represents a significant amount of time. The youngest Potomac strata are early Cenomanian in age (approximately 96 Ma) whereas the oldest Merchantville strata are Campanian in age (approximately 83 Ma) (Sugarman, 2004; McLaughlin, 2006).

In some locations, erosion at the base of the Quaternary section removed the Merchantville Formation and the Potomac Formation is instead unconformably overlain by the Columbia Formation. The most notable instance is along the trend of a deeply incised north-south trending paleochannel in the eastern part of the study area (Fig. 3). The basal slope of the axis of this Columbia Formation paleochannel dips approximately 0.45 to 0.50 degrees trending just west of south (Plate 2, I-I'). This is steeper than the apparent dip of approximately 0.3 degrees for the top of the Potomac Formation in the same direction, which results in progressive southward downcutting of the paleochannel into the top of the Potomac.

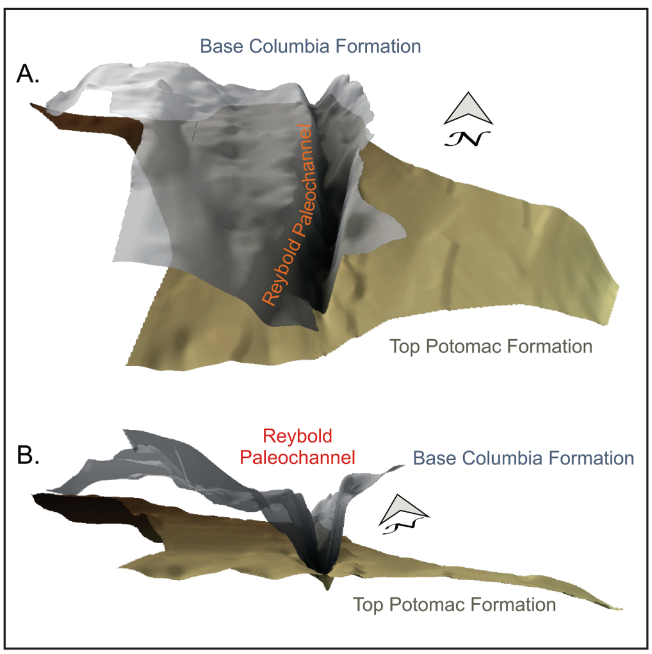

Figure 3. Three-dimensional relationship of Pleistocene-age Columbia Formation and Cretaceous-age Potomac Formation. The surfaces depicted are three-dimensional representations of hand-drawn structural contour maps of the base of the Columbia Formation (silver) and top of the Potomac Formation (bronze). A. Oblique overhead view from the south illustrating the deep erosional scour at the base of the Columbia Formation in the elongate, north-south trending Reybold paleochannel and its contrast to the gently undulating and step-like nature of the base of the Columbia Formation west of the paleochannel. B. Side view, from south looking north, showing the deep erosion of the base of the Columbia Formation in the Reybold paleochannel incised into the significantly older Potomac Formation. Rendering done using ArcScene software to view surface grids created using multiquadric radial basis function interpolation of digitized contour line data.

In the parts of the study area where the Potomac Formation is overlain by the Columbia Formation, the character of the highly erosive contact is variable. Where sand facies occur at the top of the Potomac Formation, the contact with overlying Columbia sands can be difficult to distinguish on geophysical logs (e.g., Plate 2, Ec13-15 on D-D', Ec13-25 and Ec13-34 on F-F', Ec13-27 on G-G' and Ec13-68 on I-I'). However, where the top of the Potomac Formation is muddy, the contact with sandy Columbia deposits is readily recognizable on lithologic and geophysical logs (e.g., Plate 2, Ec13-21 on E-E', Ec13-37 on G-G', and Dc53-38 on I-I').

Magothy Formation

Definition and Age

The Magothy Formation was first described by Darton (1893) along the Magothy River in Maryland, where its coarser, looser sands are differentiated from the denser, finer sands of the underlying Potomac Formation that grade laterally into white and pink sandy clays. Clark (1904) recognized the Magothy Formation from Maryland northeastward through Delaware to the Raritan Bay area of New Jersey.

Fossil spores and pollen recovered from Magothy samples from northern Delaware and nearby New Jersey are indicative of pollen Zone V, consistent with a Turonian or Coniacian age, although the formation includes sequences of other ages farther north in New Jersey (Jengo, 1995, 1999; Sugarman et al., 2005; McLaughlin, unpublished data).

Composition, Textures, and Depositional Environment

In Delaware, the Magothy Formation has been described from outcrops at the Chesapeake and Delaware Canal. The formation is characterized by “sugary” sands and dark clays (Groot, 1955; Pickett, 1970a; Jordan, 1962). The sands include cross-bedded, well-sorted, fine- to medium-grained, tan quartz sand, and white “sugary” quartz sand with heavy minerals that accentuate cross-bedding (Carter, 1937; Groot, 1955; Jordan, 1962). Muds are typically less common than sands and are mostly characterized by dark gray to black carbonaceous silts and clays (Carter, 1937; Groot, 1955; Jordan, 1962; Rasmussen et al., 1957). Groot and Glass (1960) described the clay minerals as a kaolinite-mica-chlorite assemblage. Woody material, including large trunk- and branch-size pieces, and lignite are common (Jordan, 1962). Similar lithologies are known from borehole data in the subsurface of New Castle County (Groot, 1955; Rasmussen et al., 1957; Jordan, 1962). The thick, clean sand facies of the Magothy Formation serve as an important confined aquifer in parts of southern New Castle County (Sundstrom and Pickett, 1971; Dugan et al., 2008).

The lithologies observed in outcrops and boreholes in Delaware are a combination of high-energy cross-bedded sands, low-energy organic-rich muds, and large woody debris, indicating that the Magothy sediments were deposited in a coastal alluvial plain or in an estuarine setting (Groot, 1955; Jordan, 1983).

Thickness, Distribution, and Bounding Relations

As noted by Rasmussen et al. (1957), the Magothy Formation is discontinuous in the area of the Chesapeake and Delaware Canal and absent in most of the Delaware City area. Jordan (1962) noted that the Magothy Formation, though similar to the Potomac Formation in many aspects in Delaware, can be differentiated by the generally thinner, more continuous nature of its bedding and the absence of variegated clays. The contact between these two formations is unconformable (Groot, 1955; Jordan, 1962). The Magothy Formation in the Canal area is discontinuous at its northern pinch-out because it represents incised valley fill that only occurs in paleotopographic lows related to incision at its basal unconformity (McLaughlin et al., 2003; McLaughlin and Benson, 2005). Farther downdip, the formation is more extensive, with the continuous character of the sand beds also differentiating it from the underlying Potomac Formation. The top of the formation appears to be an unconformity (Groot, 1955) that is eroded progressively deeper in a northward direction (Benson and Spoljaric, 1996). In New Castle County, the formation ranges from 15 to 85 ft thickness between these unconformities (Ramsey, 2005; Dugan et al., 2008).

We have not identified any definite occurrences of the Magothy Formation in the study area based on core samples from several locations. Although a more consistent occurrence of sands is recognized at the contact with the overlying Merchantville or Columbia formations in a number of borings south of Wrangle Hill Road, these facies have been assigned to the Potomac Formation because there is no definitive trend or lithologic characteristic persuasive enough to assign those sands to the Magothy Formation.

Merchantville Formation

Definition and Age

The Merchantville Formation is characterized by micaceous, glauconitic, dark blue-gray sandy silt and silty fine sand (Groot et al., 1954; Jordan, 1962; Pickett, 1970a; Ramsey, 2005). The name Merchantville was first used by Knapp (Salisbury, 1899) for "marly clay" beds that occur in the area of Merchantville, New Jersey and the unit was subsequently mapped as a clay formation by Kümmel and Knapp (1904). The Merchantville Formation has been examined in a number of outcrops along the Chesapeake and Delaware Canal just southwest of the study area. In addition, the Merchantville strata (which would be under the name Matawan Formation) were mapped by Bascom and Miller (1920) in the bank of Red Lion Creek in the northern part of the study area. Groot et al. (1954) described the Merchantville Formation as dark blue to black, micaceous glauconitic silt that coarsens upward into gray, silty, very fine quartz sand with some mica and glauconite. Clay minerals include kaolinite, illite, and vermiculite (Pickett, 1970b). The formation is between 10 and 50 ft thick in New Castle County (Ramsey, 2005).

The lithologic differences within the Merchantville Formation explain why it has been subdivided in past studies in Delaware and why three formations are recognized in this interval in nearby areas of New Jersey. Sugarman et al. (2004) recognized the Cheesequake, Merchantville, and Woodbury Formations in this interval on the basis of cores obtained at Fort Mott, New Jersey, directly across the Delaware River from the study area (Figure 1). There the Merchantville Formation designation was restricted to glauconitic sandy silts and silty sands that occur in the middle of this interval. The Cheesequake Formation was differentiated in the bottom of this interval by the reduced abundance of glauconite compared to the Merchantville Formation and by more abundant mica. The name Woodbury Clay was applied to the mica-rich and glauconite-poor silty sands and sandy silts at the top of this interval. This differentiation follows Owens et al. (1977), which divided this interval in Delaware into a lower glauconitic portion, placed in the Merchantville, and an upper micaceous portion, placed in the Woodbury. This entire interval had been grouped together as the Crosswicks Clay by Carter (1937) on the basis of outcrop studies along the Chesapeake and Delaware Canal. Owens et al. (1970) and Pickett (1970a) mapped these sediments as the Merchantville Formation, a designation that has been maintained in Delaware since that time. The Merchantville strata are regarded as a confining unit in New Castle County (Dugan et al., 2008).

In Delaware, the basal Merchantville strata unconformably overlie the Magothy Formation (Groot et al., 1954; Pickett, 1970a; Owens et al., 1977) where the Magothy is present, or the Potomac Formation where the Magothy is absent. The top of the Merchantville is conformable with the overlying Englishtown Formation in most places; however, the contact can be difficult to identify because of the gradational transition from the sandier upper Merchantville to the sands of the Englishtown. In some locations, especially near its northerly, updip limit, the Merchantville Formation is unconformably and directly overlain by Quaternary sediments.

At Fort Mott, across the Delaware River from this study area, calcareous nannofossils from strata equivalent to the upper part of the Merchantville in Delaware, but referred to as Woodbury in New Jersey, indicate a Late Cretaceous, early Campanian age (CC18) (Sugarman et al., 2004). The ammonite *Placenticeras placenta,* reported from the formation in Delaware, also indicates a Campanian age.

Composition, Textures, and Depositional Environment

In the study area, the Merchantville Formation is composed of dark gray to black silt to clayey silt with intervals of fine-grained sandy silty clay, silty clay and trace to little fine-grained sand. The formation is characterized by an abundance of muscovite and the presence of glauconite, which in places are concentrated in glauconite-rich laminations. Pyritized nodules, embedded wood fragments, shell fragments, trace fossil burrows, and siderite concretions may also be present. The lowermost part of the formation, at its contact with the underlying Potomac Formation, may be partially lithified. The upper section of the Merchantville

Formation can have a brownish-yellow oxidized appearance near its upper contact.

The fossiliferous and glauconitic character of the Merchantville Formation indicates deposition in a shallow-marine environment (Pickett, 1970a); rare occurrences of foraminifera in borehole samples just south of the Chesapeake and Delaware Canal suggest mid- to outer-shelf water depths (Houlik et al., 1983). In the study area, the Merchantville Formation generally has an overall upward coarsening trend. Near the base of the formation, many geophysical logs exhibit high natural gamma ray (gamma) and low resistivity values that gradually transition upward to slightly lower gamma and higher resistivity values (e.g., Plate 2, Ec12-02 on E-E', Ec13-33 on F-F', and Ec22-16 on G-G'). Together with the lithologies, the logs indicate an upward trend of shallower environments within a shelfal succession.

Thickness, Distribution, and Bounding Relations

The Merchantville Formation is present throughout most of the study area but is absent where the Columbia Formation paleochannel eroded through it and into the Potomac Formation. The formation is approximately 75 ft thick at its thickest occurrence in the southeastern part of the study area (Plate 2, J-J'); however, it can be significantly thinner where it was eroded beneath Quaternary unconformities. The Merchantville Formation is consistently underlain by the Potomac Formation. The contact is unconformable and can have a degree of relief, as described in the Potomac Formation section of this report.

The Englishtown Formation caps the Merchantville Formation in the southern part of the study area. The contact between these Upper Cretaceous units is conformable but can be difficult to recognize in rudimentary descriptive logs because the units share a number of characteristics (e.g., muscovite content, occurrences of glauconite). However, where high quality, detailed lithologic observations are available, it is possible to clearly distinguish the silty, fine-grained sandy Englishtown Formation from the predominantly clayey silts of the Merchantville Formation. On geophysical logs, the gradational nature of the contact makes its exact placement challenging but feasible (e.g., Plate 2, Ec13-13 on D-D', Ec14-01 on F-F', and Ec13-24 on F-F' and on H-H'). In a cross-section transect (J-J') relatively unaffected by the paleochannel, the dip of the top of the Merchantville Formation is 0.413 degrees.

Quaternary deposits overlie the Merchantville Formation in its northernmost and eastern occurrences. Because the top of the Merchantville Formation dips more steeply than the overall elevation trend of the base of the Columbia Formation, the base of the Columbia Formation eroded progressively deeper into the Merchantville Formation to the north, resulting in thinner Merchantville sections. Where the Columbia Formation paleochannel is present, the top of the Merchantville Formation is more deeply incised, with the formation eroded entirely in places.

The Merchantville–Columbia contact is represented by a lithologic shift from silt to unconsolidated sand, allowing the boundary to be picked clearly on gamma and resistivity logs (e.g., Plate 2, Dc53-50 on A-A', Dc51-03 on B-B', Dc52-05 on C-C', Ec13-14 on D-D', Ec13-05 on E-E', Ec13-33 on F-F', Ec12-41 on G-G', and Dc52-56 on J-J'). In the easternmost portion of the study area, near the Delaware River, the Quaternary unconformity at the top of the Merchantville Formation can be overlain by either Holocene-age sediments or anthropogenic fill (Plate 2, A-A', B-B', and C-C'). Because of the deep Quaternary erosion in parts of the study area, the elevation of the top of the Merchantville varies significantly both in the vicinity of the paleochannel (in particular, Plate 2, B-B', D-D' and G-G') and where the Holocene-age sediments eroded and offlapped the formation (i.e., Plate 2, A-A', B-B', and C-C').

Englishtown Formation

Definition and Age

The Englishtown Formation in New Castle County is a body of micaceous, fine-grained sand that lies above the silts of the Merchantville Formation. The Englishtown sand was named by Kümmel (1907) to identify white to yellow quartz sands in the area of Englishtown, New Jersey. The sand was originally identified as a distinct unit named the Columbus sand by Knapp (in Salisbury, 1899).

Englishtown sediments have been described in detail in a number of studies of outcrops along the Chesapeake and Delaware Canal (Carter, 1937; Groot et al., 1954; Jordan, 1962; Owens et al., 1970). The formation consists of light gray, white, yellow, buff, and rusty quartz sand that is very micaceous and slightly glauconitic. It may be clean or somewhat silty, is generally well sorted, and has been described as having a soft "fluffy" texture in outcrop. *Ophiomorpha* trace fossils, which are large burrow traces with nodose-textured surfaces, are common, especially in the upper part of the formation. Thin laminae of silty sand and clay have been noted to occur; the clays are kaolinite and illite (Pickett 1970b). Sands in the Englishtown Formation may function locally as a minor confined aquifer in New Castle County, particularly in updip areas where sandier facies occur (Woodruff, 1990; Dugan et al., 2008).

The Englishtown Formation occurs in the subsurface of the Chesapeake and Delaware Canal area and to the south. The formation ranges from 5 to 75 ft in thickness in New Castle County (Dugan et al., 2008; Ramsey, 2005), and is generally around 15 ft thick where it is exposed along the Canal (Carter, 1937; Owens et al., 1970). The Englishtown's contact with the underlying Merchantville Formation is conformable. Although the contact has been described as distinct in some outcrops (Owens et al., 1970) and in the subsurface (Houlik et al., 1983), in many areas, it appears to reflect a gradual upward coarsening from silt (Merchantville) to sand (Englishtown), and the precise contact is difficult to detect on some geophysical logs (Benson and Spoljaric, 1996). The contact with the overlying Marshalltown Formation to the south is unconformable. In outcrop, the Englishtown-Marshalltown contact is sharp and heavily burrowed, with a pebble layer and woody debris present at the base of the Marshalltown Formation (Carter, 1937; Owens et al., 1970).

In some of the past studies of the Chesapeake and Delaware Canal area outcrops, this interval was referred to as the Wenonah sand (Spangler and Peterson, 1950; Groot et al., 1954; Jordan, 1962) and it was distinguished by the presence of *Ophiomorpha* (then called *Halymenites*) tubes. However, since the geologic map of Pickett (1970a), which was consistent with Carter (1937) and Owens et al. (1970), the name Englishtown Formation has been accepted for these strata in Delaware because of the strong lithologic similarity to the Englishtown Formation at its New Jersey type locality.

The age of the Englishtown Formation in Delaware is Late Cretaceous, specifically Campanian. Though the Englishtown strata lack calcareous fossils in most places, samples from the Fort Mott corehole yield nannofossils indicative of Campanian nannofossil zone CC19 (Sugarman et al., 2004), which is consistent with results from Dover (well Je32-04) reported by Benson and Spoljaric (1996).

Composition, Textures, and Depositional Environment

In the study area, the Englishtown Formation is composed of silty fine-grained sand, with some medium-grained sand, and interbedded fine-grained sandy silt to silt (e.g., Plate 2, Ec13-114 on H-H'). The sands are commonly muscovite-rich, contain glauconite, and may be oxidized. Weak to moderate cementation has been noted. The color, one of several tones of brown, yellow, orange, olive, or gray, is typically a bit lighter than that of the underlying Merchantville Formation.

The environment of deposition of the Englishtown Formation regionally is likely shallow-marine; *Ophiomorpha* are consistent with energetic nearshore environments and rare foraminifera retrieved from the formation indicate less than 150 ft water depths (Houlik et al., 1983). Owens and Gohn (1985) suggested that Delaware localities represent delta-margin barrier shorelines. On the study area geophysical logs, the Englishtown Formation is characterized by generally low gamma and high resistivity values that represent the culmination of an upward coarsening trend from the underlying Merchantville Formation (e.g., Plate 2, Ec13-13 on D-D', Ec14-01 on F-F', and Ec13-24 on F-F' and on H-H'). The lithologies and log patterns are consistent with the interpretation of a nearshore depositional environment.

Thickness, Distribution, and Bounding Relations

The thickness of the Englishtown Formation varies from 5 ft at its most updip extent (Plate 2, C-C′) to nearly 30 ft in the southeast portion of the study area (Plate 2, D-D', E-E', F-F', and H-H').

Geographically, the Englishtown Formation is restricted to the southeastern portion of the study area, except for a thin interval of sand attributed to the Englishtown Formation at one westerly location (Plate 2, Ec12-02 on E-E'). The farthest updip extent of the formation (Plate 2, Dc54-90 on C-C') occurs about 2,600 feet north of Wrangle Hill Road, east of Route 13. In general, the facies of the Englishtown Formation may be too fine-grained and silty to be a productive, high quality aquifer; however, the unit has the potential to be adequately permeable with a sufficient areal extent to allow it to transmit groundwater within and beyond the study area.

The Englishtown Formation is conformably underlain by the Merchantville Formation. The contact can be difficult to identify because of the gradational nature of the Merchantville-to-Englishtown transition. In the eastern and southern parts of the site, the Englishtown is unconformably overlain by the Marshalltown Formation and the contact may be burrowed (e.g., Plate 2, Ec13-114 on H-H'). Closer to its updip limit in the central portion of the eastern side of the study area (Plate 2, D-D' and E-E'), the Englishtown Formation is overlain by the Scotts Corners Formation and/or by Holocene sediments. Columbia Formation deposits unconformably overlie the Englishtown Formation in a narrow band immediately east of the eastern margin of the paleochannel (Plate 2, D-D' and F-F').

Marshalltown Formation

Definition and Age

The Marshalltown Formation in New Castle County is characterized by dark, very muddy sand with abundant glauconite. The formation was named by Knapp (Salisbury, 1899) to encompass a "marly-clay sand" and was described as "micaceous, black, greasy clay, or fine, ashy sand-marl." The Marshalltown overlies the Englishtown Formation, with a regional unconformable contact that is characterized by significant bioturbation where it is exposed along the Chesapeake and Delaware Canal. The formation is overlain by the Mount Laurel Formation.

In Delaware, the Marshalltown Formation has been described by Carter (1937) and Owens et al. (1970) from outcrops on the Chesapeake and Delaware Canal. There it is comprised of clayey, silty, grayish green to greenish black sand and black, calcareous sandy clay with abundant glauconite. Houlik et al. (1983) noted that a basal unit of dark gray to black clay and silty clay occurs in the subsurface downdip of the Canal. From the visual examination of washed samples, Ramsey (2005) noted that glauconite composes 30 to 40 percent of the sand fraction of the Marshalltown Formation in New Castle County. The formation is 14 to 16 ft thick at Canal outcrops (Carter, 1937; Owens et al., 1970), increasing to 30 ft or more southward and downdip (Houlik et al., 1983; Benson and Spoljaric, 1996). Outcrops along the Canal have been assigned to the Mount Laurel/Navesink interval by some workers (Groot et al., 1954; Richards et al., 1957).

The Marshalltown Formation is Late Cretaceous in age and contains fossils of late Campanian age. Houlik et al. (1983) reported the late Campanian planktonic foraminiferal species *Globotruncanita calcarata* in a borehole (Eb44-12) from east of Summit, Delaware. The bivalve *Exogyra ponderosa* is a conspicuous macrofossil in this formation; Sugarman et al. (1995) reported a late Campanian age of 73.4 Ma based on strontium isotope ratios in a specimen of *Exogyra* from St. Georges, Delaware.

Composition, Textures, and Depositional Environment

The Marshalltown Formation in the study area is dark gray glauconitic sandy silt with some quartz sand and mica. The color is typically darker than that of the underlying Englishtown Formation. The Marshalltown Formation cannot be confidently distinguished on many of the lithologic logs where it is interpreted to occur because indefinite lithologic descriptions make it difficult to differentiate from the underlying Englishtown strata. The Marshalltown can be clearly recognized on many geophysical logs, exhibiting the same high-gamma character that it displays in New Castle County.

The environment of deposition of the Marshalltown Formation regionally is considered shelfal marine but significantly deeper than the underlying Englishtown Formation. Benthic foraminifera in samples from just south of the Canal (Eb44-12) suggest that the Marshalltown Formation was deposited in an outer shelf environment at water depths between 400 and 600 ft (Houlik et al., 1983) or 200 to 400 m (Olsson and Nyong, 1984). The study area lithologies and geophysical log patterns are consistent with a depositional setting in deeper shelf environments.

Thickness, Distribution, and Bounding Relations

The Marshalltown Formation is a thin unit, ranging from a few feet thick under Quaternary or Holocene erosional surfaces (Plate 2, D-D′) to approximately 10 to 18 ft thick where the complete thickness of the formation is present (Plate 2, F-F' and H-H'). The Marshalltown is only locally present in the southeastern part of the study area where the Cretaceous section was not significantly eroded before the base of the Pleistocene was deposited. The farthest updip extent of the formation is along a trend on the south side of the refinery complex at Wrangle Hill Road east of Clarks Corner Road.

The Marshalltown Formation unconformably overlies the Englishtown Formation, which is recognized by a clear shift to muddier, more glauconite rich beds with higher gamma log values on geophysical logs (e.g., Plate 2, Ec13-24, Ec14-01, and Ec15-27 on F-F'). The contact is burrowed in some locations (e.g., Plate 2, Ec13-114 on H-H'). Where the Mount Laurel Formation is present in the southeasternmost part of the study area, it overlies the Marshalltown Formation (Plate 2, F-F' and G-G'). Quaternary deposits of the Columbia Formation, Lynch Heights Formation, or Scotts Corners Formation unconformably overlie the Marshalltown Formation in a narrow band just east of the eastern margin of the paleochannel (Plate 2, E-E', F-F', G-G', and H-H'). Holocene-age swamp sediments overlie the Marshalltown very locally (Plate 2, F-F′).

Mount Laurel Formation

Definition and Age

The Mount Laurel sand was initially described by Clark (1897) as an interval of sand in the lower part of what was then defined as the Monmouth Formation in Burlington County, New Jersey. The name is now used as a formation-level designation for the fossiliferous, glauconitic sand that lies near the top of the Upper Cretaceous section in Delaware and New Jersey. The Mount Laurel Formation conformably overlies the Marshalltown Formation, with biostratigraphy and strontium isotope data suggesting that the contact represents a continuous transition from the muddy Marshalltown deposits to the cleaner nearshore sands of the Mount Laurel Formation (Sugarman et al., 1995, 2005). It should be noted, however, that Kennedy and Cobban (1997) suggested the possibility of an unconformity along the Chesapeake and Delaware Canal based on their ammonite zonation interpretations. The Mount Laurel Formation is overlain by the Navesink Formation in Delaware; the boundary is a regional unconformity (Sugarman et al., 1995).

In New Castle County, the Mount Laurel Formation is characterized by quartz sand with shells, burrows, and variable amounts of glauconite, giving it a salt-and-pepper appearance (Carter, 1937; Owens et al., 1970; Pickett, 1970a; Benson and Spoljaric, 1996). Macrofossils include *Belemnitella americana, Exogyra cancellata,* and a number of upper Campanian ammonite taxa (Kennedy and Cobban, 1994). The thickness of the Mount Laurel Formation has been reported at 15 ft or less at outcrops along the Chesapeake and Delaware Canal near St. Georges (just south of the area of the present study), where the top of the formation is eroded under Quarternary sands (Owens et al., 1970; Ramsey, 2005). Greater thicknesses have been described to the west, with 60 ft or more noted near the western end of the Canal in Maryland (Owens et al., 1970). In the subsurface of New Castle County, the formation thickens southward to attain thicknesses approaching 100 ft (Dugan et al., 2008).

The Mount Laurel Formation is of Late Cretaceous age. Sugarman et al. (1995) reported two strontium isotope measurements on a specimen of *Belemnitella americana* from the Chesapeake and Delaware Canal that yielded an age of 71.4 Ma. This is consistent with the upper Campanian strontium ages and calcareous nannofossil biostratigraphy from sites in nearby areas of southern New Jersey (Miller et al., 2004).

Composition, Textures, and Depositional Environment

The Mount Laurel Formation is characterized by glauconitic shelly sand in the study area. In descriptions from several rotosonic cores (e.g., Plate 2, Ec13-91 on H-H'), the formation is brownish in color with fine- to coarse-grained sands and laminae to thin beds of clay.

The Mount Laurel Formation was deposited in mid-shelf to nearshore, shoreface environments in New Castle County (Owens and Sohl, 1969; Houlik et al., 1983; Olsson and Nyong, 1984). On study area geophysical logs, the Mount Laurel Formation has lower gamma values than the more glauconite-rich underlying Marshalltown strata, suggesting a shallowing of water depths from the deeper shelf Marshalltown Formation.

Thickness, Distribution, and Bounding Relations

Like the Marshalltown Formation, the Mount Laurel Formation is only present very locally in the study area where the unconformity at the base of the Pleistocene did not erode significantly into the underlying Cretaceous section. The Mount Laurel Formation is less than 10 ft thick in most locations where it is identified, and has a maximum thickness of around 20 ft (Plate 2, Ec15-28 on F-F').

The Mount Laurel Formation overlies the Marshalltown Formation, with the boundary representing a transition from sandy silt to cleaner sand. The Mount Laurel is unconformably overlain by Pleistocene beds of the Scotts Corners Formation.

Quaternary Geology

Geomorphology

Geomorphology is important for delineating Quaternary stratigraphic units in the Delaware City area. The late Quaternary units of the Delaware Bay Group, the Lynch Heights and Scotts Corners Formations, can be recognized in part by terraces associated with their deposition (Fig. 4). However, recognizing these terraces can be complicated by the landscape modifications that are associated with the construction of industrial facilities, dredge spoil impoundments, wetland fill, and waterway excavation. Therefore, our description of the geomorphology relies heavily on preconstruction topographic maps and aerial photographs of the study area.

Based on pre-construction topographic maps, the study area prior to the construction of the refinery complex in the mid-1950s consisted of an upland with a flat plain to the west, two terraces that stepped down to the east, and an area of marsh between the terraces and the Delaware River. The upland area is bordered on the north and south by two streams (Red Lion Creek and Dragon Run, respectively) that trend due eastward to the Delaware River. The stream valleys are steep-sided where they have dissected the upland, but their surfaces are at or near present sea level downstream where they flow through swamps and marshes. The western half of the upland is a relatively flat plain with elevations from 72 ft to about 54 ft that gently slope to the east (Plate 1).

A distinctive break in topography, the western scarp, trends north-south just east of the Route 9 (River Road) and Clarks Corner Road and separates the upland from a terrace ranging in elevation from 42 to 32 ft that slopes toward the east. Another scarp on the east side of the main refinery complex separates this terrace from another east-sloping terrace, this one with an elevation of 22 ft to about 18 ft The area between the east edge of this terrace and the shoreline of the Delaware River was once occupied by marsh with an elevation from two feet above sea level to sea level (Plate 1); however, most of this area is now covered by dredge spoil impoundments. Just south of the confluence of Red Lion Creek and the Delaware River, there was an island surrounded on three sides by a marsh, with the Delaware River to the east, which is now mostly covered by dredge spoil.

The geomorphology reflects the geology of the area (Fig. 4). The western upland is underlain by the Columbia Formation. The terrace with surface elevations between 42 and 32 ft is underlain by the Lynch Heights Formation. The Scotts Corners Formation lies under the eastern terrace with elevations between 22 and 18 ft. The area occupied by the modern swamp, stream channel and marsh is underlain by Holocene deposits.

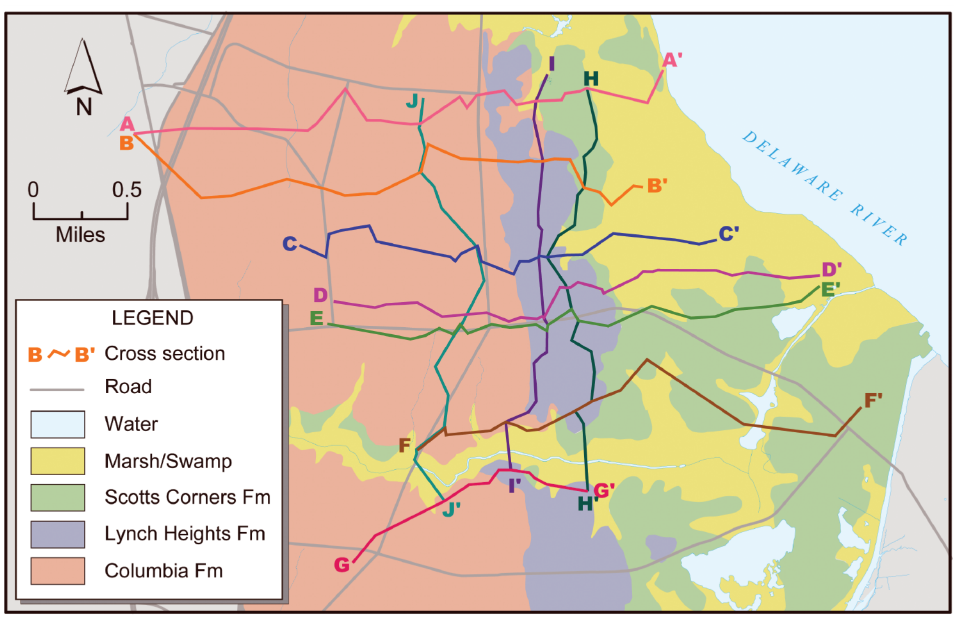

Figure 4. Generalized surficial geologic map of the study area prior to construction of the industrial complex. Extent of the surficial units (Ramsey, 2005) is interpreted from geomorphology (USGS 1:24,000-scale topographic maps for Delaware City (1951) and St. Georges (1953) quadrangles) and examination of samples from the study area in the DGS core and sample repository. Geology of areas in gray uninterpreted.

Columbia Formation

Definition and Age

The Pleistocene-age Columbia Formation is the surficial geologic unit covering much of the Coastal Plain of New Castle County. The name Columbia was first used by McGee (1886a, b) for an interval of sand, gravel, and clay found in the District of Columbia and was later extended to the nearby inner margin of the Coastal Plain (Jordan, 1962). Columbia sediments in New Castle County have long been referred to as “Pleistocene deposits” (Bascom and Miller, 1920; Groot and Rasmussen, 1954; Marine and Rasmussen, 1955; Ward and Groot, 1957) and in some older studies were referred to as the “Columbia Group” (Bascom and Miller, 1920). Jordan (1962) established the use of the name Columbia Formation for these Pleistocene sediments in Delaware; however, not all the sediments that were placed in the Columbia Formation in previous studies (Jordan, 1962, 1964) are assigned to this unit today. For example, Ramsey (2005, 2007) recognized that most of what was previously mapped as the Columbia Formation in southernmost New Castle County and the western two-thirds of Kent County now can be mapped as the Beaverdam Formation. In addition, sediments previously included in the Columbia Formation adjacent to the Delaware Bay coastline are now recognized as the Delaware Bay Group (Ramsey, 1997). Even the Columbia name may be problematic because a Pleistocene age has not been definitively established for the Columbia Formation where it was originally defined in the District of Columbia.

In New Castle County, the Columbia Formation is predominantly composed of medium- to coarse-grained quartz sand with laminae and thin beds of pebbles to pebble gravel with cobbles and boulders in places, especially near the bottom of the formation (Jordan 1962, 1964; Spoljaric and Woodruff, 1970; Ramsey, 2005). The sand is yellow to tan to reddish brown, apparently due to iron oxidation; although the formation is mostly unconsolidated, in places the sands are lithified with iron-oxide cements. In well-exposed outcrops, cross-bedding is commonly observed, with bed set thicknesses ranging from a few inches to 10 ft, and mostly between 0.5 and 1.5 ft. The sand is predominantly quartz, with lesser amounts of feldspar (commonly 10 to 30 percent) and a few percent mica and heavy minerals. Larger clasts include vein quartz, sandstone, quartzite, chert, and lesser abundances of a variety of other clast types, such as siltstone, shale, pegmatite, schist, and amphibolite. Beds of tan, gray, and reddish silt and clayey silt also occur.

The base of the Columbia Formation shows considerable relief in New Castle County and, as a result, the formation varies greatly in thickness, from less than 10 ft to more than 100 ft (Jordan, 1964; Ramsey, 2005). Because its basal unconformity truncates the more steeply dipping older Coastal Plain strata, the formation is underlain by a variety of geological units. The oldest underlying unit is the Potomac Formation in the northern part of the Coastal Plain, and there are successively younger units underlying the Columbia toward the south, ranging up to Miocene sediments of the Calvert Formation in southern New Castle County (Ramsey, 2005). Although the Columbia Formation is the topographically highest stratigraphic unit in most parts of the Coastal Plain of New Castle County, locally it is truncated and unconformably overlain by younger Pleistocene and Holocene-age deposits along the Delaware River and in stream valleys.

The exact age of the Columbia Formation is uncertain due to the lack of diagnostic fossils. The unit is older than the middle Pleistocene Lynch Heights Formation (as old as 425,000 yrs BP; Ramsey, 2010), which overlies the Columbia Formation. If these deposits are correlated with the glacial stratigraphic record in the Delaware River drainage basin, then the Columbia Formation could be older than 770,000 yrs. BP (the age of pre-Illinoian tills in Pennsylvania; Braun, 2008) or as old as early Pleistocene tills (2 Ma) mapped in New Jersey (Stanford, 1997).

Composition, Textures, and Depositional Environment

In the study area, the Columbia Formation is composed of orange to yellow to brown, fine- to coarse-grained, poorly-sorted quartz sand with silt and gravel. Within this matrix, there are layers of interbedded, moderately-sorted, medium- to coarse-grained sand, and fine-to coarse-grained sandy gravel beds. The sandy gravel are primarily composed of pebbles and cobbles of rounded gray, white, and clear quartz and quartzite, and etched to smooth chert. Beds of pale yellow, moderately micaceous, very fine-grained sandy silt to silty very fine- to fine-grained sand are common. Beds of very pale brown finely laminated silty clay are also present.

The formation is often highly oxidized, with moderate interstitial cementation in some horizons and cemented ironstone layers and nodules in some places. The base of the formation is commonly characterized by sandy fine-to coarse-grained gravel, iron cemented sandy zones and the presence of rip-up clasts of either Merchantville or Potomac-derived clays, often encapsulated into ironstone nodules. Thin beds of silty clay (<2 ft thick) are commonly found interbedded with these gravels. In the most deeply eroded zones, such as at the base of the paleochannel (discussed below) that bisects the study area, these deposits include pebble to cobble gravel that passes upward into medium- to coarse-grained sand beds with scattered intervals of pebble gravel. Large-scale bed sets were observed in the thick section of the Columbia Formation that was exposed within a deep excavation (formerly used as a propane storage cavern) that is bordered by borehole locations Dc53-34, Ec13-14, Ec13-15, and Ec13-16 (Plate 2, D-D' and H-H').

The Columbia Formation has been interpreted to have been the result of fluvial deposition by glacial melt water under cold to cool-temperate climatic conditions during the Pleistocene (Jordan, 1964; Groot and Jordan, 1999). Some workers have the Columbia Formation being the Delaware nomenclature equivalent of the Pensauken Formation of New Jersey (Pazzaglia, 1993; Stanford, 2006a), with the Pensauken being deposited by a large, southwesterly proto-Hudson River from the New York City area that shifted to the south and southeast on the Delmarva peninsula (Owens and Minard, 1979; Stanford, 2003). Stanford (2006a) surmised that "the Delaware River may have continued to deposit the Pensauken in the Delaware Valley and the Columbia Formation on the Delmarva Peninsula into the early and middle Pleistocene." Although this could explain the younger Pleistocene age data in Groot and Jordan (1999) and the glacial depositional setting that differs markedly from the warm-temperate depositional setting of the Pensauken (Berry and Hawkins, 1935), the DGS considers the Beaverdam Formation to be age equivalent to the Pensauken (Groot and Jordan, 1999), with the overlying Columbia being deposited under fluvial conditions during the transition from a cold to a temperate period or from a glacial to an interglacial interval.

Thickness, Distribution, and Bounding Relations

The Columbia Formation is the most extensive surficial unit in the study area (Fig. 4) and exhibits remarkable stratigraphic relief. The most noteworthy feature is a deeply incised trough, here called the Reybold paleochannel, that traces a relatively narrow north-south trending band across the study area about a thousand feet to the east of Route 9 (River Road) (Fig. 3; Plate 2, A-A' through G-G', and Plate 4). The presence of a significant paleochannel was first suggested by Rasmussen, et al. (1957). The paleochannel is named for the former Reybold railroad station near the intersection of River Road and the railroad tracks that cross the study area. This feature was named to differentiate it from other shallower paleochannels noted elsewhere in New Castle County in other studies (Spoljaric, 1967a; Pickett, 1970a; Sundstrom and Pickett, 1971).

The elevation of the base of the Columbia Formation varies across the study area from 36 ft to –111.6 ft, resulting in wide variations in thickness (Plate 4; Appendix 4). In some parts of the Reybold paleochannel, the Columbia deposits are as much as 139 ft thick (Plate 2, Ec13-56 on I-I'). Across most of the study area west of the Reybold paleochannel, the formation is significantly thinner, commonly between 50 and 75 ft The formation also occurs in a narrow belt on the east side of the paleochannel, thinning by stratigraphic pinchout and/or erosion to a well-defined eastern limit between the paleochannel and the Delaware Bay marshes.

The shape and width of the Reybold paleochannel within the study area exhibits subtle variations (Plate 4). To the north, the paleochannel has a steeper western slope and a width of approximately 1,700 ft (Plate 2, A-A′). In the center of the study area, the side slopes steepen and the paleochannel appears to narrow to approximately 1,500 ft wide (Plate 2, C-C' and E-E'). where it cuts more deeply into the Merchantville Formation and upper Potomac Formation. In the south, the paleochannel broadens to over 2,400 ft with a much steeper eastern slope (Plate 2, F-F' and G-G').

Cross section I-I′, (Plate 2) follows the axis of the Reybold paleochannel and illustrates the drop in elevation of the base of the paleochannel in the north (–44.3 ft in Dc53-38) to the center of the study area (–101.3 ft in Ec13-21). The cross section also depicts the deepest portion of the channel at boring Ec13-56 (–111.6 ft) and a fairly uniform basal elevation (approximately –100 ft) moving toward the southernmost data point in the study area. Calculations of basal paleochannel slope dips along this transect vary between 0.447 and 0.504 degrees. Because the Reybold paleochannel downcut at a slightly steeper slope than the apparent dip of the Potomac-Merchantville contact in the same direction (approx. 0.3 degrees), the paleochannel eroded completely through the Merchantville Formation and incised into the top of the Potomac Formation (Plate 3).

The considerable erosional relief at the base of the Columbia Formation is reflected in disconformable contacts with underlying Cretaceous formations, including the Marshalltown, Englishtown, Merchantville, and Potomac. The upper surface of the Columbia Formation is also variable. West of the Reybold paleochannel, the top of the Columbia Formation is at the land surface or is covered by a thin soil veneer. Along the Reybold paleochannel trend, and in the limited exposure of the unit east of the paleochannel, the Columbia Formation is overlain by the Delaware Bay Group deposits. Local post-Columbia erosion is also evident in stream valleys that cross the study area where Holocene swamp and marsh deposits fill the base of the valleys and cap the Columbia deposits. Small inset terraces of Lynch Heights Formation and Scotts Corners Formation are found on the flanks of the stream valleys (Plate 2, Ec13-63 to Ec13-33 on F-F', and Ec13-25 and Ec13-27 on I-I').

Delaware Bay Group

Definition and Age

The Delaware Bay Group in Delaware (Ramsey, 1997, 2003, 2010) is comprised of the Lynch Heights Formation and the Scotts Corners Formation. The group has been mapped from Lewes, Delaware, to the Delaware-Pennsylvania border (Ramsey, 2003, 2005, 2007). Both formations were recognized in the study area by Ramsey (2005) in the recent DGS surficial geologic map of New Castle County.

The Lynch Heights and Scotts Corners Formations are found in the eastern part of the study area. These formations are composed of step-like terrace deposits along the margins of the Delaware Bay and River (Ramsey, 1993, 2005, 2010). The western margins of the terraces are delineated by steep erosive slopes, called scarps, that are cut into older stratigraphic units (Ramsey, 2010, Fig. 24). The land surface of the units is a terrace tread, a surface that gently slopes toward the present Delaware River, that formed as the nearshore to offshore estuarine bottom during high sea level during the interglacial. Successive terrace treads are separated by drops in elevation over relatively short distances along younger scarps. The scarps were produced by shoreline erosion that formed bluffs during the subsequent sea level rise. The lower contact of these units is an unconformity formed by shoreline migration due to sea level rise during mid- to late-Pleistocene interglacial periods. Two distinctive terraces are recognized in the study area. One, with surface elevations between 42 and 35 ft, is underlain by the Lynch Heights Formation; the other, with elevations between 24 and 18 ft, is underlain by the Scotts Corners Formation (Ramsey, 2005).

The Cape May Formation of New Jersey (Salisbury and Knapp, 1917; Newell et al., 1995, 2000; O'Neal and McGeary, 2002; Stanford, 2006b) is correlative to the Delaware Bay Group (Ramsey 1997).

Lynch Heights Formation

Definition and Age

The Lynch Heights Formation constitutes the older of the two units that compose the Delaware Bay Group in the study area. Regionally, the formation represents a complex of middle Pleistocene-age estuarine and marsh sediments found on two terraces along the margin of the Delaware Bay and River (Ramsey, 1993, 1997, 2010). The higher terrace is between 45 and 40 ft and is correlative with marine isotope stage (MIS) 11 (approx. 400,000 yrs BP). The lower terrace occurs at an elevation of 30 to 25 ft and is correlative with MIS 9 (approx. 330,000 yrs BP).

Composition, Textures, and Depositional Environment

Samples were examined from two rotosonic core holes through the Lynch Heights Formation in the study area, Ec13-22 and Ec13-24 (Plate 1). The lower part of the Lynch Heights Formation consists of a 5 to 10 ft thick, fining-upward unit of pale yellow to yellow fine- to coarse-grained sand with thin (<1 ft) beds of pale yellow clayey silt and scattered laminae, to thin beds of pebbly coarse-grained sand to gravel. A thin bed (about 1 ft thick) of pebble to cobble gravel to a laminae of scattered pebbles and cobbles is found at the base of the unit. The upper part of the formation is a 5 to 10 ft thick unit of very pale brown clayey silt. This clayey silt has interbeds (0.5 to 1.5 ft thick) of fine- to coarse-grained sand with pebbles that become less common upward. The Lynch Height sediments in these core holes are interpreted as nearshore estuarine deposits. To the north of these core sites, the Lynch Heights Formation also contains beds of 2 to 10 ft thick light brown silty clay to clayey silt with varying proportions of fine- to very fine-grained sand (Plate 2, Dc53-45 to Dc53-118 on B-B' and Dc53-96 to Dc53-186 on C-C'). These beds are interpreted to be muddy tidal flats to estuarine deposits.

The depositional environment of the Lynch Heights Formation is interpreted as a nearshore estuarine adjacent to a bluffed shoreline. The gravel at the base of the unit represents a transgressive lag of Columbia Formation materials that were eroded from a landward migrating bluff and incorporated into beach and nearshore deposits. The interbedded tidal flat and estuarine clayey silts and silty clays are interpreted as deposits from periods when the shoreline was relatively stable, and as a result, there was minimal erosion and transport of coarser materials into the estuary. During peak sea-level stand, clayey silts were deposited in nearshore estuarine environments.

Thickness, Distribution, and Bounding Relations

The Lynch Heights Formation occurs in the eastern part of the study area in a narrow zone associated with a terrace between 42 and 35 ft in elevation, indicating that only the older, higher terrace level of the Lynch Heights Formation is present. The Lynch Heights deposits are most commonly between 10 and 20 ft thick, but have a maximum thickness of 30 ft and a thickness of zero where they pinch out at the western limit of the formation at the toe of the scarp with the Columbia Formation. The base of the Lynch Heights Formation is an unconformity marked by the occurrence of gravel to a layer of single scattered pebbles and cobbles.

Because the Lynch Heights Formation in the study area is primarily reworked sand from the adjacent Columbia Formation, the contact between the two formations is difficult to distinguish because of basic lithologic similarities, which can only be differentiated when cores are available or if descriptive logs record specifics on the grain size and composition of the sands. The Lynch Heights-Columbia contact was picked at the base of a gravel layer at a depth consistent with the thickness of the Lynch Heights from other evidence. In some cross sections, the contact could not be recognized and was interpolated from adjacent holes. The Lynch Heights Formation is readily differentiated from underlying marine Cretaceous units because it is coarser grained and lacks mica and glauconite.

Scotts Corners Formation

Definition and Age

The Scotts Corners Formation is the younger unit of the Delaware Bay Group. Defined by Ramsey (1993, 1997), the formation includes the deposits that occur beneath two terraces that approximately parallel the Delaware Bay and River at elevations 18 to 10 ft, and 7 ft to sea level (Ramsey, 2010). The Scotts Corners Formation is mapped along the entire western margin of the Delaware estuary (Ramsey, 2005, 2007), seaward of the Lynch Heights Formation and up the margins of some of the tidal river tributaries of the Delaware River. It is considered to be Late Pleistocene in age with two parts, one dated at approximately 120,000 years (MIS 5e) and the other at 80,000 years (MIS 5a) (Ramsey, 2010), which are represented by the higher and lower terraces, respectively.

Composition, Textures, and Depositional Environment

The Scotts Corners is finer grained than the underlying Quaternary Columbia and Lynch Heights Formations and also may contain beds of micaceous sands that were reworked from the underlying Cretaceous units. Compared with the underlying Cretaceous units, however, the formation is coarser grained, with lighter hues, and contains much less mica and glauconite, except for a few thin beds where the Cretaceous sediments were locally reworked.

Samples of the Scotts Corners Formation taken from two rotosonic core holes, Ec13-112 and Ec14-11 (Plate 2, F-F′), reveal the heterogeneity of the unit in the study area. Ec13-112 is located nearer the scarp that separates the unit from the Lynch Heights Formation to the west. The Scotts Corners Formation is capped by 1.5 ft of silt overlying 13 ft of interbedded pale yellow fine- to medium-grained sand, pale yellow coarse- to medium-grained sand with very coarse grained sand to granules, and pale olive very fine- to fine-grained micaceous sand. The interbedding appears to be sediment reworked from different source materials, with coarser beds derived from the adjacent Columbia and Lynch Heights Formations and the very fine-grained, micaceous sands from underlying Cretaceous units (Marshalltown and Englishtown Formations). These sands were likely deposited in a nearshore setting near the scarp (shoreline bluff) where shoreline erosion into the Lynch Heights was interspersed with sand from just offshore from the exposed Cretaceous sediments.

In contrast, farther east in Ec14-1, the Scotts Corners has 4 ft of silt overlying a mottled yellow and light gray clayey silt with laminae of silt to very fine-grained sand. Near the base of the unit, laminae of coarse- to very coarse-grained sand are found with rare small pebbles. At this locality, with the exception of the base, the sediment is interpreted to have been deposited in a tidal estuarine (tidal flat) setting.

Samples of the Scotts Corners Formation were examined from a well just north of Red Lion Creek (Dc44-02; Fig. 1) and consisted of about 10 ft of yellow to light gray, slightly micaceous, silty very fine-grained sand that grades down to moderately silty fine- to very fine-grained sand. These deposits are similar to those of Ec13-112.

Ramsey (1997) interpreted the Scotts Corners Formation to be stream, swamp, marsh, estuarine barrier and beach, tidal flat, and shallow offshore estuarine deposits. This composite formation accumulated during transgressive periods of two separate high stands of sea level.

Thickness, Distribution, and Bounding Relations

The Scotts Corners Formation can be as thick at 30 ft, but is more typically between 4 to 20 ft in the study area. The unit thins to 0 ft at the toe of the scarp with the adjacent Lynch Heights or Columbia Formation where the Lynch Heights is not present (Plate 2, D-D′). The base of the unit is an unconformity with underlying Quaternary or Cretaceous formations and is commonly marked by a bed of coarse-grained to pebbly sand.

The Scotts Corners Formation is located in a narrow zone in the eastern part of the study area. The formation is associated with a terrace of between 24 and 18 ft These elevations are slightly higher than the 18 to 10 ft documented for the unit in Sussex County (Ramsey, 2010) but are within the range observed in Kent and New Castle Counties (Ramsey, 2005, 2007). The formation is recognized in the study area in the older, higher-elevation terrace; the younger and lower terrace occurs nearby, to the southeast, in the area of Delaware City.

Marsh and Swamp Deposits

Summary of Lithologic and Stratigraphic Features

In New Castle County, marsh deposits are structureless to finely laminated, black to dark-gray, organic-rich silty clay to clayey silt with discontinuous beds of peat and rare shells; in-place or transported fragments of marsh grasses are common (Ramsey, 1997; 2005). Marsh sediments occur in the eastern portion in the study area near the Delaware River (Plate 2, A-A' through E-E'). The deposits are typically saturated, very dark brown to dark gray, slightly micaceous, organic silt and clayey silt with trace to some sand and gravel, and lesser interbedded dark silty clay. At the base of the unit and adjacent to the Delaware River, the deposits contain beds of strong brown to grayish brown, fine- to medium-grained sand with some coarse-grained sand and gravel. Beds of dark brown to black peat occur locally, most consisting of compacted plant fragments. The presence of peat deposits in most of the borings, and at different stratigraphic horizons, suggests that these locations represented lateral marsh fringe and marsh depositional settings. The marsh deposits are overlain by fill that may have deformed or displaced them by loading or compaction. At the base of the marsh deposits is an unconformable contact with Pleistocene or Cretaceous-age deposits. The thickness of the marsh deposits ranges from about 4 ft in the most inland locations to greater than 30 ft approaching the present-day river.

In New Castle County, swamp deposits are structureless, black to brown, organic-rich silty and clayey, fine- to coarse-grained quartz sand with thin interbeds of medium- to coarse-grained sand; organic materials consist of leaves, twigs, and larger fragments of deciduous plants (Ramsey, 1997; 2005). The unit is defined primarily on the presence of deciduous vegetation in stream valleys (Ramsey, 2005). The swamp deposits observed in borings from the study area were gray to dark gray silt, clayey silt, and silty clay with wood fragments and a high organic content (Plate 2, A-A', C-C', and I-I'). These swamp deposit occurrences are included with the marsh deposits in the Appendix 2 table of stratigraphic picks used for the cross sections. At the base of the swamp deposits is an unconformable contact with the Pleistocene or Cretaceous-age deposits. The thickness of the swamp deposits in the study area ranges up to about 22 ft.

Radiocarbon Age Dating

Holocene deposits were difficult to separate from some Pleistocene sediments in the study area and, in some locations, they also bear superficial similarity to Cretaceous formations. As such, an effort was made to recognize Holocene deposits so that the contact with underlying older formations could be accurately delineated. Radiocarbon or ^{14}C dating is an important tool for distinguishing Holocene (modern marsh and swamp deposits) from similar-looking older Pleistocene deposits formed in the same type of depositional environments. Accurate ^{14}C age dating is also a useful tool for locating where dredge fill from the modern estuary and marshes has been emplaced over undisturbed Holocene marsh deposits because this situation would yield inverted (older over younger) or spurious ages that would differ markedly from the expected stratigraphic succession.

Radiocarbon age analyses were conducted on five marsh deposit peat samples from beds that were considered to be undisturbed by human activity. All but one of the samples (Dc54-19) were from basal deposits approximately 0.7 to 4 ft above the contact between the Holocene and Cretaceous deposits. These samples yielded ages ranging from Cal BP 1270 to 1060 (1230 ± 40 yrs BP conventional age) in boring Dc54-20 (between B-B′ and C-C′), to Cal BP 4880 to 4790/Cal BP 4770 to 4620 (4240 ± 60 yrs BP conventional age) in boring Dc53-127 (C-C′) (Table 1). The radiocarbon ages confirm that the deposits are Holocene; as a general principle, the data from the Holocene basal peats record the maximum age of the incursion of tidal deposits at the sample site (Belknap and Kraft, 1977; Engelhart et al., 2009).

A curve can be extrapolated from plots of sample age versus sample elevation to indicate changes in sea level, which was done for the Delaware Bay coast by Nikitina et al. (2000). Such plots are useful for analyzing the reliability of the radiocarbon dates by highlighting samples that lie off the trend. The ages of radiocarbon samples from the study area, along with samples from along the margins of the Delaware River north and south of the site (Jengo, 2006; Ramsey and Baxter, 1996), are shown in a plot in Figure 5. The ^{14}C dates from the study area are numbered 306, 307, 308, 310 and 311 (Tables 1 and 2) and regional sample dates have numbers lower than 306 (Table 2). The line shown in Figure 5 is not a statistical curve; rather it is drawn to help visualize the general sea level curve for the region. The closer the data points cluster along this non-statistical curve, the greater their reliability. Outliers that plot below the curve may indicate contamination by modern carbon or post-depositional compaction; outliers that plot above the curve may not represent initial sea level incursion within the area.

Study area samples 307, 308, and 310 plot near the sea level curve and their close correlation to the regional database indicates their reliability as undisturbed representative samples (Fig. 5). Samples 306 and 311 plot below the curve, indicating they were affected by either contamination from modern carbon or by compaction from the loading of fill, which pushed them down in elevation. These ^{14}C ages,

Table 2. Radiocarbon dates used in sea level curve (from Ramsey and Baxter, 1996 and unpublished DGS data). The 300-series data were analyzed for this study. The sample numbers between 53 and 83 are from the along the Delaware River in New Castle County, with two (61 and 62) from north of this study area and the others from the south. The 200-series data are from the Marcus Hook area, along the Delaware River just north of the Delaware–Pennsylvania border.

DGS RC No.	DGS ID	Laboratory Sample ID	Northing	Easting	Sample Elev. (ft NAVD 88)	Converted Age (yrs BP)	Converted Range Age (yrs BP)	Calibrated Age (yrs BP)
53	Fc15-03	I-6575	4371887	449442	-17	2685	90	2851
54	Fc15-03	I-6576	4371887	449442	-34	4515	100	5099
55	Fc15-03	I-6577	4371887	449442	-40	5600	110	6424
56	Ed22-10	I-6587	4379022	451470	-16	1410	90	1326
57	Ed22-10	I-6588	4379022	451470	-29	4265	95	4787
61	Be32-18	I-7036	4403878	459630	1	2355	85	2419
62	Be32-18	I-7038	4403878	459630	-4	2450	85	2451
67	Fc31-40	I-7037	4367118	443675	-46	6170	115	7022
83	Fb45-07	I-7525	4365224	441246	-17	2875	90	2999
271	Bf11-18	Beta-193394	4408466	465733	-1.07	1090	40	970
272	Bf11-16	Beta-129641	4407899	465599	-3.9	1130	40	1050
273	Bf11-16	Beta-129642	4407899	465599	-8.8	2110	40	2105
274	Bf12-04	Beta-129644	4408044	465963	-4.5	1140	40	1055
275	B12-04	Beta-129645	4408044	465963	-10.8	2730	40	2795
276	Bf11-15	Beta-129646	4407551	465156	-7.2	1270	40	1180
277	Bf11-15	Beta-129647	4407551	465156	-13.9	2750	40	2845
278	Bf11-15	Beta-129648	4407551	465156	-18.7	3370	50	3620
279	Bf11-15	Beta-129649	4407551	465156	-31.3	4700	40	5403
280	Bf11-14	Beta-129643	4407609	465524	-10.3	2380	40	2355
281	Bf21-07	GX-22967	4407243	465109	-11.4	2390	50	2355
282	Bf21-05	Beta-129650	4407253	465186	-11.9	2460	80	2545
283	Bf21-08	Beta-197355	4407079	465035	-21	3520	50	3830
284	Bf21-09	Beta-207057	4407402	465189	-36.9	5030	60	5740
293	Bf11-16	Beta-193393	4407899	465599	-13.1	980	40	920
306	Dc53-188	Beta-233549	4382912	447055	-14.6	1540	40	1410
307	Dc53-127	Beta-233550	4382151	446979	-24.3	4240	60	4840
308	Dc54-18	Beta-233551	4381835	447302	-10.1	2420	60	2425
310	Dc54-19	Beta-233553	4382544	447148	-9.5	1490	50	1370
311	Dc54-20	Beta-233554	4382502	447228	-15.8	1230	40	1170

particularly sample 307, suggest that development of marshes and the incursion of tidal deposits began in the study area around Cal BP 4880 to 4620 (4240 ± 60 yrs BP conventional age). The incised-valley system of the Delaware estuary was largely filled during middle to late Holocene time (Fletcher et al., 1992) and the late Holocene ^{14}C ages obtained from basal peats in this study area are younger than other ages in this part of the Delaware estuary (Jengo, 2006). As such, the deposits analyzed for ^{14}C ages in this study do not represent the initial incursions of tidal deposits regionally, but rather are interpreted to represent marshes developed within the broad, relatively flat flood basin subenvironment that was inundated in late Holocene time.

Fill Deposits

Fill in this study area includes anthropogenic fill, disturbed soils, and near-surface lithologies that may have been disturbed. Fill was identified in soil boring and well records based on lithological characteristics and on the comparison between pre-construction topography and aerial photographs with recent aerial photographs and LIDAR-derived photography.

The significant areas of anthropogenic fill along the Delaware River include material dredged from the river and from clearing tidal channels through the marsh to the refinery site. This fill is primarily mud that is comprised of a mix of

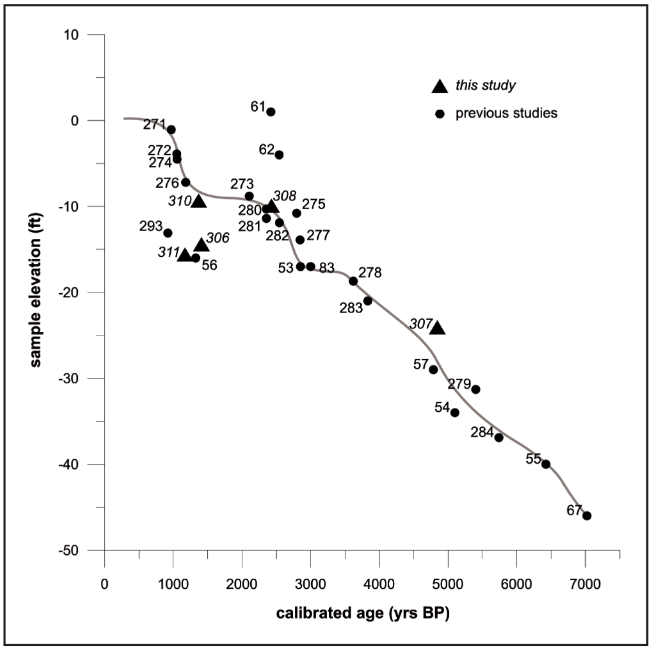

Figure 5. Plot of radiocarbon dates versus sample elevation from the study area and the margin of the Delaware River in nearby locations (Table 2). The line on the plot represents a generalized sea level rise curve for the area, not a statistical fit of the points on the plot. Data points from study area suggest development of marshes and the incursion of tidal deposits began in the study area between 4,500 and 5,000 years before present, with younger ages reflecting deposition as the marshes expanded in extent during sea level rise.

fine-grained sand, silt, and clay. In some places, distinguishing between this fill and naturally occurring marsh deposits and alluvium is difficult because of their similar lithologies, particularly when the fill was derived from the adjacent marsh deposits and the dredging of the Delaware River just offshore at the refinery docks. The thickness of this fill is commonly from 20 to 40 ft where former marsh areas near Delaware River have been built up as dredge spoil disposal areas (Plate 1).

In the central and western portions of the study area, where the Columbia Formation is exposed at or near the land surface, Columbia materials were backfilled into some of the adjacent lower-lying areas. As a result, it can be difficult to determine the topography of the original land surface of the Columbia Formation in these areas. Distinguishing between the disturbed and undisturbed materials was further complicated because of the fine-grained sand and/or silt of variable thickness that is often present overlying the Columbia Formation. This material is interpreted to be periglacial eolian sand and loess that post-dates the deposition of the Columbia Formation (Rebertus, 1998; Rebertus et al., 1989). For the purposes of this report, however, these sediments are mapped with the Columbia Formation. In areas where the Columbia Formation was affected by disturbances, the fill is up to 15 ft thick, with a few locations where deeper excavations or significant buildup has resulted in fill thicknesses of around 30 ft.

Because many of the borehole records with identified fill are of local occurrences with minor thicknesses of material, and because the differentiation of fill from native materials can be ambiguous, the illustration of fill thicknesses on the Plate 2 cross sections is generalized in many areas. Only where fill was more than 5 ft thick and areally extensive was it deemed worthwhile to depict it on the cross sections.

DISCUSSION

Origin of the Reybold Paleochannel and Columbia Formation Deposits

Workers dating back to the mid-1950s recognized Pleistocene-age channels in the Chesapeake and Delaware Canal area. Groot et al. (1954) first noted the presence of "sand-filled river channels which at times cut deep into the underlying formations [and] are visible in the Canal." Rasmussen et al. (1957) suggested that four areally extensive channels could be recognized in New Castle County. The existence of a major paleochannel in the Delaware City area was first described in that report, part of what they called their "middle-level" channel, designated "M" (p. 124):

> The channel identified by the symbol M, meaning "middle-level" is the channel along which high-capacity wells and some large gravel pits have been developed. The wells now used by the Atlas Point plant; the wells of the Artesian Water Co. at Swanwyck, at Wilmington Manor Gardens, at Llangollen Estates, and at Midvale; and the wells at the Tidewater refinery [now the Delaware City Refinery Company] are all in this channel. The lowest altitudes recorded in wells for the base of this channel are 82 ft below sea level at the north end (Cd43-5) and 90.5 ft below sea level near Delaware City (Ec13-6). Control on this channel loses accuracy from Llangollen Estates to Red Lion Creek, and from Dragon Creek to the Canal. These are areas in which test drilling is needed, and in which large capacity wells may yet be developed. It is still a matter of hypothesis whether this filled channel continues to the southwest beyond the Canal, or makes a right angle bend to the southeast, somewhere near Dragon Creek, paralleling the present river.

Rasmussen et al. (1957) identified the base of this channel, although it was at a slightly higher elevation (–90.5 ft) at well Ec13-06 than what we recognize at in a well at the same location (–101.3 ft in replacement well Ec13-21).

Paleochannels in the Columbia Formation were also recognized in later DGS studies, including Jordan (1964), Spoljaric (1967a), Spoljaric and Woodruff (1970), Sundstrom and Pickett (1971), and Woodruff (1986). Spoljaric (1967a) depicted a broad "eastern channel" that encompassed the study area, which was represented by a thick local pod of Columbia sediments that had been mapped at the refinery. A similar isolated thick section of Quaternary sediment was mapped in Sundstrom and Pickett (1971). Woodruff (1986) recognized a thick zone of Columbia sediments around well Ec13-06 on a cross section that illustrated the geohydrology of the Chesapeake and Delaware Canal area. Although these previous studies recognized significant relief at the base of the Columbia Formation and an area of especially thick Columbia sediments on the refinery property, the specific geometry and trend of the Reybold paleochannel and consideration of whether it was part of a drainage network required further investigation, which was the primary objective of our study.

Compared to the studies mentioned above, this work has access to a much larger dataset, with a significantly denser coverage of well and borehole data, allowing us to create a more precise delineation of the base of the Columbia Formation and to develop a better understanding of the character of the Reybold paleochannel. The total relief we mapped for this basal surface was nearly 148 ft, with the elevation ranging from 36 ft above sea level in the western part of the study area to nearly 112 ft below sea level in the deepest part of the Reybold paleochannel (Plate 4).

An assessment of the surface topography allows the identification of three geomorphological realms across a west-to-east transect of the study area: upland, paleochannel margin, and Reybold paleochannel. The upland makes up most of the western portion of the study area where the elevation of the base of the Columbia Formation is higher than 20 ft, which is typical in much of this part of New Castle County outside of paleochannels. The elevation of the upland surface decreases toward the western margin of the study area, beyond which another paleochannel has been identified (Spoljaric, 1967a). On the east side of the upland, a buried scarp has been located where the base of the Columbia Formation drops approximately 25 ft in elevation in a horizontal distance of less than 1,000 ft. The surface defining the base of the Columbia Formation east of this scarp and west of the Reybold paleochannel is a broad flat area where the base of the Columbia Formation ranges in elevations from –5 to –15 ft This represents the paleochannel margin area, which underlies much of the refinery complex. On its eastern edge, the paleochannel margin slopes into the Reybold paleochannel, dropping 40 to 60 ft in a short distance.

The Reybold paleochannel is the one of the most distinctive subsurface geologic features in the Delaware City area but cannot be clearly traced outside of the study area. The deep axial portion of the paleochannel rises in elevation northward and cannot be clearly distinguished north of the study area. Similarly, available data south of the study area reveal no clear evidence for an extension of the Reybold paleochannel southward. Rasmussen et al. (1957) lumped into their channel "M" what we call the Reybold paleochannel and other zones of thick Columbia Formation to the north in the New Castle area. However, the elevation of the base of their channel "M" deposits is deeper in the New Castle area (–82 ft at Cd43-05) than what we recognize for the base of the Reybold paleochannel in the northern part of this study area (–44.3 ft at Dc53-38), suggesting that the New Castle feature cannot be traced as a continuous channel to our study area. Although additional study is warranted to define the exact extent of Columbia Formation channels outside of this study area, at present we conclude that the Reybold paleochannel is a local deep scour and that no evidence exists to trace it as a continuous feature north or south of the study area.

The possibility that the Reybold paleochannel is a pre-Lynch Heights middle Pleistocene channel was considered. The Reybold paleochannel occurs, however, west of the scarp that defines the western limit of the Lynch Heights Formation in areas where Columbia deposits are known at and near the land surface. The channel-fill deposits described from deep parts of boreholes in the paleochannel trend are lithologically identical to those mapped as Columbia Formation near the land surface outside of the paleochannel trend. On the basis of these observations, we consider the Reybold paleochannel deposits to be older than the Lynch Heights Formation and lithologically assignable to the Columbia Formation.

Several origins and depositional settings have been proposed for the paleochannels of the Columbia Formation. Jordan (1964) suggested that the channels identified by Rasmussen at al. (1957) may represent "valleys cut at four different elevations during glacial stages and filled in interglacials." Spoljaric (1967a) and Sundstrom and Pickett (1971) depicted the surface as a landscape of channel lows and interfluvial highs associated with a braided river system. Spoljaric (1967a) characterized the channels north of the Chesapeake and Delaware Canal as being straighter and deeper than those located south of the Canal, which were described as glacial outwash deposited in a braided river system dominated by sediment bedload (Spoljaric, 1967a; Spoljaric and Woodruff, 1970). However, none of these studies addressed the origin of the especially thick sediment zones identified in the Columbia Formation.

On the basis of the observations of lithology, distribution, and geometry, we conclude that the Columbia Formation was deposited by braided rivers carrying glacial outwash from melting ice sheets during transitions between glacial and interglacial periods in the Pleistocene. Such braided river systems are common near glaciated areas where meltwater provides high stream power and high suspended load. The presence of cobbles and scattered boulders in some parts of the unit indicates that very strong currents existed at times.

Although no definite evidence exists for the exact timing of, or process for, the formation of the Reybold paleochannel, we believe that the deep local scour documented herein cannot be explained by normal braided stream processes. We believe that the most likely scenario is catastrophic flooding related to glacial ice dam bursts in the paleo-Delaware River valley to the north, similar to the processes that created the Channeled Scablands of eastern Washington (Baker, 2009). The topography of the Channeled Scablands was shaped by powerful flows of glacial meltwater following the failure of an ice dam that impounded Ice Age Lake Missoula. The flow transported large boulders, deposited sand bodies tens of feet thick, and carved channels and potholes into bedrock as much as much as 100 ft (30 m) deep (Baker, 2009). Similar Pleistocene catastrophic flooding events have been suggested as explanations for geomorphological features of major river valleys in the Mid-Atlantic region, including the Susquehanna River (Braun, 2008), the Hudson River (Donnelly et al., 2005), and its submarine extension, the Hudson Shelf Valley (Thieler et al., 2007).

In this scenario, the Reybold paleochannel would have been eroded by the initial powerful outflow of water, followed by deposition of sediment associated with the flood event or from the braided river system that subsequently deposited most of the Columbia Formation. The amount of time that passed between paleochannel erosion and fluvial deposition is unclear. No well-developed paleosol is evident beneath the Columbia Formation in the study area; even if paleosols formed below the erosional surface, the subsequent Columbia braided stream systems would have eroded them. Additionally, paleosols would be difficult to differentiate from post-depositional diagenesis at the contact between the highly permeable Columbia Formation and the less permeable stratigraphic units beneath.

Implications for Hydrogeology

Two main aquifer intervals were studied: the confined Potomac aquifers and the unconfined Columbia aquifer. Although this work does not address the hydrology of these aquifers, the cross sections and maps presented here provide important geological constraints on the distribution and connectivity of aquifer sand bodies.

The complexity of sand connectivity in the Potomac aquifers has long been recognized. Sundstrom et al. (1967) concluded that the occurrence of sand bodies in the Potomac Formation was so random that individual bed correlation was not possible even over short distances. Sundstrom et al. (1967) proposed the delineation of two relatively sandy zones separated by a "persistent clayey zone" and informally named the sandy zones the lower hydrologic and upper hydrologic zones of the Potomac Formation. The zones were practical working subdivisions and were not lithostratigraphic, biostratigraphic or chrono-stratigraphic horizons because their "continuity as a physical boundary is not evident." Using a combination of well log stratigraphy and pollen biostratigraphy, McLaughlin and Benson (2002, 2005) and Benson (2006) established an updated correlation framework for the Potomac Formation that differentiated upper and lower, sandy, aquifer-prone intervals separated by a middle, muddy aquitard-prone interval. This approach was incorporated into an aquifer modeling project, conducted by the U.S. Army Corps of Engineers, which recognized three layers for modeling: a sandy upper A zone, a muddy middle B zone, and a sandy lower C zone (USACE, 2004).

The confined Potomac aquifer system is "extremely heterogeneous on the megascopic scale and connectivity of permeable fluvial units is poorly constrained" (McKenna et al., 2004). Recent stratigraphic analyses of the Potomac Formation in New Castle County utilizing geophysical logs (Benson, 2006, McKenna et al., 2004) indicate that the sand bodies were deposited by a series of fluvial systems and are variably distributed through the formation. Fluvial sand bodies make up only 20 to 30 percent of the volume of the formation (Benson, 2006); seismic reflection surveys just to the west of the study area indicate that individual channels are modest in size, only hundreds of meters wide (Velez-Zullo, written communication, 2011). Given the geological complexity and the low density of deep well control at this site, this study does not address aquifer correlation in the Potomac Formation. Instead, the reader is referred to Benson (2006) cross sections B-B′ and E-E′ for the most recent DGS stratigraphic framework for the Potomac Formation in the study area.

Over most of the study area, the Potomac Formation is confined by a thick aquitard of clays and silts of the overlying Merchantville Formation. There are two areas where Merchantville sediments have been eroded under the Quaternary unconformity: in the Reybold paleochannel (Fig. 3) and in the shallow subsurface on the northwest side of the study area (Plate 2, A-A'). In these two areas, the unconfined aquifer system, called the Columbia aquifer in Delaware, is in direct contact with the Potomac Formation.

The unconfined Columbia aquifer encompasses several Quaternary geological units. Across much of the study area, the Columbia Formation is the unconfined aquifer; however, on the eastern margin of the Reybold paleochannel, the Columbia Formation thins and is cut out by the terrace-related deposits of the Lynch Heights and Scotts Corners Formations. Although Lynch Heights and Scotts Corners Formations are more lithologically heterogeneous than the Columbia Formation, they include significant amounts of sand and even gravel that locally make them the unconfined aquifer.

Although a complete description of the groundwater flow regime in the study area is beyond the scope of this report, a few implications of the geological findings can be noted. West of the Reybold paleochannel, the base of the Columbia aquifer deepens from west to east toward the Delaware River. In the interior regions of the study area, it is likely that groundwater in the unconfined Columbia aquifer flows in the same general direction, west to east, in many areas, based on basic hydrological principles. However, the Reybold paleochannel likely exerts a significant influence on the flow of unconfined groundwater, perhaps capturing the west-to-east flow from the western part of the study area and redirecting it along the north–south trend of the paleochannel. Near the north and south sides of the study area, groundwater flow may be expected to move toward the east-west-oriented streams of Red Lion Creek and Dragon Run.

Additionally, the deeply erosive contact at the base of Columbia Formation aquifer may allow hydrological communication between the highly permeable sands and gravels in the Reybold paleochannel and the transmissive facies of the Englishtown Formation and Potomac Formation; this could be manifested as recharge from or discharge to the Columbia Formation. The potential for flow from the Columbia Formation into the Potomac Formation has important implications for groundwater recharge and potential contaminant pathways and transport. The absence of the Merchantville confining layer in the deep parts of the Reybold paleochannel could allow the channel to function as a recharge gallery for the Potomac Formation. A detailed identification of such potential pathways for groundwater flow and industrial contamination would require the differentiation of areas where this recharge gallery puts Columbia sands on Potomac sands from areas where the Columbia sands rest on low permeability Potomac clays; such an effort is dependent on a high density of data, given the complex mosaic of alluvial facies present in the Potomac Formation. Using the detailed boring logs that compose I-I′, (Plate 2), which follows the axis of the Reybold paleochannel from north to south, Columbia sands overlie Potomac clays between Dc53-38 and Dc53-98, overlie primarily Potomac sands between Ec13-48 and Ec13-68 (just north and south of Wrangle Hill Road), overlie Potomac clays between Ec13-89 and Ec13-98, and overlie Potomac sands from Ec13-25 and Ec13-27.

SUMMARY

This study presents an updated Cretaceous and Quaternary geological framework for the area between Wrangle Hill and Delaware City, New Castle County, Delaware. A closely spaced network of lithological and geophysical logs from 490 sites provides a uniquely dense, detailed dataset of the subsurface geology, with radiocarbon dating providing the ages of the youngest sediments. On the basis of these data, a closely-spaced grid of structural-stratigraphic cross sections was constructed, providing detailed documentation of the stratigraphy, distribution, and correlation of geological units in the study area. Additionally, structural contour maps were constructed for two stratigraphic surfaces that are critical for understanding the geological constraints on aquifer distribution and connectivity, the base of the Columbia Formation and the top of the Potomac Formation. The following conclusions about the study area were reached:

- The geological units include five Cretaceous formations (Potomac, Merchantville, Englishtown, Marshalltown, Mount Laurel), three Pleistocene formations (Columbia, Lynch Heights, Scotts Corners), Holocene sediments associated with the modern Delaware River, and anthropogenic fill. The Potomac, Merchantville, and Columbia Formations are present across much of the study area. The Englishtown, Marshalltown, and Mount Laurel Formations appear to be restricted to the southeastern portion of the study area. The Lynch Heights Formation, Scotts Corners Formation, and Holocene sediments occur, for the most part, along the eastern side of the study area. The Magothy Formation is not interpreted to be present in the study area, pinching out just to the south.
- Sandy sediments of the unconfined Columbia aquifer and confined Potomac aquifers are the most significant water-bearing units in the study area. The Merchantville Formation is a relatively thick fine-grained unit that composes the most significant confining layer.
- The Potomac Formation unconformably overlies lower Paleozoic-age crystalline rocks and associated saprolite. The elevation of the base of the formation was encountered in wells between –716.1 ft and –748.9 ft and, though somewhat irregular, this surface generally deepens southeastward across the study area. The elevation of the top of the Potomac Formation ranges from –1.0 ft to deeper than –120 ft. Like the base of the formation, the top of the Potomac also generally dips to the southeast. As a result of erosion and filling of a Pleistocene-age Reybold paleochannel, the top of the Potomac Formation is significantly deeper in a narrow north-south trending belt in the eastern part of the study area.
- The Columbia Formation is predominantly poorly sorted, fine-to coarse-grained quartz sand with some silt and gravel. The elevation of the base of the formation varies from 36 ft to –111.6 ft, with its greatest depth along the axis of the Reybold paleochannel located near the eastern limits of the formation. The Columbia Formation unconformably overlies the Merchantville Formation over much of the site; in the southern portion, it locally overlies the Englishtown and Marshalltown Formations, and in the Reybold paleochannel, it overlies the Potomac Formation. In much of the western and central part of the study area, Columbia Formation sands occur near the surface, and are capped by soils, fill, or a thin zone of younger surficial deposits. In its easternmost occurrences, the formation is unconformably overlain by the Lynch Heights Formation or Holocene deposits.
- The most significant geological feature in the study area is the Reybold paleochannel, a narrow north – south trending sand-filled trough that eroded through the entire thickness of the Merchantville Formation and into the Potomac Formation. On the basis of the relatively dense subsurface control utilized in this study, it appears that the Reybold paleochannel represents a localized, notably deep scour at the base of the Columbia Formation formed as a result of the sudden release of powerful floodwaters associated with one or more Pleistocene deglaciations.
- The Reybold paleochannel was subsequently filled by Columbia sands and is evident on a map of the elevations of the base of the Columbia Formation. Within the paleochannel axis, the Columbia Formation varies in thickness from 30 ft to 139 ft, and varies in width from approximately 1,700 ft in the north to 1,500 ft in the most deeply scoured sections in the center and then broadens to more than 2,400 ft in the south.
- The base of the Columbia Formation cuts progressively deeper into the Potomac Formation southward across most of the trend of the Reybold paleochannel because of the difference in the slope and dip of the surfaces. The top of the Potomac Formation exhibits a southeasterly dip of approximately 0.4 degrees away from the Reybold paleochannel, resulting in an apparent dip of approximately 0.3 degrees along the north – south trend of the paleochannel. The elevation of the base of the Reybold paleochannel decreases from the northern (–44.3 ft) to the central portion of the site (–101.3 ft) and continues southward through the deepest channeling in the study area (–111.6 ft) before leveling off at a fairly uniform base elevation (approximately –100 ft) in the southern part of the study area. The slope of the base of the paleochannel ranges from approximately 0.45 to 0.50 degrees to the south until becoming more level in the southern reaches of the study area.
- Holocene peats in several locations were analyzed for radiocarbon dates, which provided a context for the timing of the incursion and development of the Holocene marsh deposits that overlie Pleistocene or Cretaceous-age deposits in the eastern portion of the study area. The Holocene sediments along the eastern portion of the study area contain peat deposits with ages ranging from Cal BP 1270 to 1060 (1230 ± 40 yrs BP conventional age) to Cal BP 4880 to 4790/Cal BP 4770 to 4620 (4240 ± 60 yrs BP conventional age). The ^{14}C results suggest these deposits represent the maximum age of the local incursion of tidal deposits within the broad, relatively flat flood basin subenvironment adjacent to the Delaware River that was inundated in late Holocene time.

• The orientation of the Reybold paleochannel likely exerts a significant influence on the flow of unconfined groundwater, perhaps capturing the west-to-east flow from the western part of the study area and redirecting it along the north-south trend of the paleochannel. The paleochannel may also allow hydrological communication between the highly permeable sands and gravels of the Columbia Formation and the transmissive facies of the Englishtown Formation and Potomac Formation. The absence of the Merchantville confining layer in the deep parts of the Reybold paleochannel could allow the channel to function as a recharge gallery for the Potomac Formation in those locations where Columbia sands are in direct contact with Potomac sands.

REFERENCES

Baker, V. R., 2009, The Channeled Scabland: a retrospective: Annual Review of Earth and Planetary Sciences, v. 37, p. 393–411.

Bascom, F., and B. L. Miller, 1920, U. S. Geological Survey Atlas, Elkton-Wilmington folio (no. 211).

Belknap, D. F., and J. C. Kraft, 1977, Holocene relative sea-level changes and coastal stratigraphic units on the northwest flank of the Baltimore Canyon Trough Geosyncline: Journal of Sedimentary Petrology, v. 47, p. 610–629.

Benson, R. N., 2006, Internal stratigraphic correlation of the subsurface Potomac Formation, New Castle County, Delaware, and adjacent areas in Maryland and New Jersey: Delaware Geological Survey Report of Investigations No. 71, p. 1–8, 3 plates.

Benson, R. N., and N. Spoljaric, 1996, Stratigraphy of the post-Potomac Cretaceous-Tertiary rocks of central Delaware: Delaware Geological Survey Bulletin No. 20, 28 p.

Berry, E. W., and A. C. Hawkins, 1935, Flora of the Pensauken Formation in New Jersey: Geological Society of America Bulletin, v. 46, p. 245–252.

Braun, D., 2008, The Pleistocene record in the middle and lower Susquehanna River Basin and the longer term evolution of the Susquehanna Basin landscape: Guidebook for the 20th Biennial Meeting of the American Quaternary Association, 58 p.

Carter, C. W., 1937, The Upper Cretaceous deposits of the Chesapeake and Delaware Canal: Maryland Geological Survey, Volume XIII, p. 237–281.

Clark, W. B., 1897, Report upon the Upper Cretaceous formations: Geological Survey of New Jersey Annual Report of the State Geologist, 1897, p. 161–210.

Clark, W. B., 1904, The Matawan Formation of Maryland, Delaware and New Jersey and its relations to overlying and underlying formations: American Journal of Science, 4th series, v. 18, p. 435–440.

Darton, N. H., 1893, The Magothy Formation of northeastern Maryland: American Journal of Science, 3rd series, v. 45, p. 407–419.

Donnelly, C. A. and K. C. Hinaman, 1996a, Potentiometric maps and groundwater-level data for the industrial area, northwest of Delaware City, Delaware: U. S. Geological Survey Open-File Report 95-0318, 2 sheets.

Donnelly, C. A., and K. C. Hinaman, 1996b, Water-level data for the industrial area northwest of Delaware City, Delaware, 1993–94: U. S. Geological Survey Open-File Report 96–0125, 23 p.

Donnelly, J. P., N. W. Driscoll, E. Uchupi, L. D. Keigwin, W. C. Schwab, E. R. Thieler, and S. A. Swift, 2005, Catastrophic meltwater discharge down the Hudson Valley; a potential trigger for the intra-Allerod cold period: Geology, v. 33, no. 2, p. 89–92.

Doyle, J. A., and E. I. Robbins, 1977, Angiosperm pollen zonation of the continental Cretaceous of the Atlantic Coastal Plain and its application to deep wells in the Salisbury Embayment: Palynology, v. 1, p. 43–78.

Dugan, B. L., M. P. Neimeister, and A. S. Andres, 2008, Hydrogeologic framework of southern New Castle County: Delaware Geological Survey Open File Report No. 49, 22 p.

Engelhart, S. E., B. P. Horton, B. C. Douglas, W. R. Peltier, and T. E. Tornqvist, 2009, Spatial variability of late Holocene and 20th century sea-level rise along the Atlantic Coast of the United States: Geology, v. 37, p. 1115–1118.

Fletcher, C. H., H. J. Knebel, and J. C. Kraft, 1992, Holocene depocenter migration and sediment accumulation in Delaware Bay: a submerging marginal marine sedimentary basin: Marine Geology, v. 103, p. 165–183.

Groot, J. J., 1955, Sedimentary petrology of the Cretaceous sediments of northern Delaware in relation to paleogeographic problems: Delaware Geological Survey Bulletin 5, 157 p.

Groot, J. J. and H. D. Glass, 1960, Some aspects of the mineralogy of the northern Atlantic Coastal Plain, *in* Swineford, Ada, ed., Clays and clay minerals: Proceedings of the Seventh National Conference on Clays and Clay Minerals, Washington, D. C., p. 271–284.

Groot, J. J. and R. R. Jordan, 1999, The Pliocene and Quaternary deposits of Delaware: Palynology, ages, and paleoenvironments: Delaware Geological Survey Report of Investigations No. 58, 36 p.

Groot, J. J., D. M. Organist, H. G. Richards, 1954, Marine Upper Cretaceous formations of the Chesapeake and Delaware Canal: Delaware Geological Survey, Bulletin No. 3, 64 p.

Groot, J. J., and W. C. Rasmussen, 1954, Geology and groundwater resources of the Newark area, Delaware: Delaware Geological Survey Bulletin 2, 123 p.

Hansen, H. J., 1982, Hydrogeologic framework and potential utilization of the brine aquifers of the Waste Gate Formation, a new unit of the Potomac Group underlying the Delmarva Peninsula, part 1, of H. J. Hansen, and J. A. Doyle. Waste Gate Formation: Maryland Department of Natural Resources, Geological Survey Open-File Report, p. 1–50.

Hochuli, P. A., U. Heimhofer, and H. Weissert, 2006, Timing of early angiosperm radiation: recalibrating the classical succession: Journal of the Geological Society, London, v. 163, p. 1–8.

Houlik, C. W., Jr., R. K. Olsson, and R. W. Aurisano, 1983, Upper Cretaceous (Campanian-Maestrichtian) marine strata in the subsurface of northern Delaware: Southeastern Geology, v. 24, p. 57–65.

Jengo, J. W., 1995, Stratigraphic framework and sequence stratigraphy of sections of the Cretaceous-Age Raritan-Magothy Formations, Middlesex County, New Jersey: Northeastern Geology and Environmental Sciences, v. 17, no. 3, p. 223–246.

Jengo, J. W., 1999, Hydrostratigraphy of the Cretaceous-Age Potomac, Raritan, Magothy, and Merchantville formations and Holocene-Age Delaware River alluvium, Gloucester County, New Jersey: Northeastern Geology and Environmental Sciences, v. 21, no. 3, p. 148–178.

Jengo, J. W., 2006, Stratigraphy and radiocarbon dates of Pleistocene and Holocene-Age deposits, Delaware County, Pennsylvania — Rectifying the presence of the Cape May Formation and the Trenton Gravel in the Delaware Valley: Northeastern Geology and Environmental Sciences, v. 28, no. 1, p. 45–76.

Jordan, R. R., 1962, Stratigraphy of the sedimentary rocks of Delaware: Delaware Geological Survey Bulletin No. 9, 51 p.

Jordan, R. R., 1964, Columbia (Pleistocene) sediments of Delaware: Delaware Geological Survey Bulletin No. 12, 69 p.

Jordan, R. R., 1983, Stratigraphic nomenclature of nonmarine Cretaceous rocks of inner margin of Coastal Plain in Delaware and adjacent states: Delaware Geological Survey Report of Investigations No. 37, 41 p.

Kennedy, W. J. and W. A. Cobban, 1994, Upper Campanian ammonites from the Mount Laurel Sand at Biggs Farm, Delaware: Journal of Paleontology, v. 68, no. 6, p. 1285–1305.

Kennedy, W. J. and W. A. Cobban, 1997, Upper Campanian (Upper Cretaceous) ammonites from the Marshalltown Formation — Mount Laurel boundary beds in Delaware: Journal of Paleontology, v. 71, no. 1, p. 62–73.

Kümmel, H. B., and G. N. Knapp, 1904, The stratigraphy of the New Jersey clays: The clays of the Cretaceous Formation, in H. Ries, H. B. Kümmel, and G. N. Knapp. The clays and clay industry of New Jersey: Geological Survey of New Jersey, Annual Report of the State Geologist for the Year 1898, v. 6, Chapter 8, p. 149–203.

Kümmel, H. B., 1907, Stratigraphic paleontology introduction, *in* S. Weller, A report on the Cretaceous paleontology of New Jersey based upon the stratigraphic studies of George N. Knapp: Geological Survey of New Jersey Paleontology Series, v. 4, text vol., p. 17.

Marine, I. W., and W. C. Rasmussen, 1955, Preliminary report on the geology and groundwater resources of Delaware: Delaware Geological Survey Bulletin No. 4, 336 p.

McGee, W. J., 1886a, Geological formations underlying Washington and vicinity: Report of the Health Officer of the District of Columbia for the year ending June 30, 1885, p. 19–21, 23–25.

McGee, W. J., 1886b, Geological formations underlying Washington and vicinity: American Journal of Science, 3rd series, v. 31, p. 473–474.

McKenna, T. E., P. P. McLaughlin, and R. N. Benson, 2004, Characterization of the Potomac Aquifer, an extremely heterogeneous fluvial system in the Atlantic Coastal Plain of Delaware: Delaware Geological Survey Open File Report No. 45, three-panel poster online, approx. 1.6 mb, *http://www.udel.edu/dgs/Publications/pubsonline/OFR45.pdf*

McLaughlin, P. P., 2006, Preliminary report on the palynology of the Potomac Formation of Delaware, *in* Benson, R.N., Internal stratigraphic correlation of the subsurface Potomac Formation, New Castle County, Delaware, and adjacent areas in Maryland and New Jersey: Delaware Geological Survey Report of Investigations No. 71, p. 9–15.

McLaughlin, P. P., and R. N. Benson, 2002, Application of palynomorph biostratigraphy to correlation of aquifer units in non-marine facies of the Cretaceous Potomac Formation, Delaware Coastal Plain: Palynology, v. 26, p. 270.

McLaughlin, P. P., and R. N. Benson, 2005, Application of micropaleontology to water resource problems: Aquifer stratigraphy in the Coastal Plain of Delaware (Middle Atlantic Region, United States): Geological Problem Solving with Microfossils Conference, March 6–8, 2005, North American Micropaleontology Section (NAMS) of SEPM, Program with abstracts, p. 13.

McLaughlin, P. P., P. J. Sugarman, R. N. Benson, K. G. Miller, T. E. McKenna, and J. V. Browning, 2003, The application of sequence stratigraphy to aquifer geology problems in the Middle Atlantic Coastal Plain, United States: Leveraging petroleum geoscience learnings to public-needs issues: Geological Society (London) Conference, New Insights into Petroleum Geoscience Research through Collaboration between Academia and Industry, Abstracts with Program.

Miller, K. G., P. J. Sugarman, J. V. Browning, M. A. Kominz, R. K. Olsson, M. D. Feigenson, and J. C. Hernandez, 2004, Upper Cretaceous sequences and sea-level history, New Jersey Coastal Plain: Geological Society of America Bulletin, v. 116, p. 368–393.

Newell, W. L., D. S. Powars, J. P. Owens, and J. S. Schindler, 1995, Surficial geologic map of New Jersey, southern sheet. U.S. Geologic Survey Open File Map 95–272, scale 1:100,000.

Newell, W. L., D. S. Powars, J. P. Owens, S. D. Stanford, and B. D. Stone, 2000, Surficial geologic map of central and southern New Jersey. U.S. Geologic Survey Miscellaneous Investigations Series Map I-2540-D, scale 1:100,000, 21 p.

Nikitina, D. L., J. E. Pizzuto, R. A. Schwimmer, and K. W. Ramsey, 2000, An updated Holocene sea-level curve for the Delaware coast: Marine Geology, v. 171, p. 7–20.

Olsson, R. K. and E. E. Nyong, 1984, A paleoslope model for Campanian-Lower Maestrichtian foraminifera of New Jersey and Delaware: Journal of Foraminiferal Research, v. 14, no. 1, p. 50–68.

O'Neal, M. L., and S. McGeary, 2002, Late Quaternary stratigraphy and sea-level history of the northern Delaware Bay margin, southern New Jersey, USA: a ground penetrating radar analysis of composite Quaternary coastal terraces: Quaternary Science Reviews, v. 21, p. 929–946.

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

Owens, J. P., J. P. Minard, N. F. Sohl, and J. F. Mello, 1970, Stratigraphy of the outcropping Post-Magothy Upper Cretaceous Formations in southern New Jersey and northern Delmarva Peninsula, Delaware and Maryland: U. S. Geological Survey Professional Paper 674, 60 p.

Owens, J. P., J. P. Minard, and N. F. Sohl, eds., 1977, A field guide to Cretaceous and lower Tertiary beds of the Raritan and Salisbury Embayments, New Jersey, Delaware, and Maryland: American Association of Petroleum Geologists — Society of Economic Paleontologists and Mineralogists Annual Convention, Washington, D.C., 113 p.

Owens, J. P., and G. S. Gohn, 1985, Depositional history of the Cretaceous series in the U.S. Atlantic Coastal Plain: Stratigraphy, paleoenvironments, and tectonic controls of sedimentation, *in* C. W. Poag, ed., Geological evolution of the United States Atlantic Margin, Van Nostrand Reinhold Co., New York, p 25 86.

Owens, J. P., and N. F. Sohl, 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations for the New Jersey Coastal Plain, *in* S. Subitzky, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Geological Society of America and associated societies, November 1969, Annual Meeting, Atlantic City, New Jersey. Rutgers University Press, New Brunswick, New Jersey, p. 235–278.

Pazzaglia, E. J., 1993, Stratigraphy, petrography, and correlation of late Cenozoic middle Atlantic Coastal Plain deposits: Implications for late-stage passive-margin geologic evolution: Geological Society of America Bulletin, v. 105, p. 1617–1634.

Pickett, T. E., 1970a, Geology of the Chesapeake and Delaware Canal area, Delaware: Delaware Geological Survey, Geologic Map Series No. 1, scale 1:24,000.

Pickett, T. E., 1970b, Delaware Clay Resources: Delaware Geological Survey Report of Investigations No. 14, 70 p.

Ramsey, K. W., 1993, Geologic Map of the Milford and Mispillion River Quadrangles: Delaware Geological Survey Geologic Map Series No. 8, scale 1:24,000.

Ramsey, K. W., 1997, Geology of the Milford and Mispillion River Quadrangles: Delaware Geological Survey Report of Investigations No. 55, 40 p.

Ramsey, K. W., 2003, Geologic Map of the Lewes and Cape Henlopen quadrangles, Delaware: Delaware Geological Survey Map Series No. 12, scale 1:24,000.

Ramsey, K. W., 2005, Geologic map of New Castle County, Delaware: Delaware Geological Survey Geologic Map Series No. 13, scale 1:100,000.

Ramsey, K. W., 2007, Geologic map of Kent County, Delaware: Delaware Geological Survey Geologic Map Series No. 14, scale 1:100,000.

Ramsey, K. W., 2010, Stratigraphy, correlation, and depositional environments of the middle to late Pleistocene interglacial deposits of southern Delaware: Delaware Geological Survey Report of Investigations No. 76, 43 p.

Ramsey, K. W., and S. J. Baxter, 1996, Radiocarbon dates from Delaware: a compilation: Delaware Geological Survey Report of Investigations No. 54, 18 p.

Rasmussen, W. C., J. J. Groot, R. O. R. Martin, E. F. McCarren, V. C. Behn, and others, 1957, The water resources of northern Delaware: Delaware Geological Survey Bulletin No. 6, v. 1, 223 p., w/plates.

Rebertus, R. A., 1998, Loessial soils of Delaware: taxonomy and map-unit assessment: Soil Science Society of America Journal, v. 62, p. 412–422.

Rebertus, R. A., J. A. Doolittle, and R. L. Hall, 1989, Landform and stratigraphic influences on variability of loess thickness in Northern Delaware: Soil Science Society of America Journal, v. 53, p. 843–847.

Richards, H. G., J. J. Groot, and R. M. Germeroth, 1957, Cretaceous and Tertiary geology of New Jersey, Delaware and Maryland: Geological Society of America, Guidebook for Field Trips, Atlantic City Meetings, Field Trip No. 6, p. 183–216.

Salisbury, R. D., 1899, Part 1, Report on surface geology: Geological Survey of New Jersey, Annual Report of the State Geologist for the Year 1898, p. 1–41.

Salisbury, R. D., and G. N. Knapp, 1917, The Quaternary formations of southern New Jersey: New Jersey Geological Survey Final Report Series, v. 8, 218 p.

Spangler, W. B., and J. J. Peterson, 1950, Geology of the Atlantic Coastal Plain in New Jersey, Delaware, Maryland, and Virginia: American Association of Petroleum Geologists Bulletin, v. 34, no. 1, p. 1–99.

Spoljaric, N., 1967a, Pleistocene Channels of New Castle County, Delaware: Delaware Geological Survey Report of Investigations No. 10, 15 p.

Spoljaric, N., 1967b, Quantitative lithofacies analysis of Potomac Formation, Delaware: Delaware Geological Survey Report of Investigations No. 12, 26 p.

Spoljaric, N., 1973, Normal Faults in Basement Rocks of the Northern Coastal Plain, Delaware: Geological Society of America Bulletin, v. 84, no. 8, p. 2781–2783.

Spoljaric, N., and K. D. Woodruff, 1970, Geology, hydrology, and geophysics of Columbia sediments in the Middletown — Odessa area, Delaware: Delaware Geological Survey Bulletin 13, 156 p.

Stanford, S. D., 1997, Pliocene-Quaternary geology of Northern New Jersey: an overview, *in* Stanford, and R. W. Witte, eds., Pliocene-Quaternary Geology of Northern New Jersey: Guidebook for the 60th Annual Reunion of the Northeastern Friends of the Pleistocene, p. 1–1 to 1–26.

Stanford, S. D., 2003, Late Miocene to Holocene geology of the New Jersey Coastal Plain: *in* M. J. Hozik, and M. J. Mihalasky, eds., Periglacial features of southern New Jersey: Field Guide and Proceedings, Geological Association of New Jersey 20th Annual Meeting October 10–11, 2003, p. 21–49.

Stanford, S. D., 2006a, Surficial geology of the Bridgeport and Marcus Hook Quadrangles, Gloucester and Salem Counties, New Jersey: New Jersey Geological Survey Geologic Map Series GMS 06–2, scale 1:24,000, cross section.

Stanford, S. D., 2006b, Surficial geology of the Penns Grove and Wilmington South quadrangles, Salem and Gloucester Counties, New Jersey: New Jersey Geological Survey Geologic Map Series GMS 06–5, scale 1:24,000, 2 cross sections.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, G. McCormac, J. van der Plicht, and M. Spurk, 1998, INTCAL98 Radiocarbon Age Calibration, 24000-0 cal BP: Radiocarbon, Vol. 40, No. 3, p. 1041–1083.

Sugarman, P. J., K. G. Miller, J. V. Browning, A. A. Kulpecz, P. P. McLaughlin, and D. Monteverde, 2005, Hydrostratigraphy of the New Jersey Coastal Plain: Sequences and facies predict continuity of aquifers and confining units: Stratigraphy, v. 2, no. 3, p. 259–276.

Sugarman, P. J, K. G. Miller, D. Bukry, and M. D. Feigenson, 1995, Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain: Geological Society of America Bulletin, v. 107, no. 1, p. 19–37.

Sugarman, P. J., K. G. Miller, P. P. McLaughlin, Jr., J. V. Browning, J. Hernandez, D. Monteverde, J. Uptegrove, S. J. Baxter, T. E. McKenna, A. S. Andres, R. N. Benson, K. W. Ramsey, T. Keyser, M. E. Katz, A. Kahn, A. Friedman, M. Wojtko, M. D. Feigenson, R. K. Olsson, G. Brenner, J. M. Self-Trail, and G. Cobbs III, 2004, Fort Mott Site, *in* K. G. Miller, P. J. Sugarman, J. V. Browning, et al., Proc. ODP, Init. Repts., 174AX (Suppl.), 1–50 [Online]. *http://www-odp.tamu.edu/publications/174AXSIR/VOLUME/CHAPTERS/174AXS_4.PDF.*

Sundstrom, R. W., and others, 1967, The availability of groundwater from the Potomac Formation in the Chesapeake and Delaware Canal area, Delaware: University of Delaware Water Resources Center, 95 p.

Sundstrom, R. W., and T. E. Pickett, 1971, The availability of groundwater in New Castle County, Delaware: University of Delaware Water Resources Center, 156 p.

Thieler, E. R., B. Butman, W. C. Schwab, M. A. Allison, N.W. Driscoll, J. P. Donnelly, and E. Uchupi, 2007, A catastrophic meltwater flood event and the formation of the Hudson Shelf Valley: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 246, p. 120–136.

U.S. Army Corps of Engineers (USACE), 2004, Conceptual hydrogeologic model summary, upper New Castle County, Delaware: U.S. Army Corps of Engineers Philadelphia District, March 2004, 39 p., 48 figs.

Ward, R. F., and J. J. Groot, 1957, Engineering materials of northern New Castle County: Delaware Geological Survey Bulletin No. 7, 103 p.

Woodruff, K. D., 1986, Geohydrology of the Chesapeake and Delaware Canal area, Delaware: Hydrologic Map Series No. 6, Sheet 1 – Basic Geology, scale 1:24,000.

Woodruff, K. D., 1988, Geohydrology of the Chesapeake and Delaware Canal area, Delaware: Hydrologic Map Series No. 6, Sheet 2 – Thickness of Confining Unit Beneath the Water-Table Aquifer.

Woodruff, K. D., 1990, Geohydrology of the Middletown-Odessa area, Delaware: Delaware Geological Survey Hydrologic Map Series No. 8, Sheet 1 – Basic Geology and Hydrology, scale 1:24,000.