HYDROGEOLOGIC FRAMEWORK OF THE VIRGINIA COASTAL PLAIN

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REGIONAL AQUIFER-SYSTEM ANALYSIS

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stratigraphic test wells and high-capacity production wells can be used to correlate this unit.

Clay beds comprising the lower Potomac confining unit are not a continuous, areally extensive layer. Instead, these clays are a series of interlensing clayey deposits. Water-level measurements from observation wells indicate that these deposits act locally as confining units and when viewed regionally, represent a single confining unit, as shown by the thickness map of the lower Potomac confining unit (fig. 10). In some areas, such as in the western and central regions, the confining unit is relatively thin, ranging from 15 to 30 ft in thickness; in other areas, such as in the northern region, it attains a thickness of more than 200 ft.

Typical electric-resistivity log patterns of the lower Potomac confining unit sediments are best illustrated in geophysical logs of wells 51R5, plate 2, A-A'; 53P4, plate 2, A-A' and B-B'; 54P3, plate 2, A-A'; 52N16, plate 2, B-B'; 57J3, plate 3, D-D'; 58F3, plate 3, E-E'; 54G10, plate 3, D-D' and F-F'; 53D3, plate 3, G-G'; 55C12, plate 3, G-G' and plate 4, H-H'; and 58A2, plate 3, G-G' and plate 4, I-I'. Generally, these resistivity patterns are blocky in profile, indicating relatively sharp lithologic contacts between the thickly bedded confining clays with the overlying and underlying aquifer sands. Corresponding natural-gamma log patterns reflect the massively bedded nature of these clays; few interbedded sands are present. Drillers often refer to the lower Potomac confining unit clays as "hard" or "tough" and as "gray, red, or brown clay." Like the underlying interbedded clays of the lower Potomac aquifer, drillers commonly observe an increase in drilling time and resistance when penetrating these sediments, and the resulting cuttings are commonly small, angular pieces. Also, the underlying interbedded clays of the lower Potomac aquifer usually contain significantly more interbedded sands and sandy clays than are present at this horizon.

Studies (Brenner, 1963; Glaser, 1969; Hansen, 1969a, 1982; Reinhardt and others, 1980) of correlative strata to the lower Potomac confining unit suggest a change in the paleoenvironment from that of the lower Potomac aquifer. These studies indicate that the depositional environment and drainage patterns changed from a high-gradient to a lower-gradient fluvial flood plain, based on the predominance of finer grained clayey materials and their associated bedding characteristics. These studies also suggest that the resulting paleoenvironment consisted of quiet, shallow, discontinuous backswamp basins with little sediment input.

MIDDLE POTOMAC AQUIFER

The middle Potomac aquifer, by definition, consists of sandy palynostratigraphic Zone II sediments of the Potomac Formation. These sediments are late Early Cretaceous (middle to late Albian) in age and correlate with the lower part of the Patapsco aquifer in Maryland and the lower Cape Fear aquifer of North Carolina (pl. 1). The middle Potomac aquifer is the second lowest and thickest confined aquifer in the hydrogeologic framework. This aquifer crops out just east of the lower Potomac confining unit in the northwestern region of the study area and in a small area along the James and Appomattox Rivers near the Fall Line. It overlies the lower Potomac confining unit and is overlain by the middle Potomac confining unit. The middle Potomac aquifer attains a maximum known thickness of 929 ft (well 66M1) in the northeastern part of the study area and thins to a featheredge along its western limit near the Fall Line. It dips eastward at approximately 15 ft/mi in the western half of the study area and at 25 ft/mi in the eastern half. The middle Potomac aquifer consists of interlensing medium sands, silts, and clays of differing thickness. This aquifer is equivalent to the Patapsco Formation in Maryland as defined by Brenner (1963).

From outcrops in Maryland, Glaser (1968, p. 8) describes the Patapsco Formation as a thick sequence of interbedded variegated silty clay and fine to medium, gray to yellow sand. Glaser (1968) also reports that the clay lenses are typically thick, internally massive, and brightly mottled in red, yellow, gray, and purple, whereas the sands, occasionally with gravels, are similar to those in the Patuxent Formation, although they tend to be finer grained, more uniform, and more argillaceous. Berry (in Clark and Miller, 1912, p. 67) describes "Patapsco" sediments in Virginia much the same as Glaser describes them in Maryland, although Berry notes that the outcropping Virginia deposits are generally much more evenly colored than those in Maryland. Analysis of the Oak Grove core (well 54P3, fig. 7) by Reinhardt and others (1980, p. 41) reveals that sediments of Cretaceous pollen Zone II contain a lower sand-dominated interval characterized by distinct fining-upwards sand sequences interbedded with laminated or massive clays. This lower interval of pollen Zone II strata is herein identified in the hydrogeologic framework of the Virginia Coastal Plain as the middle Potomac aquifer. Typically, the sands of these fining-upwards sequences are composed of coarse to fine, angular to subangular quartz, and some plagioclase. These sands are also commonly micaceous and contain abundant heavy minerals. Reinhardt and others (1980) also note that the laminated and massive clays of this sequence are composed of mixed kaolinite and highly expandable illite/smectite.

More wells drilled in the study area penetrate this aquifer (fig. 11) than the underlying lower Potomac aquifer. Generally, most industrial and municipal wells throughout the western half of the study area use this aquifer, sometimes in combination with the underlying or overlying Potomac aquifers. This aquifer is capable of producing large quantities of high-quality water in the western half of the study area, but, like the underlying lower Potomac aquifer, it contains increasingly higher chloride concentrations in the downdip direction, which restricts its use as a source of potable water. In addition, the middle Potomac aquifer generally lies too deep for all but large industrial users in the eastern half of the study area.

Typical electric-resistivity log patterns of the middle Potomac aquifer sediments are best illustrated in geophysical logs of wells 53Q9, 53P4, and 54P3, plate 2, A-A'; 52N16, 53P8, 53P4, 54Q11, and 54R3, plate 2, B-B'; 52J11, plate 2, C-C'; 52K6, 54J4, 55H1, and 58F3, plate 3, E-E'; 54G10, 57E10, and 60C7, plate 3, F-F'; 53D3, plate 3, G-G'; and 53A3, 58B115, and 59C28, plate 4, J-J'. Generally, these resistivity log patterns are both triangular and saw-toothed in profile. The triangular profiles indicate the fining-upwards sequences characteristically associated with the aquifer sands. The saw-toothed profiles indicate the extensively interbedded sequences of sands, silts, and clays also characteristic of these sediments. These electric-resistivity patterns are both massive and narrow in profile and the sands usually contain sharp, lower lithologic contacts. Resistivity logs of the middle Potomac aquifer also characteristically show high-resistance values for the sandy sediments which help distinguish this aquifer from the underlying lower Potomac aquifer. The high-resistance values are indicative of the relatively clean sands common to this aquifer and the relatively low concentrations of dissolved solids characteristic of the water from this unit. Corresponding natural-gamma logs show pronounced saw-toothed clay and sand patterns with sharp lower and gradational upper lithologic contacts. The clay patterns of natural-gamma logs of the middle Potomac aquifer are more distinct than the sand patterns, indicating the well-bedded and massive nature of the clays. Drillers usually describe the middle Potomac aquifer sediments as "medium or coarse gray sands" with "red, brown, or multicolored clays." Drillers also commonly refer to the sands as "water sands" or "artesian sands." Generally, these sediments drill easily and the clays reach the surface as small, cohesive clay balls. The individual sand and clay beds of the middle Potomac aquifer, like the underlying lower Potomac aquifer, are also difficult to correlate between geophysical logs. The contour map delineating the top of this aquifer (fig. 11) is based on the tops of the uppermost sand beds. This map should only be used as a guide to indicate the approximate altitude to the top of this aquifer between control wells because of the interlensing nature of these sediments, the large distances between control points in some areas, and the general lack of data in the eastern half of the study area.

Studies (Glaser, 1969; Hansen, 1969a; Reinhardt and others, 1980) of Potomac strata herein defined as the middle Potomac aquifer and the correlative Patapsco strata in Maryland suggest that the paleoenvironment consisted of a low-gradient, subaerial, fluvial flood plain dominated by meandering streams. These deposits, which represent multiple fluvial processes, are dominated by channel sands, point bars, levees, flood plains, and backswamps. Reinhardt and others (1980, p. 41) note that no glauconite was observed in the cored sediments of the middle Potomac aquifer strata in the Oak Grove core and suggest that these deposits represent a more landward sedimentary assemblage than do the sediments of the underlying lower Potomac aquifer strata (p. 48). They also note (p. 47) that these deposits are distinctly continental in origin and, together with the underlying lower Potomac aquifer sediments, appear to represent the development of a continental delta.

MIDDLE POTOMAC CONFINING UNIT

The middle Potomac confining unit is defined by the major clayey strata directly above the middle Potomac aquifer. These clay beds are predominantly restricted to upper palynostratigraphic Zone II, but may also consist of younger sediments (basal Zone III), especially in the eastern half of the study area. The middle Potomac confining unit correlates with the western half of the Patapsco confining unit of Maryland and with the confining unit that overlies the lower Cape Fear aquifer of North Carolina (pl. 1). This confining unit crops out in the northwestern part of the study area between the middle Potomac aquifer and the Potomac River, and in the stream valleys of the Rappahannock, Pamunkey, James, and Appomattox Rivers just east of the outcropping middle Potomac aquifer. It overlies the middle Potomac aquifer and is overlain by the upper Potomac aquifer, except in the western part of the study area where it is transgressed by the Aquia aquifer. This confining unit attains a maximum known thickness of 203 ft at well 66M1 (fig. 7) in the northeastern part of the Eastern Shore Peninsula and thins to nearly zero thickness along its western limit near the Fall Line (fig. 12). Its thickness is highly variable, but the middle Potomac confining unit is commonly the thickest bedded clay or interbedded clay and sandy clay sequence of pollen Zone II sediments.

Definitive lithologic data are obtained from analysis of the Cretaceous section in the Oak Grove core (well 54P3, fig. 7) by Reinhardt and others (1980) and

Estabrook and Reinhardt (1980). Reinhardt and others (1980) identify and describe an upper interval of pollen Zone II sediments as a clay-dominated sequence characterized by highly sheared and locally mottled montmorillonitic red clay. This upper interval of pollen Zone II sediments in the Oak Grove core (well 54P3) is herein identified as the middle Potomac confining unit in the hydrogeologic framework of the Coastal Plain of Virginia. Typically, the clays of this confining unit are massive to thick-bedded, but are also finely laminated in places. These clays are similar in composition to the clays of the lower Potomac confining unit in that they consist primarily of mixed kaolinite and highly expandable illite/smectite (Reinhardt and others, 1980, p. 41). The laminated clays are silty, sandy, micaceous, and highly carbonaceous, whereas the massive clays are mottled, highly oxidized, and highly fractured. The middle Potomac confining unit is commonly characterized by a thick sequence of brightly colored, variegated, plastic clays. These variegated clays are used to identify this confining unit on drillers' logs.

Numerous water wells drilled in the western and central regions of the study area penetrate this confining unit. In areas where the upper Potomac aquifer overlies this unit, drillers commonly cease drilling upon reaching this thick variegated clay horizon. The clays identified as the middle Potomac confining unit are not a single, continuous, and areally extensive layer, but rather, are a series of interfingering deposits. Water-level data indicate that these clays act locally as confining units and, when viewed regionally, constitute a single confinement, as shown by the thickness map of the middle Potomac confining unit (fig. 12).

Typical electric-resistivity log patterns of the middle Potomac confining unit sediments are best illustrated in geophysical logs of wells 51R5, 54P3, 56N7, plate 2, A-A'; 52N16, 54R3, plate 2, B-B'; 52K6, 54J4, 54H11, 55H1, plate 3, E-E'; 53D3, 54D2, 55C8, plate 3, G-G'; and 52A1, 53A3, 54A3, 55A1, 56B9, plate 4, J-J'. Generally, these resistivity patterns are blocky in profile, indicating thickly bedded clays in relatively sharp lithologic contact with the aquifer sands above and in gradational lithologic contact with the aquifer sands below. The lithologies indicated by the resistivity patterns range from massive clays, as in wells 54P3, plate 2, A-A' and 56N7, plate 2, C-C', to thick clays interbedded with thin sands and sandy clays, as in well 55A1, plate 4, H-H'. Corresponding natural-gamma log patterns also typically indicate massively bedded clays with few interbedded sands or sandy clays. Drillers commonly refer to the middle Potomac confining unit clays as "slick or sticky" and as "multicolored or mixed colored clays." These multicolored clays, which are characteristically red, purple, gray, brown, olive, and yellow, are also referred to as mottled clays.

Studies on the paleoenvironment of the Potomac strata suggest that deposition of the middle Potomac confining unit occurred on broad, low-gradient, fluvial-deltaic plains containing extensive flood plains and swampy interfluves (Glaser, 1969, p. 73). Reinhardt and others (1980, p. 47) note that this clay-dominated upper pollen Zone II interval is a product of overbank deposition that was modified by weathering and diagenesis, and that these backswamp and flood basin deposits are distinctly continental in origin.

UPPER POTOMAC AQUIFER

The upper Potomac aquifer, by definition, consists of sandy palynostratigraphic Zone III and Zone IV sediments of the Potomac Formation. These sediments are early Late Cretaceous (Cenomanian) in age and correlate with the upper, easternmost sediments of the Patapsco aquifer in Maryland and the upper Cape Fear aquifer in North Carolina (pl. 1). This aquifer is restricted to the subsurface; it overlies most of the middle Potomac confining unit and is overlain by the upper Potomac confining unit. The upper Potomac aquifer dips eastward at approximately 15 ft/mi, attains a maximum known thickness of 425 ft at well 66M1 in the northeastern part of the study area, and pinches out along its western subsurface limit throughout the west-central part of the study area. The upper Potomac aquifer, like the other underlying Potomac aquifers, is a multizone unit consisting of stratified sands and clays.

The presence of lower Upper Cretaceous sediments at the top of the Potomac Formation in the study area has been alluded to by many investigators (Cederstrom, 1945a, 1957; Spangler and Peterson, 1950; Dorf, 1952; Richards, 1967), but the actual presence of these sediments in Virginia was not verified until the use of pollen analysis as a stratigraphic indicator. Palynostratigraphic analyses by Robbins and others (1975), Doyle and Robbins (1977), and L.A. Sirkin (Adelphi University, written commun., 1982, 1983) have indicated the presence of pollen Zones III and IV at the top of the Potomac Formation throughout the eastern half of the study area. These sediments are correlatable with the Raritan Formation of New Jersey and comprise the uppermost aquifer of the Potomac Formation in the study area.

The sands of the upper Potomac aquifer, as described from drillers' logs, are characteristically white, micaceous, very fine to medium quartz, and commonly contain carbonaceous material. Gravel is uncommon, and very coarse sand is rare. The interbedded clays of this aquifer, as described from drillers' logs, are characteristically dark, silty, highly micaceous, and typically contain carbonaceous material. Limited data are available that describe the lithologic characteristics of the upper Potomac aquifer in the study area; only one set of core samples from this unit has ever been analyzed. These core samples were obtained as part of the "Artificial Recharge" project conducted by the U.S. Geological Survey in cooperation with the city of Norfolk at the Moore's Bridge Water Treatment Facility, and are represented by well 61C1 in figure 7. Brown and Silvey (1977, p. 4) report that this unit consists of moderately sorted, angular to subangular, micaceous, fine to medium quartz sands that contain wood fragments and minor interstitial clays. Typical onsite core descriptions (D.L. Brown, U.S. Geological Survey, written commun., 1971) of the sandy intervals indicate that they are light yellow to greenish gray, clayey to clean, micaceous, slightly calcareous, poor to well sorted, subangular to subrounded, and very fine to medium grained. Similarly, the interbedded silty-clay intervals are described as yellow green to dark greenish gray, glauconitic, calcareous, micaceous, plastic, locally sandy, and containing shell fragments. More wells drilled in the study area penetrate the upper Potomac aquifer (fig. 13) than the underlying middle and lower Potomac aquifers. Generally, most light industrial and municipal ground-water users throughout the central part of the study area use this aquifer. This aquifer is capable of producing large quantities of generally good quality water suitable for most uses, but like the underlying Potomac aquifers, this aquifer contains water having chloride concentrations that increase downdip, thus precluding the use of the aquifer as a potable source of water in the eastern areas.

Typical electric-resistivity log patterns of the upper Potomac aquifer sediments are best illustrated in geophysical logs of wells 58J11, 58J5, plate 3, D-D′; 57G25, 57F2, plate 3, E-E′; 56F42, 57E10, 58D9, 60C7, plate 3, F-F′; 55D5, 55E3, plate 4, H-H′; 58B115, 58C51, plate 4, I-I′; and 54A3, 55A1, 59C28, 60C25, plate 4, J-J′. Generally, these resistivity patterns are very similar to the resistivity patterns of the underlying middle Potomac aquifer, but they are characteristically more massive and rounded in profile and are more easily correlated among logs. Also, the massively bedded sand sequences are commonly separated by thinner interbedded clays, as shown by the log of well 59C28 (pl. 4, J-J′). Corresponding natural-gamma logs commonly indicate the presence of interbedded sands and clays.

Drillers commonly refer to the upper Potomac aquifer sediments as "fine, white micaceous sands" and "dark micaceous clays," that frequently contain "wood fragments." They also note that these sediments are penetrated easily. On drillers' logs, the terms "variegated clay" and "red, brown and yellow clay" are noticeably absent from the descriptions of clays in this aquifer.

The contour map delineating the top of the upper Potomac aquifer (fig. 13) is based on the tops of the uppermost sand bodies identified at the control wells. Therefore, this map should only be used as a guide to indicate the approximate altitude of the top of this aquifer between control wells because of the interlensing nature of these sediments, the large distances between control points in some areas, and the general lack of data in the northern and eastern sections of the study area.

Sediments of the upper Potomac aquifer represent the effects of the first major marine transgression that inundated the study area. As the seas progressively encroached onto the delta complex, deposition occurred in everwidening estuaries and intertidal basins. Brown and Silvey (1977, p. 4) postulate that, based on grain size, deposition of the lower Upper Cretaceous sediments at well 61C1 (Moore's Bridge Water Treatment facility) took place in a littoral environment, possibly a tidal flat, with a semiprotected shoreline. Other studies of equivalent sediments in Maryland (Glaser, 1969; Hansen, 1969a) note the absence of typical marine transgressive strandline features, such as barrier beach and dune sediments, and suggest that deposition occurred in a marginal marine outer-delta environment with a vegetated, swampy shoreline.

UPPER POTOMAC CONFINING UNIT

The upper Potomac confining unit is defined by the major clayey strata directly above the upper Potomac aquifer. These clay beds are predominantly restricted to upper palynostratigraphic Zone IV, but also include clay beds of palynostratigraphic Zone III in the west-central parts of the study area and undifferentiated clays of latest Cretaceous age in the eastern regions of the study area. The upper Potomac confining unit correlates with the eastern part of the Patapsco confining unit in Maryland and the confining unit that overlies the upper Cape Fear aquifer in North Carolina (pl. 1). This confining unit is restricted to the subsurface; it overlies the upper Potomac aquifer and is overlain by the Brightseat aquifer in the north-central and northeastern regions of the study area, and by the Aquia aquifer throughout the remainder of its extent. It attains a maximum known thickness of 126 ft at well 66M1 in the northeastern part of the study area and pinches out along its western subsurface limit in the west-central part of the study area. The thickness of this confining unit is variable, but generally it thickens and dips to the northeast.

As in the case for the underlying upper Potomac aquifer, detailed lithologic data are available to the authors only from core samples obtained at well 61C1 located at the city of Norfolk during the Artificial Recharge project. The core information indicates (Brown and Silvey, 1977, p. 7) that the confining unit clays consist of highly expandable silty-clay to clayey-silt mixed-layer illite and montmorillonite, and minor amounts of kaolinite. On-site core descriptions (D.L. Brown, U.S. Geological Survey, written commun., 1971) describe this confining unit as a dark greenish-gray, micaceous, calcareous, slightly glauconitic and sandy, silty clay.

Numerous water wells drilled throughout the central and east-central regions of the study area penetrate and provide information on this confining unit. The clay beds identified as the upper Potomac confining unit are not a single, areally extensive layer, but rather, a series of interlayered clayey deposits. These individual clay layers are more extensive than the clayey deposits of the underlying middle and lower Potomac confining units and, therefore, are more easily correlated between wells. Water-level data indicate that individual clay units act locally as confining units and when viewed regionally, they constitute a single confinement as depicted by the thickness map of the upper Potomac confining unit (fig. 14).

Typical electric-resistivity log patterns of the upper Potomac confining unit sediments are best illustrated in geophysical logs of wells 58J11, 58J5, plate 3, D-D′; 57G22, 57G25, plate 3, E-E′; 57A1, plate 3, G-G′; and 60B1, plate 4, K-K′. Generally, these resistivity logs show broad U-shaped profiles that commonly contain numerous thin, interbedded sequences of sands and sandy clays. These sequences produce an erratic appearance in resistivity logs of the thick clay deposits of the upper Potomac confining unit. Drillers commonly refer to the upper Potomac confining unit sediments as "dark micaceous clays" or "dark sandy clays," that may contain shells or wood.

Like the underlying sediments of the upper Potomac aquifer, these confining units sediments also are the result of the first major marine transgression in the sedimentary section. The depositional environment was similar to that of the upper Potomac aquifer, but was a lower energy regime in a broad, low-lying outer delta.

UPPERMOST CRETACEOUS SEDIMENTS, UNDIFFERENTIATED

Marine deposits of latest Cretaceous age represent the next distinctive group of sediments in the sedimentary section. These deposits are sparsely represented in the eastern part of the study area. Uppermost Cretaceous sediments typically form relatively thin veneers of glauconitic clays, sandy clays, and chalky marls. The sediments attain a maximum known thickness of 70 ft at well 66M1 in the northeastern part of the study area and approximately 50 ft at well 61C1 in the southeastern part. These sediments are included as part of the upper Potomac confining-unit sequence and are not further differentiated in this report because of their restricted areal extent and their predominantly clayey composition.

After the regionwide Turonian erosional period, marine seas extensively covered the downwarped Coastal Plain areas of Maryland and North Carolina, depositing thick, extensive Upper Cretaceous marine sediments in the structural lows of the Salisbury and Albemarle embayments. Based on lithologic and paleontologic evidence, it appears that most of the Virginia Coastal Plain was elevated, in relation to sea level, throughout this time. Hansen (1978) proposes basement faulting along the southern limb of the Salisbury embayment as the mechanism responsible for the truncation or nondeposition of the uppermost Cretaceous deposits in the north-central and northwestern parts of the study area.

Cederstrom (1945a) suggests a Late Cretaceous age for deposits in the southeastern part of the study area, based on paleontological analysis of well cuttings. These sediments are reported to range from 10 to 100 ft thick and consist predominantly of clays and sandy clays. From correlation of geophysical logs and recent stratigraphic data, the authors determined that the thickness is 10 to 30 ft in southeastern Virginia. Brown and others (1972) also found the uppermost Cretaceous deposits in the southernmost part of the study area and, like Cederstrom, determined that the deposits are thin, predominantly clayey sediments, interbedded with a few thin sands. The Norfolk arch is undoubtedly the predominant controlling influence for the northern limit of these Upper Cretaceous deposits in southeastern Virginia.

PALEOCENE AND EOCENE PAMUNKEY GROUP

Marine deposits of Paleocene and Eocene age constitute the lower Tertiary (Paleogene) stratigraphic section known as the Pamunkey Group. From oldest to youngest, six formations consisting of the Brightseat, Aquia, Marlboro Clay, Nanjemoy, Piney Point, and Chickahominy comprise this group. From these six formations, five hydrogeologic units—three aquifers and two confining units—are identified. Throughout the study area, major regional unconformities separate the Pamunkey Group from the underlying Cretaceous deposits and the overlying upper Tertiary deposits. Within the Pamunkey Group lesser unconformities separate most of the formations. Generally, the

Pamunkey Group consists of glauconitic sands, silts, and clays, with varying amounts of shells. The notable exception is the Marlboro Clay, which consists solely of nonglauconitic, dense, plastic clay. Within the Aquia, Nanjemoy, and Piney Point Formations, cobble and boulder-sized calcareous concretions are common, as are thin layers of calcareous-cemented shell beds. By studying the sediment core collected at Oak Grove, Reinhardt and others (1980, p. 2) report that the depositional structures and sedimentary fabrics within the Pamunkey Group are representative of a depositional environment that was either extremely stable or a somewhat restricted marine shelf. Sedimentation occurred in a shallow, low-energy, inner to middle marine basin in the area north of the Norfolk arch (L. W. Ward, U.S. Geological Survey, personal commun., 1981). In the immediate area of the Norfolk arch, drillers' logs and geophysical logs indicate that the Pamunkey Group sediments thin considerably and become slightly coarser and less glauconitic, thus indicating a higher energy environment. South of the arch, the sediments again become noticeably finer, more glauconitic, and commonly contain a limy-mud matrix with numerous thin layers of limestone.

The reported presence of exposed greensand sediments in the study area dates back to the early 1800's. In 1891, the name Pamunkey was applied by Darton (1891) to the greensand sediments exposed along the Pamunkey River in Virginia, which he defined as a single formation of Eocene age. Shortly thereafter, Clark (1896, p. 3) identified two distinct stages—the Aquia Creek and Woodstock of the Eocene Pamunkey Formation. Subsequently, Clark and Martin (1901, p. 5) raised the Pamunkey Formation to group status and named the Aquia and Nanjemoy Formations within that group based on exposures along the Potomac River. The identifications of the remaining formations within the Pamunkey Group came much later and are discussed under the respective hydrogeologic sections.

The Pamunkey Group crops out extensively in the major stream valleys throughout the western parts of the study area. As a whole, this group of sediments thickens to the northeast, north of the Norfolk arch, and to the southeast, south of the arch. Generally, the sands of the Pamunkey Group yield abundant quantities of water that is suitable for most uses. Unlike the fluvial-deltaic deposits of the underlying Cretaceous sediments, the marine sediments of the Pamunkey Group generally consist of homogeneous and extensive blanket-type deposits that change little over large areas. Therefore, the depths to the tops of aquifers and the thicknesses of confining units tend to be fairly predictable, even between control wells separated by large distances.

BRIGHTSEAT AQUIFER

The Brightseat aquifer is herein defined as all interbedded sands of early Paleocene (Danian) age in the study area. The Brightseat aquifer correlates with the Brightseat aquifer of Maryland and pinches out southward against the north flank of the Norfolk arch (fig. 15). Therefore, no correlative hydrogeologic unit exists from the area of the Norfolk arch southward into North Carolina. This aquifer is the lowest Tertiary age aquifer in the study area. It overlies the upper Potomac confining unit and is overlain by the Brightseat confining unit throughout its extent. The Brightseat aquifer dips eastward at approximately 14 ft/mi and is lenticular in cross section. It attains a maximum thickness of more than 150 ft in the north-central part of the study area beneath the Chesapeake Bay and thins to nearly zero thickness along its western and southern limits.

As a result of the present study, the Brightseat aquifer became an identifiable and correlatable hydrogeologic unit in the Virginia Coastal Plain. Previous investigators placed these interbedded sediments within the Lower Cretaceous Potomac strata, with the exception of Darton and Keith (1901), who placed these beds in the Late Cretaceous. Recognition of this aquifer is based on geophysical-log correlations, in combination with analysis of drillers' logs and water-level data, throughout the north-central part of the study area and adjoining parts of southern Maryland. More recently, a definitive age for the unit was determined by foraminifers and pollen analysis of core samples obtained from a test well in Lexington Park, located in southern Maryland (H.J.Hansen, Maryland Geological Survey, written commun., 1983). Hansen and Wilson (1984, p. 11), from information obtained at the Lexington Park test well, tentatively identified correlative sediments in Maryland as the Mattaponi(?) Formation, and the sands as the Mattaponi(?) aquifer, based on Cederstrom's (1957) designation of Colonial Beach-type well. This report does not use the term "Mattaponi." Geophysical log interpretations, supported by paleontologic and lithologic data, have led the authors to doubt the existence of a Mattaponi Formation, as described by Cederstrom (1957) and later modified by Teifke (1973), within the study area. Definitive stratigraphic analysis obtained from the core hole at Oak Grove (Virginia Division of Mineral Resources, 1980), which is located near Cederstrom's designated Colonial Beach-type well, also raises serious doubt as to the existence of a Mattaponi Formation (Reinhardt and others, 1980, p. 4). In addition, Cederstrom (1957, p. 19) uses two drilled wells at Oak Grove to support his Mattaponi hypothesis, which, when compared to the Oak Grove core hole, show that correlative strata have been positively identified as the Aquia Formation and the Potomac Formation (Reinhardt and others, 1980).

This report follows Ward's (1984, p. 14) analysis and recommendation that the name Mattaponi be dropped from further usage because it was defined on age determinations derived from foraminifera, and that the designated strata of this formation had been previously assigned to other lithic units. The name Brightseat is derived from the Brightseat Formation, identified by Bennett and Collins (1952) from outcrops near the town of Brightseat, Md.; the Brightseat is described as a dark gray, micaceous, sandy clay, 4 to 8 ft thick, of early Paleocene age. The interbedded sand and clay facies of the Brightseat Formation, herein designated as the Brightseat aquifer, have never been recognized as a hydrogeologic unit previous to this study.

The Brightseat aquifer is restricted to the subsurface, and its eastern areal extent is not well defined owing to the lack of sufficient borehole and paleontologic information throughout the Eastern Shore Peninsula area. Thus far, correlation of this aquifer is limited to its area of extent, as shown in the aquifer top map (fig. 15), plus a small adjoining area in southern Maryland.

The Brightseat aquifer consists of interstratified blanket sands and silty clays. The sands, as described in drillers' logs, consist predominantly of fine, well-sorted, white quartz but also contain shells, lignite, mica, and minor amounts of glauconite. The clays, as described in drillers' logs, consist of dark, micaceous, silt and clay, commonly gray, dark green, and black, but also contain minor amounts of shells, sand, and lignite. From core samples of their Mattaponi(?) aquifer, Hansen and Wilson (1984, p. 11-13) describe the sands as typically gray, medium, moderately well sorted, clean and dominantly quartzose, and the clays as generally gray, but often mottled, with organic inclusions and thin laminae of light-colored, fine, micaceous sand and silt.

Numerous industrial and municipal ground-water users, especially the seafood-processing industries in the northern part of the study area, use this aquifer. This aquifer is capable of producing large quantities of high-quality water suitable for most uses. Hansen and Wilson (1984, p. 24) note that the water from this aquifer in Maryland is of excellent quality, relatively low in dissolved solids, and can be used with a minimum of treatment.

Typical electric-resistivity log patterns of the Brightseat aquifer sediments are best illustrated on geophysical logs of wells 56N7 and 60L19, plate 2, A-A'; 57P1, plate 2, C-C'; and 57J3, 58J11, and 59K17, plate 3, D-D'. Generally, the resistivity patterns are a series of U-shaped profiles. The U-shaped profiles indicate the characteristic interbedded clean sand and silty clay sequences associated with these aquifer sediments. In the updip section of this aquifer, the U-shaped patterns are commonly narrow, as in well 56N7, plate 2, A-A', and contain only one or two well-defined sand beds. In the downdip section, many more U-shaped patterns are evident; the silty clays and sands become thicker, as in well 60L19, plate 2, A-A', and typically are interstratified with thin clay beds. Corresponding natural-gamma logs exhibit well-defined clay and sand patterns with sharp lithologic contacts, which again indicate their well-bedded and alternating nature.

Drillers commonly refer to the Brightseat aquifer sediments as "fine white sands with some black sands" and "gray, dark, or black, micaceous clays," both sometimes containing shells and(or) lignite. Drillers also note that these sediments are readily penetrated in comparison to the underlying Potomac sediments. Individual sand and clay beds of the Brightseat aquifer are easily correlated among geophysical well logs because of their well-defined interbedded patterns. The contour map delineating the top of this aquifer (fig. 15) is based on the uppermost sand identified at each control well. Because of the interbedded characteristics of these sands, this map can be used to indicate, with a fair degree of accuracy, the approximate altitude of the top of this aquifer throughout its extent.

Based on its interbedded nature, lithologic characteristics, and its equivalent age and stratigraphic position with the type Brightseat Formation, this aquifer's environment of deposition seems to be dominated by intertidal marine processes and probably represents a nearshore or lagoonal environment. Hansen and Wilson (1984, p. 13) note that core analysis of their equivalent Mattaponi(?) aquifer reveals a sparse inner shelf fauna which indicates a water depth of less than 65 ft. Hansen (Maryland Geological Survey, oral commun., 1983) also suggests that these deposits probably represent a nearshore facies of the open-marine type Brightseat Formation.

BRIGHTSEAT CONFINING UNIT

The Brightseat confining unit is defined by the uppermost clay bed of the interbedded sand and clay sequence of early Paleocene (Danian) age deposits. This confining unit correlates with the Brightseat confining unit of Maryland. The Brightseat confining unit pinches out southward against the north flank of the Norfolk arch (fig. 16) and, therefore, has no correlative unit from the area of the Norfolk arch southward into North Carolina. It should be noted that geophysical and lithologic log correlations indicate the Brightseat confining unit is, for the most part, a continuation of the Brightseat Formation. The Brightseat Formation, as defined by Bennett and Collins (1952), is an early Paleocene, dark-gray, silty and sandy, micaceous clay that underlies the Aquia greensands. In the area of study, the Brightseat confining unit is areally restricted to that part of the Brightseat Formation that overlies the Brightseat aquifer. The Brightseat Formation crops out throughout the northwestern part of the study area, but its hydrogeologic significance changes. In the northwestern part of the study area, the Brightseat Formation comprises the upper part of the middle Potomac confining unit that separates the underlying middle Potomac aquifer from the overlying Aquia aquifer. In contrast, the Brightseat Formation in the north-central and northeastern parts of the study area wholly comprises the Brightseat confining unit that separates the underlying Brightseat aquifer from the overlying Aquia aquifer.

The Brightseat confining unit is restricted to the subsurface and its eastern areal extent is not well defined owing to the lack of sufficient borehole and paleontological information throughout the Eastern Shore Peninsula area. This confining unit attains a maximum known thickness of 62 ft at well 63L1 (fig. 7) in the northern part of the study area beneath the Chesapeake Bay and thins to nearly zero thickness along its western and southern limits (fig. 16). Its northwestern limit, where the Brightseat Formation continues northwestward as part of the middle Potomac confining unit, is an arbitrary break dependent on the limit of the underlying Brightseat aquifer.

The Brightseat confining unit consists of an areally extensive, silty clay bed which locally is interbedded with very thin sands or sandy clays. These clays are micaceous, commonly dark in color although light-gray, red and mottled clays are noted, and may contain shells and carbonaceous material. Hansen and Wilson (1984, p. 41) describe a core sample obtained from a correlative unit in the Lexington Park test well as a clayey silt, that contains very fine quartz sand, and is micaceous, slightly calcareous and lignitic, yellowish greenish gray, oxidized to dark orange in places.

Typical electric-resistivity log patterns of the Brightseat confining unit sediments are best illustrated on geophysical logs of wells 56N7 and 60L19, plate 2, A-A'; 56M10 and 57P1, plate 2, C-C'; and 58J11 and 59K17, plate 3, D-D'. Generally, these resistivity patterns are U-shaped in profile, indicating a well-bedded, silty clay in sharp lithologic contact with overlying and underlying aquifer sands. In some areas, the lower contact with the underlying Brightseat aquifer is gradational, as illustrated in geophysical well logs 57P1, plate 2, C-C', and 59K17, plate 3, D-D'. This confining unit may contain thin interbedded sands or clayey sands, as illustrated in geophysical well log 60L19, plate 2, A-A' and plate 3, D-D'. Corresponding natural-gamma log patterns commonly exhibit a pronounced clayey response to this confining-unit interval, again indicating a well-bedded clay or silty clay in sharp lithologic contact with overlying and underlying sands. Drillers commonly refer to Brightseat confining unit clays as "dark, micaceous clays," sometimes containing "sands, shells, and lignite." This confining unit is easily correlated among geophysical well logs because it has a large areal extent and, when evaluated in combination with drillers' logs, it immediately underlies the greensands (or blacksands) of the Aquia aquifer and overlies the predominantly white sands of the Brightseat aquifer.

AQUIA AQUIFER

The Aquia aquifer is defined by the predominantly sandy facies of the Aquia Formation. These sediments are late Paleocene (Thanetian) in age and correlate with the Aquia-Rancocas aquifer in Maryland and the Beaufort aquifer in North Carolina (pl. 1). The Aquia aquifer crops out extensively in most major stream valleys of the study area just east of outcrops of the middle Potomac confining unit and in a small area in the northwestern region just west of the Potomac River. It overlies three separate hydrogeologic units—the Brightseat confining unit in the north-central area; the upper Potomac confining unit in the central and southern regions; and the middle Potomac confining unit throughout the western region. In turn, the Aquia aquifer is overlain by the Nanjemoy-Marlboro Clay confining unit. The Aquia aquifer is a continuous, elongate-lenticular sand body that thins slightly to the west and thins greatly to the east, pinching out near the western shore of the Chesapeake Bay and along the southeastern part of the study area. In the northern and central regions the aquifer pinches out eastward. This pinch-out is based on subsurface studies by Hansen (1974) and Chapelle and Drummond (1983) in Maryland and was extrapolated into the study area by the authors. Evidence for the exact position of this pinch-out is lacking owing to the scarcity of borehole and stratigraphic data available in the eastern region of the study area. In the southern region, the eastern limit is based on lithologic and geophysical log data, but again its position is approximate because of the scarcity of data. The eastern pinch-out is due to a sand-to-clay facies change in the downdip section of this aquifer unit (Hansen, 1974, p. 15). The Aquia aquifer dips eastward at approximately 10 ft/mi and attains a maximum known thickness of 147 ft at well 54R3 (pl. 2, B-B') in the northwestern part of the study area. Generally, this aquifer is thickest in the northwestern and west-central regions of the study area, attaining an average thickness of 100 ft or more. In the north-central and central regions, its thickness commonly ranges from 40 to 70 ft, and in the southern regions its thickness is usually about 20 ft. It rapidly thins westward to nearly zero thickness and extends, mainly in the subsurface, to just east of the Fall Line along most of its length.

The Aquia aquifer consists of a predominantly massively bedded unit composed of very fine to medium glauconite and quartz sands, in variation and with minor amounts of shells and clay. From outcrops in its type area, Aquia Creek of Stafford County, Va., Clark (1896) first described the Aquia Formation as a marine unit consisting of greensands and greensand marls interbedded with local thin layers composed almost entirely of shells. From analysis of the Oak Grove core (well 54P3), Gibson and others (1980, p. 16) describe the Aquia Formation as very well-sorted, medium- to dark-green, massive, fine to medium glauconitic sand with sparse shelly intervals. Reinhardt and others (1980, p. 5), who also analyzed the Aquia section of the Oak Grove core, note that the Aquia contains illitic clay matrices (generally less than 10 percent by weight), carbonate cemented intervals, and a basal part containing coarse sands, pebbles, small bones, and fish teeth.

Numerous wells drilled in the study area penetrate this aquifer, and many light industrial, small municipal, and domestic users use the Aquia as a water-supply source. Chapelle and Drummond (1983, p. 75) report that ground water produced from the Aquia in Maryland is capable of supplying large quantities of water suitable for most uses. The Aquia in the northern two-thirds of the study area is very similar to the Aquia of Maryland, although somewhat thinner, and similar ground-water conditions exist. However, in the southern part of the study area, the Aquia is much finer grained, commonly contains a limy-mud matrix, and thin limestone beds, and is not commonly used as an aquifer.

Typical electric-resistivity log patterns of the Aquia aquifer sediments are illustrated on geophysical logs of wells 53P4, 54P3, 56N7, plate 2, A-A′; 52N16, 54Q11, 54R3, plate 2, B-B′; 53K17, 56M10, 57P1, plate 2, C-C′; 54H11, 55H1, 57G22, 57G25, plate 3, E-E′; and 54G10, 55F20, 56F42, plate 3, F-F′. Generally, these resistivity patterns are wave-shaped in profile, commonly a series of two or three waves which often contain sharp spiky peaks. The wave-shaped profiles indicate the massively bedded sequences of glauconitic sands characteristic of this aquifer, whereas the sharp spiky peaks indicate the shell beds and related, calcareously cemented shell layers also common in this aquifer. Noted in many resistivity logs, especially in the updip sections, is a pronounced thin U-shaped profile in the lowermost part of this aquifer. This U-shaped profile indicates the basal coarser part of this unit, as described previously from the Oak Grove core analysis. Resistivity logs generally indicate medium resistivity values for these sediments, except for the basal part, which generally has a high resistivity value. Also, resistivity logs exhibit sharp lower and upper lithologic contacts for the massive Aquia sand unit. Corresponding natural-gamma logs have a characteristically high erratic gamma response to these sediments, which appears to suggest an unusually high clay content, but in fact, is an indication of the high glauconite content. The hydrogeologic boundaries cannot be determined from natural-gamma logs because the lithologic contacts with the overlying and underlying clays are masked by the high gamma response to the glauconite. Drillers commonly refer to the Aquia aquifer sediments as "fine, blacksands or greensands" that often contain shells and(or) hard-streaks. Drillers note that these sediments are generally quite soft and at times refer to them as "running sands, or caving sands." The Aquia aquifer is easily correlated among geophysical logs because the resistivity pattern changes little from log to log and shows numerous correlatable shell-bed spikes. By using the combination of drillers' logs and geophysical logs, Aquia aquifer sands can be located between two distinctive clays—an upper pink, light-gray, or dark-brown clay and a lower dark-gray or black clay. The contour map delineating the top of this aquifer (pl. 17) can be used to indicate, very accurately, the altitude of the top of this aquifer throughout its extent. Thus, the top of this unit is fairly constant and can be predicted between control wells separated by large distances. Studies (Drobnyk, 1965; Hansen, 1974; Gibson and others, 1980) on the depositional environment of the Aquia Formation suggest that the Aquia was deposited in a shallow, inner shelf marine basin, below wave base, with slight fluctuation of water depths (100- to 330-ft range).

NANJEMOY-MARLBORO CLAY CONFINING UNIT

The Nanjemoy-Marlboro Clay confining unit is defined as the predominantly clayey deposits of the Nanjemoy and Marlboro Clay Formations. This confining unit is composed of two distinctly different formations—the lower Marlboro Clay and the upper Nanjemoy. These sediments are latest Paleocene to middle Eocene in age and correlate with the Nanjemoy-Marlboro confining unit in Maryland and the confining unit overlying the Beaufort aquifer in North Carolina (pl. 1). The Nanjemoy-Marlboro Clay confining unit crops out extensively in most of the major stream valleys of the study area just east of outcrops of the Aquia aquifer. It overlaps the Aquia aquifer and is overlain by the Chickahominy-Piney Point aquifer throughout most of the study area. This confining unit attains a maximum known thickness of 172 ft at well 66M1 in the northeastern part of the Eastern Shore Peninsula and thins to nearly zero thickness along its western limit near the Fall Line. Its thickness is somewhat variable (fig. 18), but generally this unit is wedge shaped and thickens towards the northeast. The lower formation (the Marlboro Clay) of this confining unit is areally restricted to the northern half of the study area and its eastern extent beneath the Chesapeake Bay and Eastern Shore Peninsula is not known owing to the lack of lithologic and stratigraphic data in these areas. The upper formation (the Nanjemoy) is areally extensive throughout the study area and comprises most of the thickness of this unit. In the southern area, the Marlboro Clay pinches out against the northern flank of the Norfolk arch and the Nanjemoy directly overlies the Aquia aquifer. The Marlboro Clay was first identified and described by Clark and Martin (1901) as a red clay and was considered, until just recently, to be the lowest member of the Nanjemoy Formation. Glaser, in 1971, raised the Marlboro Clay to formation status based on its mappability as a unit, and Gibson and others (1980, p. 29) report that it straddles the Paleocene-Eocene boundary. The name Nanjemoy also was first applied by Clark and Martin (1901) for highly argillaceous greensands and was divided into two members—a lower clayey Patapsco Member and an upper sandy Woodstock Member. In the northwestern part of the study area, the upper Woodstock Member of the Nanjemoy is considered to be part of the overlying Chickahominy-Piney Point aquifer because of its predominantly sandy facies. However, geophysical logs indicate that the Woodstock Member becomes increasingly clayey downdip and throughout the rest of the study area and it is, therefore, considered as part of the Nanjemoy-Marlboro Clay confining unit.

Lithologic analysis of the Tertiary section from the Oak Grove core hole (well 54P3) by Reinhardt, Newell, and others (1980) indicates that the Marlboro Clay consists of a compact, massively bedded, extensively burrowed, predominantly red to gray, mottled clay composed mostly of a kaolinite-illite mixture. They also note that this formation is essentially structureless, but contains irregular lenses of locally laminated and cross-laminated fine silt. Reinhardt, Newell, and others' (1980) analysis of the Nanjemoy reveals that it consists of a thick, massively bedded, dark-green to dark brown-green, variably clayey and shelly, micaceous greensand. The clay content ranges from 15 to 80 percent and is composed mostly of illite. They also note that this unit is extensively burrowed, which produces a mottled appearance to the sediments, and that the Nanjemoy becomes increasingly sandy in its upper part (i.e., Woodstock Member). The Marlboro Clay commonly ranges from 2 to 20 ft thick and the Nanjemoy commonly ranges from 20 to over 120 ft thick.

Typical electric-resistivity log patterns of the Nanjemoy-Marlboro Clay confining unit sediments are best illustrated on geophysical logs of wells 53P4, 54P3, 56N7, 59L5, 60L19, plate 2, A-A'; 52N13, 54Q11, 54R3, plate 2, B-B'; 52K10, 53K17, 56M10, 57P1, plate 2, C-C'; 55H1, 57J3, 58J11, 58J5, 59K17, 59K19, plate 3, D-D'; 52K6, 54J4, 54H11, 55H1, 57G22, 57G25, 58F3, plate 3, E-E'; 56F42, 57E10, 57D3, 58D9, 59D1, 60C6, plate 3, F-F'; and 58B115, 58C51, 58C8, plate 4, I-I'. Generally, the resistivity patterns are flat in profile, characteristic of massively bedded, predominantly clayey deposits. Commonly these flat profiles contain interbedded sandy clays or sands, which cause an erratic appearance to the generally flat resistivity patterns. The lower contact with the underlying Aquia aquifer is always sharp and pronounced, and the upper contact with the Chickahominy-Piney Point aquifer is also sharp and pronounced, but can be gradational, especially where the upper Woodstock Member of the Nanjemoy is predominantly sandy. In the southern part of the study area, this confining unit becomes considerably thinner as it approaches and transgresses the Norfolk arch area. Also, it becomes more interbedded with sands and sandy clays in the southeast, as illustrated in well logs 59C28 and 60C25, plate 4, J-J'. Corresponding natural-gamma log patterns indicate the presence of massively bedded glauconitic clayey sediments. Drillers commonly refer to the Nanjemoy-Marlboro Clay confining unit sediments as "pink, gray, or sometimes white clay" and "slick or sticky" for the Marlboro Clay, and as "dark green or brown-green, silty clays or sandy clays" commonly with "shells and black sands" for the Nanjemoy. These clayey confining-unit sediments are easily recognized on resistivity logs and drillers' logs by their characteristic thick clay pattern and stratigraphic position above the Aquia greensands. The Nanjemoy-Marlboro Clay confining unit is easily identified and correlated on resistivity logs because it is overlain and underlain by characteristic sands of the Chickahominy-Piney Point and Aquia aquifers, respectively.

Analyses from the Oak Grove core hole (Reinhardt and others, 1980; Gibson and others, 1980) indicate that the paleoenvironment, for the Marlboro Clay, consisted of a shallow and protected (ponded), low-energy, brackish water basin, such as an estuary or lagoon, and for the Nanjemoy, a stable or protected inner to middle marine shelf with water levels that ranged from about 50 to 230 ft.

CHICKAHOMINY-PINEY POINT AQUIFER

The Chickahominy-Piney Point aquifer is defined for the most part by the predominantly sandy deposits of the Chickahominy and Piney Point Formations. The Piney Point comprises most of the aquifer unit, with the Chickahominy and the Woodstock Member of the Nanjemoy Formations comprising the remainder. These sediments are middle to late Eocene in age and correlate with the Piney Point-Nanjemoy aquifer in Maryland and the Castle Hayne aquifer in North Carolina (pl. 1). The Chickahominy-Piney Point aquifer crops out in most of the major stream valleys of the study area from the James River northward, just east of outcrops of the Nanjemoy-Marlboro Clay confining unit. It overlies the Nanjemoy-Marlboro Clay confining unit and is overlain and transgressed by the Calvert confining unit. The Chickahominy-Piney Point aquifer is wedge shaped in cross section, thickens eastward, and thins to nearly zero thickness along its western limit in the western part of the study area. Similar to the Aquia aquifer, this aquifer undergoes a sand-to-clay facies change that causes it to pinch-out in the vicinity of the Eastern Shore Peninsula (fig. 19). East of this line, the aquifer becomes predominantly clayey. The eastern limit (pinch-out) of this aquifer is an approximate boundary based on subsurface studies done in Maryland and Delaware by Hansen (1972), Leahy (1982), Chapelle and Drummond (1983) and extrapolated by the authors into the study area. Evidence for the exact position of this pinch-out is lacking due to the scarcity of borehole and stratigraphic data available in the northeastern and east-central parts of the study area. In the southeastern area, lithologic and geophysical log data indicate that the Chickahominy-Piney Point aquifer is continuous throughout the area and that the facies change probably occurs offshore. The Chickahominy-Piney Point aquifer dips eastward at approximately 12 ft/mi. In the western half of the study area, the contours of the top of the aquifer are more widely spaced than in the eastern half due to postdepositional erosion and subsequent beveling of the Piney Point Formation during the Oligocene and early Miocene (Otton, 1955; Hansen, 1972, 1977). Also, the northwestern limit is not the actual margin of the Piney Point Formation, but rather reflects the limit of the upper, predominantly sandy facies, of the underlying Nanjemoy Formation (the Woodstock Member) which are hydrologically connected to the Chickahominy-Piney Point aquifer. This aquifer attains a maximum known thickness of 140 ft at well 60L19, plates 2, A-A′ and 3, D-D′, in the north-central region of the study area, and 165 ft at well 61B2, plates 3, F-F′ and 4, K-K′, in the southeastern region. It generally ranges from 50 to 100 ft thick throughout most of the study area.

The Chickahominy-Piney Point aquifer consists of thickly bedded olive-green to dark greenish-gray, fine to coarse, glauconitic quartz sands interbedded with thin glauconitic/illitic clays and calcareously cemented shell beds. The Piney Point Formation was first identified (Shifflett, 1948) from characteristic foraminifera in cuttings of drilled wells in the Coastal Plain of southern Maryland. This unit was later named and defined by Otton (1955), again based on sample cuttings in Maryland, as a fine to medium glauconitic sand interspersed with thin shell rock layers, and containing a diagnostic late Eocene age foraminiferal assemblage. The Piney Point has since been redefined by Brown and others (1972) to be middle Eocene in age. Cushman and Cederstrom (1945, p. 2) identify and define the Chickahominy Formation as a highly glauconitic clay interbedded with glauconitic sands and shell rock layers, and containing characteristic foraminiferal fauna of late Eocene age. The type well for the Chickahominy Formation is located in Yorktown, Va., but many other wells throughout the lower York-James Peninsula penetrate this formation. During this study, the authors noticed no appreciable difference or distinction between the Chickahominy and Piney Point Formations based on lithologic and geophysical log-correlations; therefore, they were combined into the same aquifer unit. It should be noted that the Chickahominy-Piney Point aquifer also contains sediments of late Oligocene and early Miocene age. These sediments are very thin and typically consist of fine-grained, white, quartzose sands with glauconite and shells interspersed throughout. The glauconite is primarily reworked material (L.W. Ward, U.S. Geological Survey, oral commun., 1983) and the shells commonly form thin indurated layers in the subsurface, much like the shell layers of the Piney Point Formation. Ward (1985) has identified these sediments in outcrops along major streams in the central part of the study area and proposes the name "Old Church Formation" for this unit, assigning it to the basal part of the Chesapeake Group. Analyses (L.E. Edwards, U.S. Geological Survey, written commun., 1982 and 1983) of core samples from Gloucester County (well 58H4) and the cities of Suffolk (well 58B115) and Chesapeake (near well 58A2) have also identified the presence of these deposits. Electric-resistivity logs, in conjunction with paleontological analysis, indicate that these sandy deposits directly overlie the Piney Point and Chickahominy Formations and, for this reason, are included in the Chickahominy-Piney Point aquifer and are not further differentiated in this report.